

La clase pasada vimos:

Efecto Hall en el modelo de Drude.

Conductividad AC (alterna u óptica) en el modelo de Drude.

Función dieléctrica: condición de transparencia de metales

Oscilaciones y frecuencia de plasma

En esta clase veremos:

Oscilaciones y frecuencia de plasma

Hetero-estructuras: Sistemas semiconductores de baja dimensionalidad

REPASO

## Modelo de Drude

$$\mathbf{j} = \sigma \mathbf{E}; \quad \sigma = \frac{ne^2\tau}{m}.$$

Conductividad DC o estática

$$R_H = \frac{E_y}{j_x H}$$

$$R_H = -\frac{1}{ne\tau}$$

Coefficiente de Hall

$$\mathbf{E}(t) = \text{Re}(\mathbf{E}(\omega)e^{-i\omega t}).$$

$$\mathbf{j}(\omega) = \sigma(\omega)\mathbf{E}(\omega),$$

$$\sigma(\omega) = \frac{\sigma_0}{1 - i\omega\tau}, \quad \sigma_0 = \frac{ne^2\tau}{m}.$$

Conductividad AC u óptica

REPASO

## Modelo de Drude

$$-\nabla^2 \mathbf{E} = \frac{\omega^2}{c^2} \epsilon(\omega) \mathbf{E}$$

Constante/función dieléctrica

$$\epsilon(\omega) = 1 + \frac{4\pi i \sigma}{\omega}$$

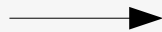
Relación entre  
**conductividad** y  
**función dieléctrica!**

$$\epsilon(\omega) = 1 - \frac{\omega_p^2}{\omega^2}$$

$$\omega_p^2 = \frac{4\pi n e^2}{m}$$

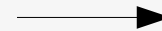
para frecuencia alta  $\omega\tau \gg 1$

$$\omega < \omega_p$$



el metal es *opaco*

$$\omega > \omega_p$$



el metal es *transparente*

# Modelo de Drude

## Oscilaciones de carga: plasmones

El gas de electrones puede tener oscilaciones de la densidad de carga

$$\omega_p^2 = \frac{4\pi n e^2}{m} \quad (1.38)$$

$$\nabla \cdot \mathbf{j} = - \frac{\hat{c}\rho}{\hat{c}t}$$

$$\nabla \cdot \mathbf{j}(\omega) = i\omega\rho(\omega).$$

$$\nabla \cdot \mathbf{E}(\omega) = 4\pi\rho(\omega).$$

$$\mathbf{j}(\mathbf{r}, \omega) = \sigma(\omega)\mathbf{E}(\mathbf{r}, \omega).$$

$$i\omega\rho(\omega) = 4\pi\sigma(\omega)\rho(\omega).$$

Pedimos que  $\rho(\omega)$  no se anule

This has a solution provided that

$$1 + \frac{4\pi i\sigma(\omega)}{\omega} = 0,$$

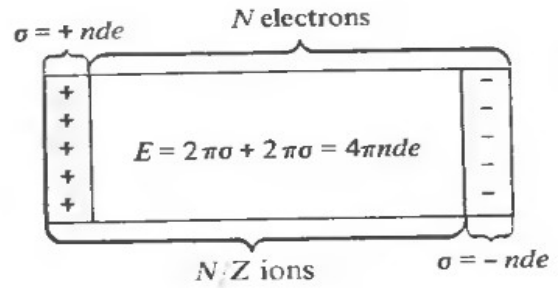
O sea, pedimos que se anule :

$$\epsilon(\omega) = 1 + \frac{4\pi i\sigma}{\omega}$$

análogo a la condición para pasar de opaco a transparente.

The nature of this charge density wave, known as a plasma oscillation or plasmon, can be understood in terms of a very simple model.<sup>23</sup> Imagine displacing the entire electron gas, as a whole, through a distance  $d$  with respect to the fixed positive background of the ions (Figure 1.5).<sup>24</sup> The resulting surface charge gives rise to an electric field of magnitude  $4\pi\sigma$ , where  $\sigma$  is the charge per unit area<sup>25</sup> at either end of the slab.

**Figure 1.5**  
Simple model of a plasma oscillation.



Consequently the electron gas as a whole will obey the equation of motion:

$$Nm\ddot{d} = -Ne|4\pi\sigma| = -Ne(4\pi nde) = -4\pi ne^2Nd, \quad (1.46)$$

which leads to oscillation at the plasma frequency.

Few direct observations have been made of plasmons. Perhaps the most notable is the observation of energy losses in multiples of  $\hbar\omega_p$  when electrons are fired through thin, metallic films.<sup>26</sup> Nevertheless, the possibility of their excitation in the course of other electronic processes must always be borne in mind.

$$\omega_p^2 = \frac{4\pi ne^2}{m}$$

<sup>26</sup> C. J. Powell and J. B. Swan, *Phys. Rev.* **115**, 869 (1959).

# Sistemas de baja dimensionalidad

## 2. Sistemas de baja dimensionalidad

Propiedades generales, crecimiento y dopaje. Ingeniería de bandas de energía. Ejemplos: pozos, cables y puntos cuánticos. Aproximación de función envolvente. Gas de electrones quasi-bidimensional. Ocupación de subbandas.

# THE PHYSICS OF LOW-DIMENSIONAL SEMICONDUCTORS

AN INTRODUCTION

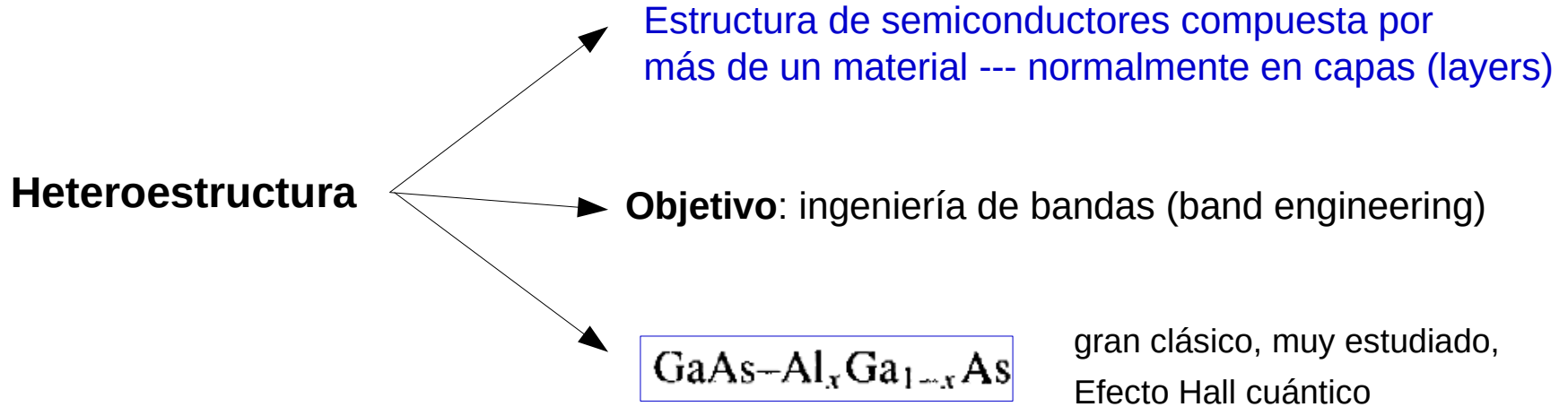
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# 3

## HETEROSTRUCTURES



Inicialmente se buscaron combinaciones con buen **matching** del **parámetro de red** para evitar la **tensión** en las capas sucesivas, pero cada vez se abandona más esa idea y se trabaja con capas tensionadas (strained layers).



# Crystal Structures of Elements at STP

STP - Standard Temperature and Pressure

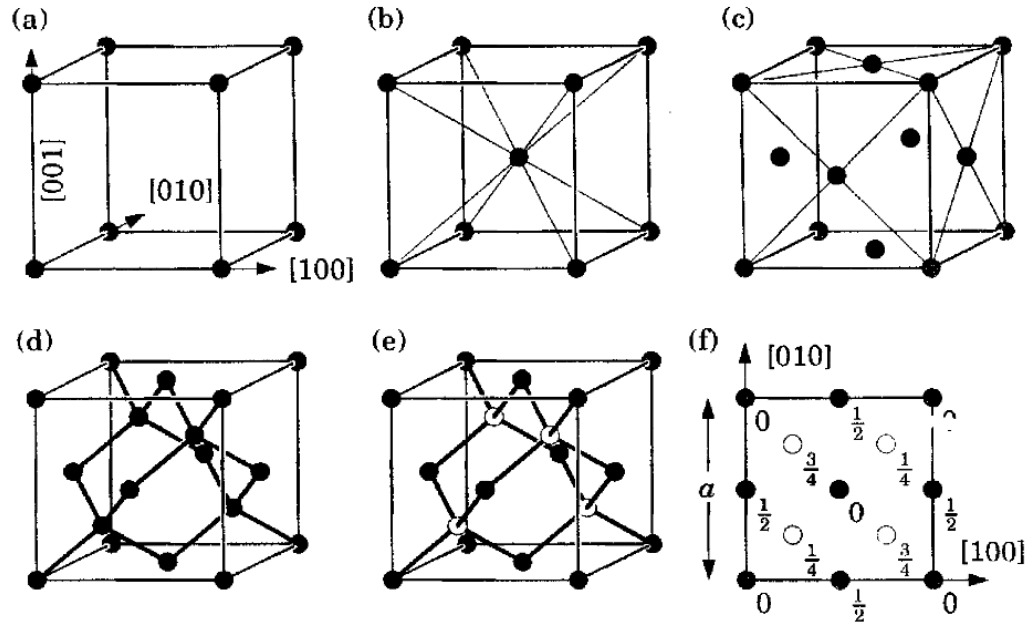
IV

<b>H</b> HEX																	<b>He</b> HCP						
<b>Li</b> BCC	<b>Be</b> HCP	BCC - Body-centered Cubic FCC - Face-centered Cubic HEX - Simple Hexagonal HCP - Close-packed Hexagonal DHCP - Double Close-packed Hexagonal RHO - Rhombohedral										BCT - Body-centered Tetragonal ORTH - Orthorhombic DC - Diamond Cubic DT - Diamond Tetragonal SC - Simple Cubic * predicted crystal structure				<b>B</b> RHO	<b>C</b> HEX	<b>N</b> complex HCP	<b>O</b> P-cubic	<b>F</b> F-cubic	<b>Ne</b> FCC		
<b>Na</b> BCC	<b>Mg</b> HCP																	<b>Al</b> FCC	<b>Si</b> DC	<b>P</b> ORTH	<b>S</b> ORTH	<b>Cl</b> complex ORTH	<b>Ar</b> FCC
<b>K</b> BCC	<b>Ca</b> FCC	<b>Sc</b> HCP	<b>Ti</b> HCP	<b>V</b> BCC	<b>Cr</b> BCC	<b>Mn</b> α-Mn	<b>Fe</b> BCC	<b>Co</b> HCP	<b>Ni</b> FCC	<b>Cu</b> FCC	<b>Zn</b> HCP	<b>Ga</b> complex F-ORTH	<b>Ge</b> DC	<b>As</b> P-RHO	<b>Se</b> complex HEX	<b>Br</b> complex ORTH	<b>Kr</b> FCC						
<b>Rb</b> BCC	<b>Sr</b> FCC	<b>Y</b> HCP	<b>Zr</b> HCP	<b>Nb</b> BCC	<b>Mo</b> BCC	<b>Tc</b> HCP	<b>Ru</b> HCP	<b>Rh</b> FCC	<b>Pd</b> FCC	<b>Ag</b> FCC	<b>Cd</b> HCP	<b>In</b> BCT	<b>Sn</b> DT	<b>Sb</b> P-RHO	<b>Te</b> complex HEX	<b>I</b> complex ORTH	<b>Xe</b> FCC						
<b>Cs</b> BCC	<b>Ba</b> BCC	57-71	<b>Hf</b> HCP	<b>Ta</b> BCC	<b>W</b> BCC	<b>Re</b> HCP	<b>Os</b> HCP	<b>Ir</b> FCC	<b>Pt</b> FCC	<b>Au</b> FCC	<b>Hg</b> RHO	<b>Tl</b> HCP	<b>Pb</b> FCC	<b>Bi</b> RHO	<b>Po</b> SC	<b>At</b> CC*	<b>Rn</b> FCC*						
<b>Fr</b> BCC*	<b>Ra</b> BCC	89-103	<b>Rf</b> HCP*	<b>Db</b> BCC*	<b>Sg</b> BCC*	<b>Bh</b> HCP*	<b>Hs</b> HCP*	<b>Mt</b> FCC*	<b>Ds</b> BCC*	<b>Rg</b> BCC*	<b>Cn</b> HCP*	<b>Nh</b> HCP*	<b>Fl</b> FCC*	<b>Mc</b> UNKNOWN	<b>Lv</b> UNKNOWN	<b>Ts</b> UNKNOWN	<b>Og</b> FCC*						

	Solid state at STP
	Liquid state at STP
	Gaseous state at STP

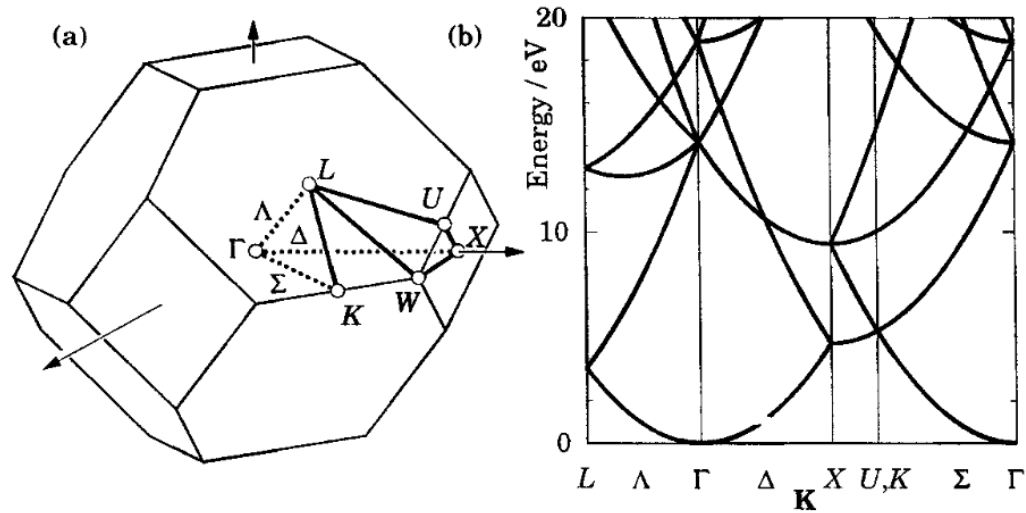
<b>La</b> DHCP	<b>Ce</b> DHCP	<b>Pr</b> DHCP	<b>Nd</b> DHCP	<b>Pm</b> DHCP	<b>Sm</b> complex RHO	<b>Eu</b> BCC	<b>Gd</b> HCP	<b>Tb</b> HCP	<b>Dy</b> HCP	<b>Ho</b> HCP	<b>Er</b> HCP	<b>Tm</b> HCP	<b>Yb</b> FCC	<b>Lu</b> HCP
<b>Ac</b> FCC	<b>Th</b> FCC	<b>Pa</b> BCT	<b>U</b> ORTH	<b>Np</b> ORTH	<b>Pu</b> MONO	<b>Am</b> DHCP	<b>Cm</b> DHCP	<b>Bk</b> DHCP	<b>Cf</b> DHCP	<b>Es</b> FCC	<b>Fm</b> FCC*	<b>Md</b> FCC*	<b>No</b> FCC*	<b>Lr</b> HCP*

# Estructuras cristalinas: FCC, diamante y zincblende



**FIGURE 2.11.** Cubic crystal structures: (a) simple, (b) body-centred, and (c) face-centred cubic lattices. The structures of the common semiconductors are (d) diamond for elements and (e) zinc blende for compounds. The plan (f) shows the height of the atoms in units of the lattice constant for the zinc-blende structure.

# Estructuras cristalinas: FCC, diamante y zincblende



**FIGURE 2.15.** (a) Brillouin zone for a face-centred cubic crystal, showing the notation for special points and directions. Solid lines are on the surface with broken lines inside the zone. (b) Band structure in the free-electron model, showing the effect of folding back the parabola into the reduced zone.

# Aleaciones ternarias de semiconductores

# ¿ Qué es $Al_xGa_{1-x}As$ ? (arseniuro de galio-aluminio)

Al: aluminio  
Ga: galio  
As: arsénico

		3A	4A	5A	6A
		BORON 1081	CARBON 1201	NITRÓGENO 1401	OXÍGENO 1600
		2.34 B 5	2.26 C 6	1.40 N 7	1.43 O 8
		$1s^2 2s^2 2p^1$	$1s^2 2s^2 2p^2$	$1s^2 2s^2 2p^3$	$1s^2 2s^2 2p^4$
		8.73 TET 8376	3.27 DIA	4.338 HEX 1361	4.42 CUB
		2800	1750 (4300)	1890	63.3 (1,79) <sup>1</sup>
		FLUORURO 18.998	SILICIO 28.086	FOSFÓRICO 30.974	SULFURO 32.06
		4.76 Al 13	3.22 Si 14	1.62 (hex) P 15	2.07 S 16
		$[Ne] 3s^2 3p^1$	$[Ne] 3s^2 3p^2$	$[Ne] 3s^2 3p^3$	$[Ne] 3s^2 3p^4$
		4.93 FCC	5.43 DIA	3.11 CUB	10.47 ORC 2326
		922	394 (682)	625 (217.2)	200
ZB					
LiFC	70.30	GALLIO 69.72	GERMANIO 72.64	ARSENICO 74.92	SELENIO 78.96
3.14 Zn 30	3.81 Ga 31	5.37 Ge 32	6.72 As 33	6.79 Se 34	
$[Ar] 3d^{10} 4s^2$	$[Ar] 3d^{10} 4s^2 3p^1$	$[Ar] 3d^{10} 4s^2 3p^2$	$[Ar] 3d^{10} 4s^2 3p^3$	$[Ar] 3d^{10} 4s^2 3p^4$	
2.88 HEX 1364	4.51 ORC 1206	5.64 DIA	4.12 RHL 94 10	4.26 HEX 1126	
642	224	302	240 (211)	260 (109)	
CADAVIO 112.41	INDIO 114.82	ESTANO 118.71	ANTIMONIO 127.4	TELURO 127.6	
6.86 Cd 48	7.31 In 49	7.26 Sn 50	6.62 Sb 51	6.24 Te 52	
$[Kr] 4d^{10} 5s^2$	$[Kr] 4d^{10} 5s^2 5p^1$	$[Kr] 4d^{10} 5s^2 5p^2$	$[Kr] 4d^{10} 5s^2 5p^3$	$[Kr] 4d^{10} 5s^2 5p^4$	
2.68 HEX 1366	4.98 TET 1476	5.82 TET 1546	4.81 RHL 87 8	4.45 HEX 1200	
504	429.8	129	505	170 (94)	
MERCURIO 200.59	TLANTANO 204.38	PLOMBO 207.2	BISMUTO 208.98	POLONIO 209	
10.5 Hg 80	11.85 Tl 81	11.4 Pb 82	9.9 Bi 83	8.4 Po 84	
$[Xe] 4f^{14} 5d^{10} 6s^2$	$[Xe] 4f^{14} 5d^{10} 6s^2 6p^1$	$[Xe] 4f^{14} 5d^{10} 6s^2 6p^2$	$[Xe] 4f^{14} 5d^{10} 6s^2 6p^3$	$[Xe] 4f^{14} 5d^{10} 6s^2 6p^4$	
2.05 RHL 79 45	2.46 HEX 1206	4.85 FCC	4.75 RHL 87 14	3.26 SC	
224.2	100	577	95	601	

AlAs

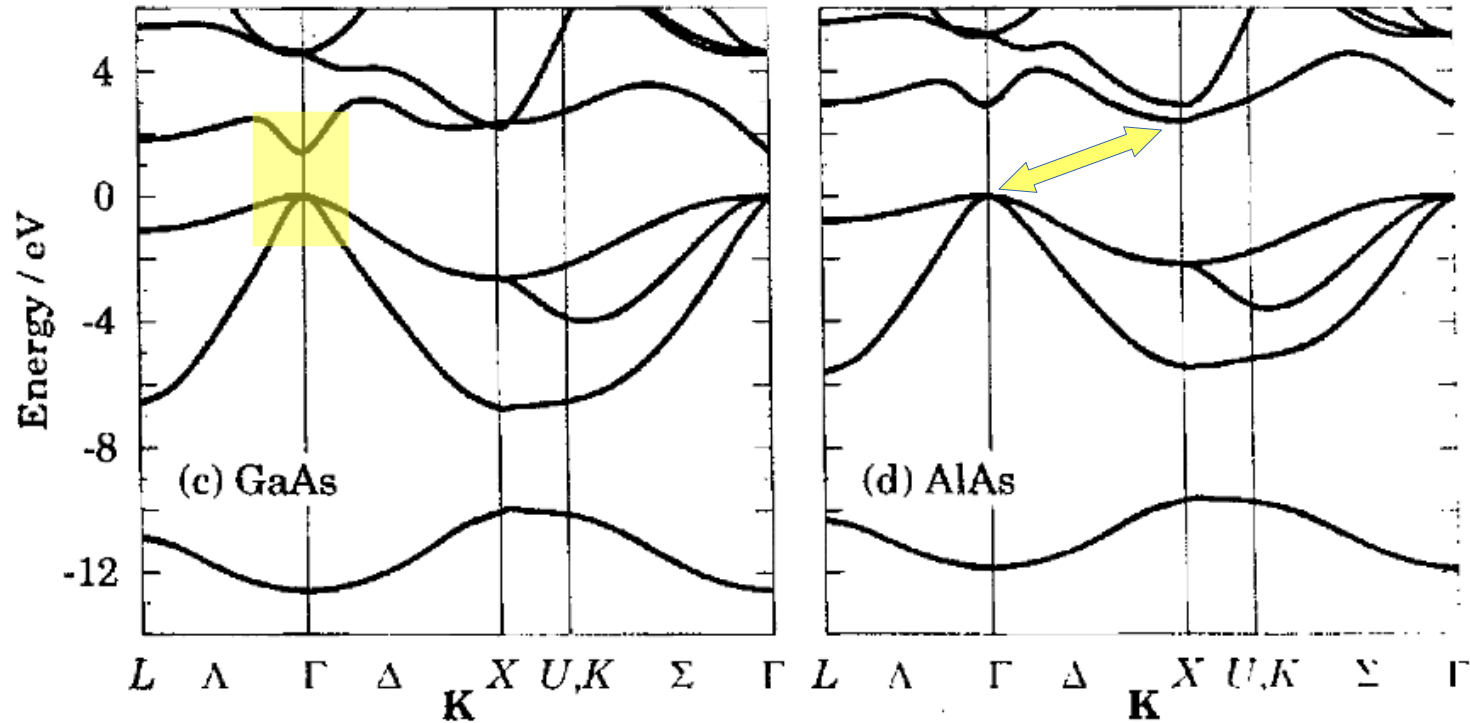
GaAs

Los iones de Al y Ga se pueden intercambiar y se forma una aleación sustitucional de tres elementos. Se pierde la periodicidad de la red: “aproximación de cristal virtual” (eufemismo)

$0 < x < 1$  proporción de Al

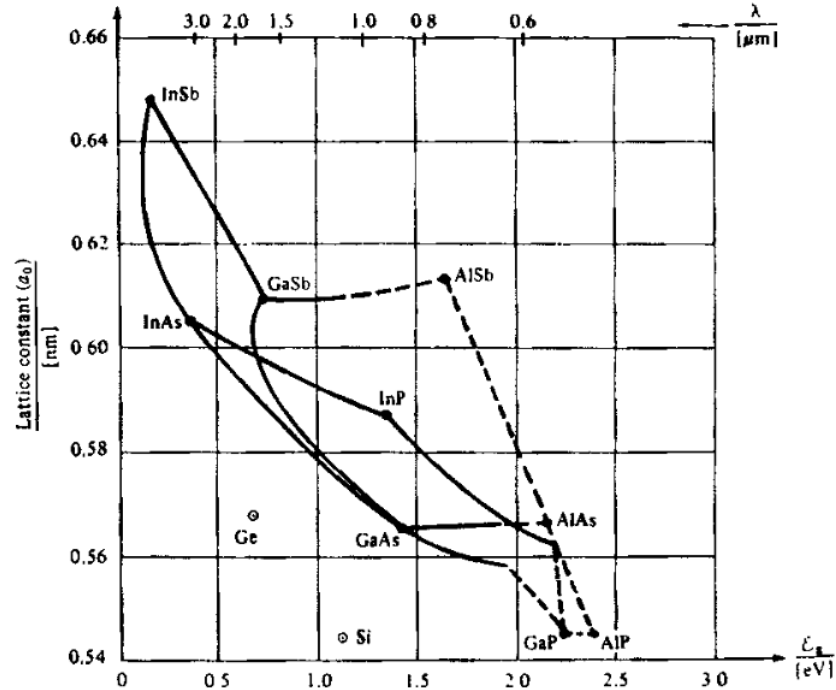
AlGaAs : abreviación genérica

¿ Qué es  $\text{Al}_x\text{Ga}_{1-x}\text{As}$  ?



El ancho del gap oscila entre 1.42 eV (GaAs) y 2.16 eV (AlAs). Para  $x < 0.4$  es un semiconductor directo.

# Matching the semiconductores para heteroestructuras



**FIGURE 3.1.** Plot of the lattice constant of various semiconductors against their minimum band gap  $E_g$ , expressed in eV and as a wavelength. Full lines show a direct band gap, with dashed lines for an indirect gap. [From Gowar (1993).]

## Resumen de la clase 4

Oscilaciones de plasma en el modelo de Drude

Heteroestructuras de semiconductores

Definiciones y ejemplos

Aleaciones ternarias