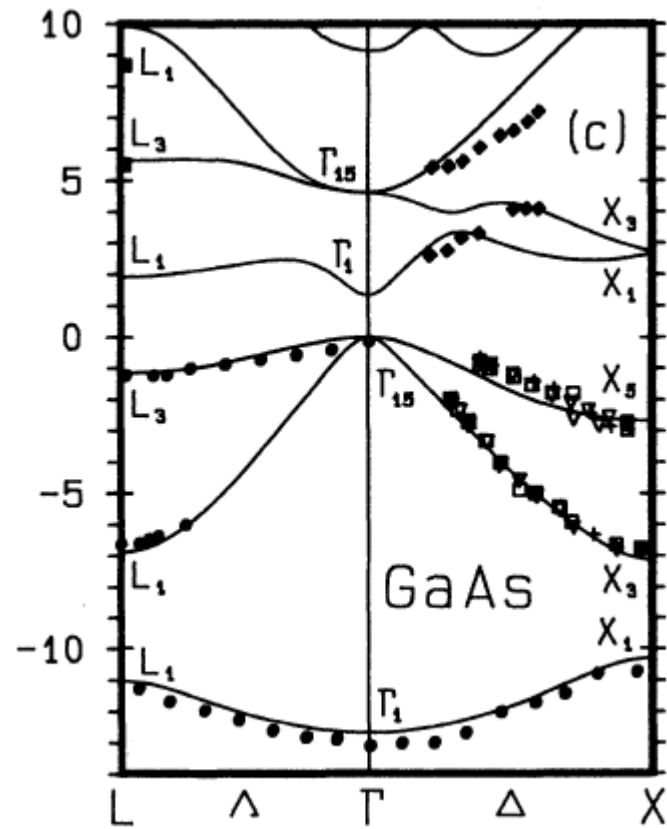
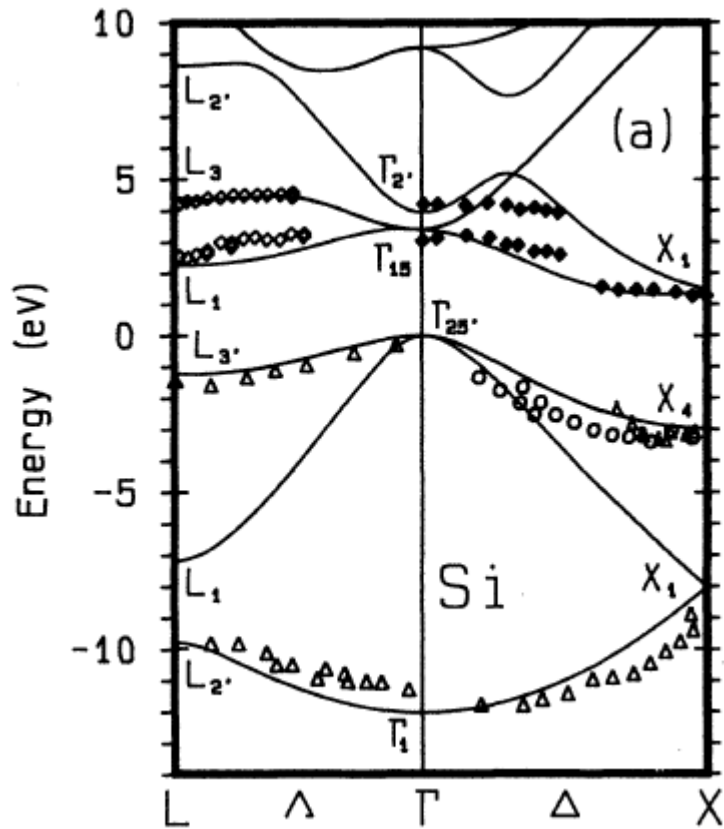




# Remember: Silicon & GaAs



## Angle-resolved photoemission, valence-band dispersions $E(\vec{k})$ , and electron and hole lifetimes for GaAs

T.-C. Chiang, J. A. Knapp,\* M. Aono,<sup>†</sup> and D. E. Eastman  
*IBM Thomas J. Watson Research Center, Yorktown Heights, New York 10598*  
(Received 3 December 1979)

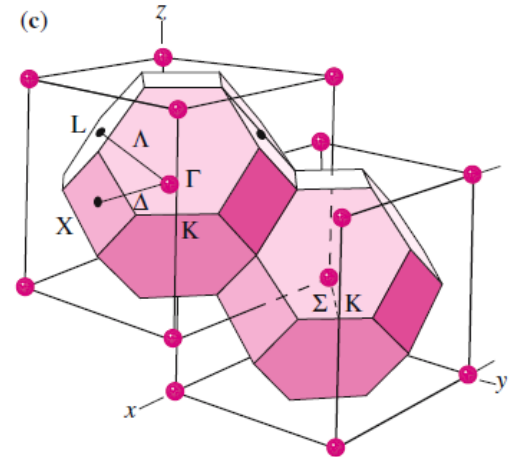
Accurate valence-band dispersions  $E(\vec{k})$  along the major symmetry directions  $\Gamma$ - $K$ - $X$ ,  $\Gamma$ - $\Delta$ - $X$ , and  $\Gamma$ - $\Lambda$ - $L$  have been determined for GaAs using simple angle-resolved photoemission techniques of general utility with synchrotron radiation for  $25 \leq h\nu \leq 100$  eV. At these photon energies, emission features can be understood within the direct-transition model, and spectral peaks can be classified roughly into two categories: one being those associated with primary cone emission with a lifetime-broadened free-electron-like final-state dispersion, and the other (usually weaker) being those associated with secondary cone-surface umklapp emission which emphasizes valence-band critical points with high state densities. Valence-band dispersions  $E(\vec{k})$  along the  $\Gamma$ - $K$ - $X$  symmetry line perpendicular to the surface are determined using normal-emission spectra (primary cone peaks) from the (110) surface at various photon energies. Valence-band dispersions  $E(\vec{k})$  along  $\Gamma$ - $K$ - $X$ ,  $\Gamma$ - $\Delta$ - $X$ , and  $\Gamma$ - $\Lambda$ - $L$  symmetry lines parallel to the surface are determined using off-normal emission spectra (primary cone peaks) from the same (110) surface with fixed perpendicular component of the electron momentum  $\hbar\vec{k}_\perp$  at a zone center (extended-zone scheme) and varying parallel component of the electron momentum  $\hbar\vec{k}_\parallel$ , which are obtained by suitably varying  $h\nu$  and emission angles. Experimental valence-band dispersions and critical points are compared with other theoretical and experimental results. Simple formulas are derived to relate the widths of spectral peaks to electron and hole lifetimes. Initial hole lifetimes at valence critical points and typical final electron lifetimes are obtained. The latter yields final-state momentum broadenings (typically  $\lesssim 10\%$  of the Brillouin-zone size) which are consistent with the direct-transition model.

# Angle-resolved photoemission, valence-band dispersions $E(\vec{k})$ , and electron and hole lifetimes for GaAs

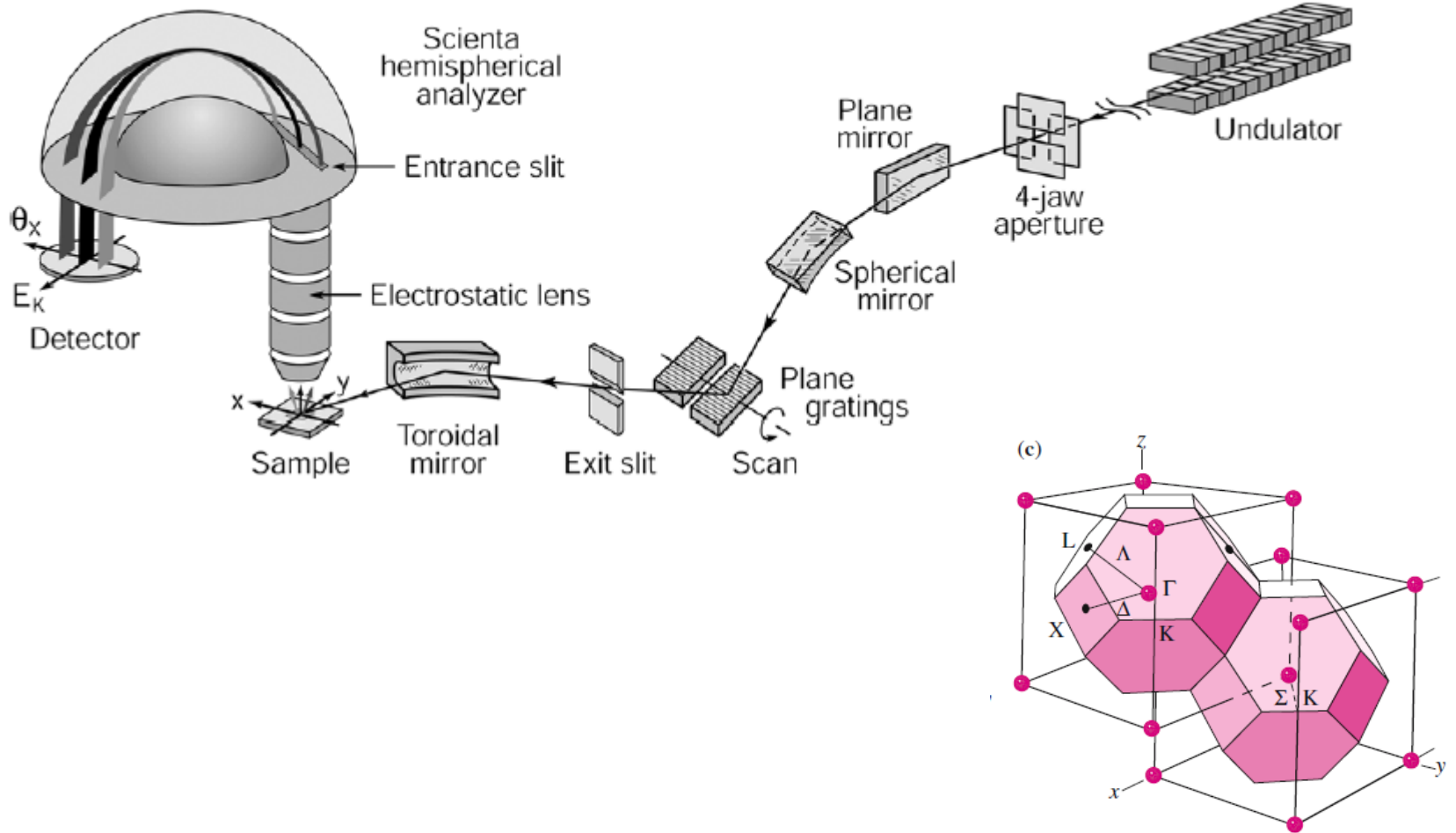
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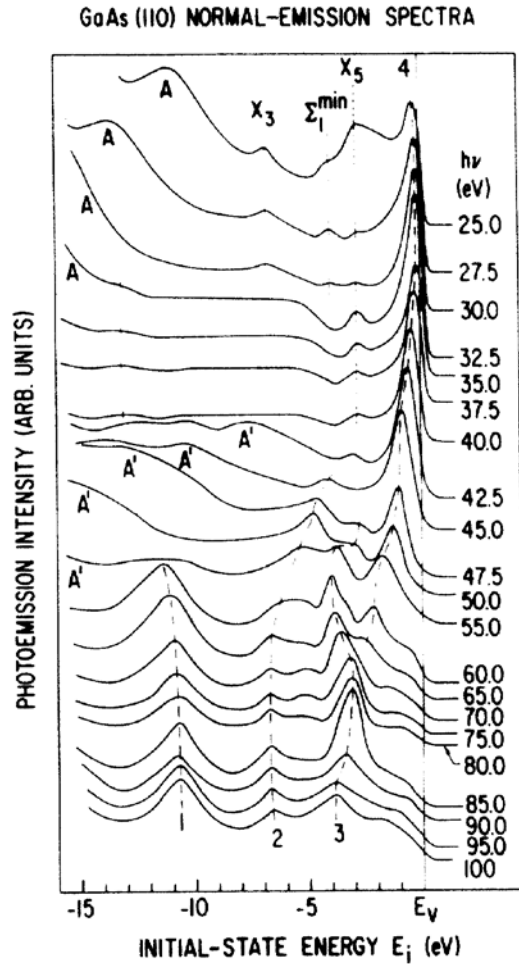
$E(\vec{k})$  along the  $\Gamma$ - $K$ - $X$  symmetry line perpendicular to the surface are determined from the (110) surface emission spectra (primary cone peaks) from the  $\Gamma$ - $K$ - $X$  symmetry line parallel to the surface normal emission spectra (primary cone peaks) from the same (110) surface component of the electron momentum  $\hbar\vec{k}_\perp$  at a zone center (extended-zone scheme) and the  $\Sigma$  component of the electron momentum  $\hbar\vec{k}_\parallel$ , which are obtained by suitably varying the photon energy. Experimental valence-band dispersions and critical points are compared with theoretical results. Simple formulas are derived to relate the widths of spectral features to the lifetimes. Initial hole lifetimes at valence critical points and typical final electron lifetimes yields final-state momentum broadenings (typically  $\lesssim 10\%$  of the Brillouin zone width) consistent with the direct-transition model.



# ARPES experiment

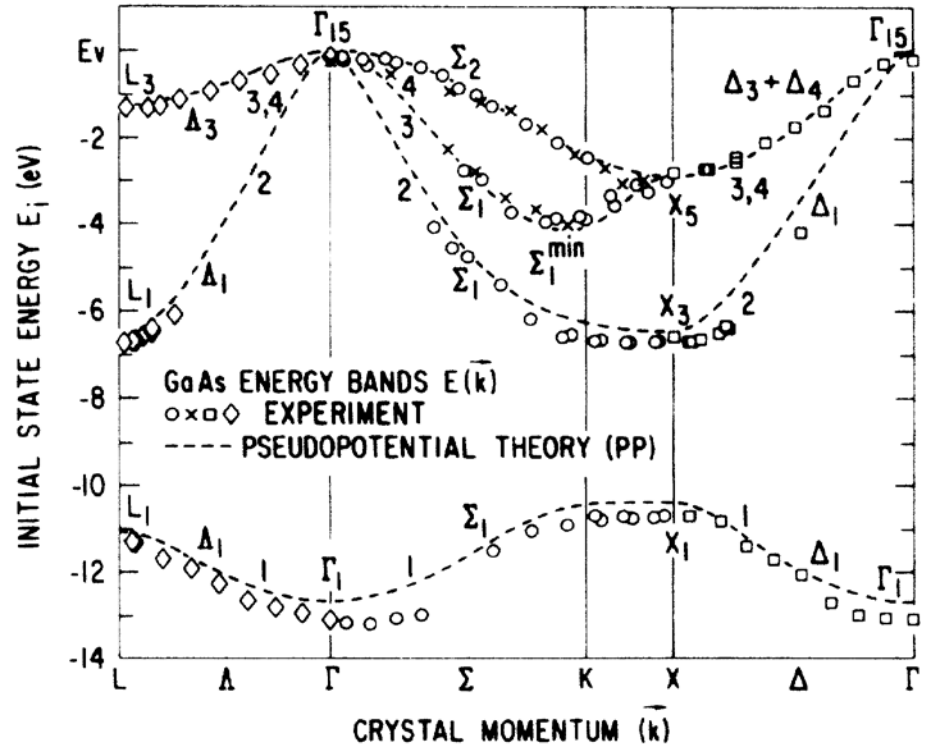
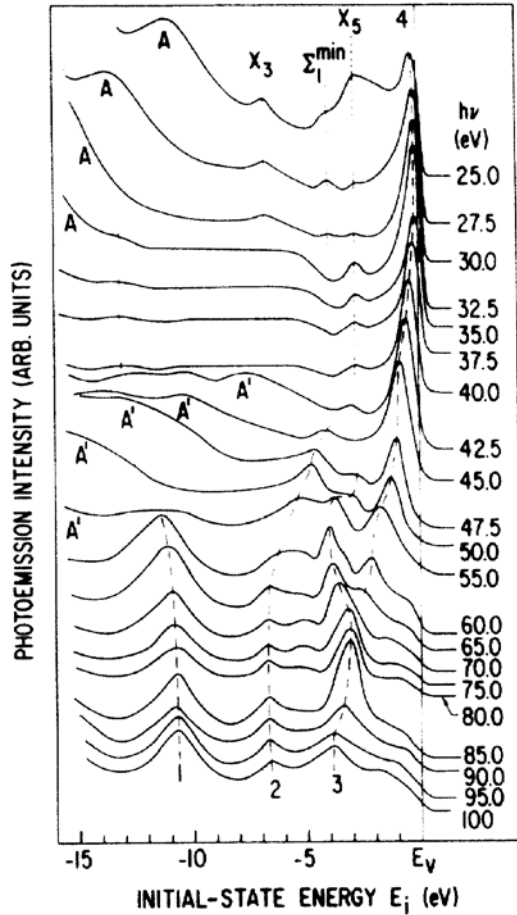


# Normal incidence

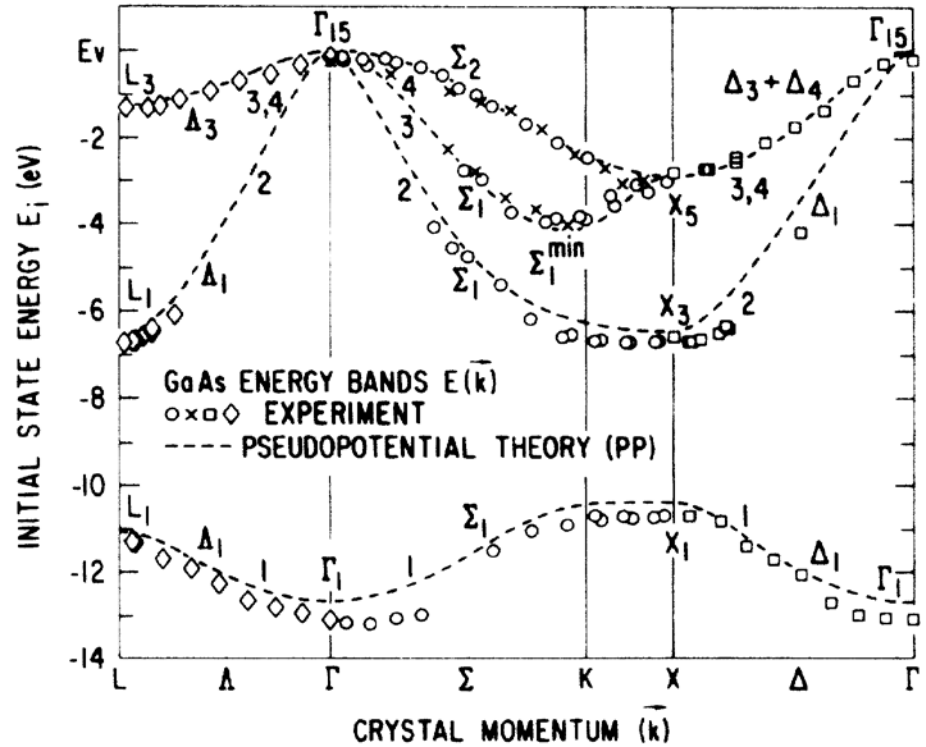
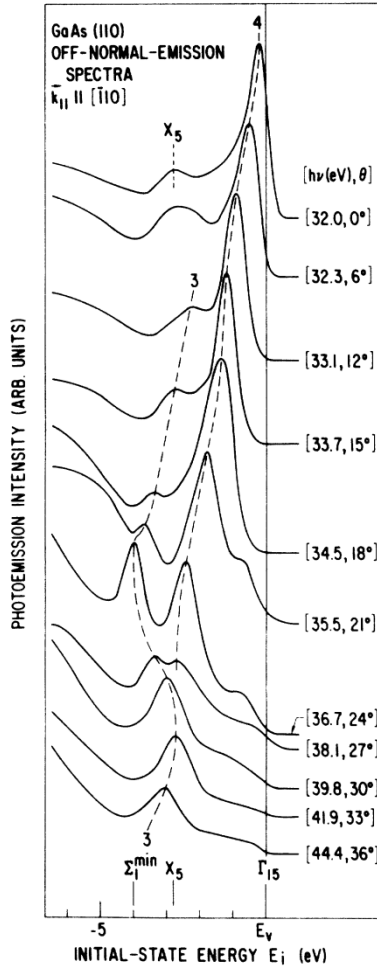


# Normal incidence

GoAs (110) NORMAL-EMISSION SPECTRA

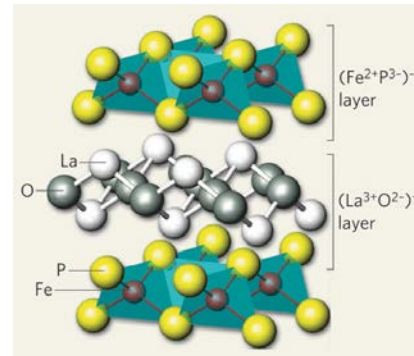
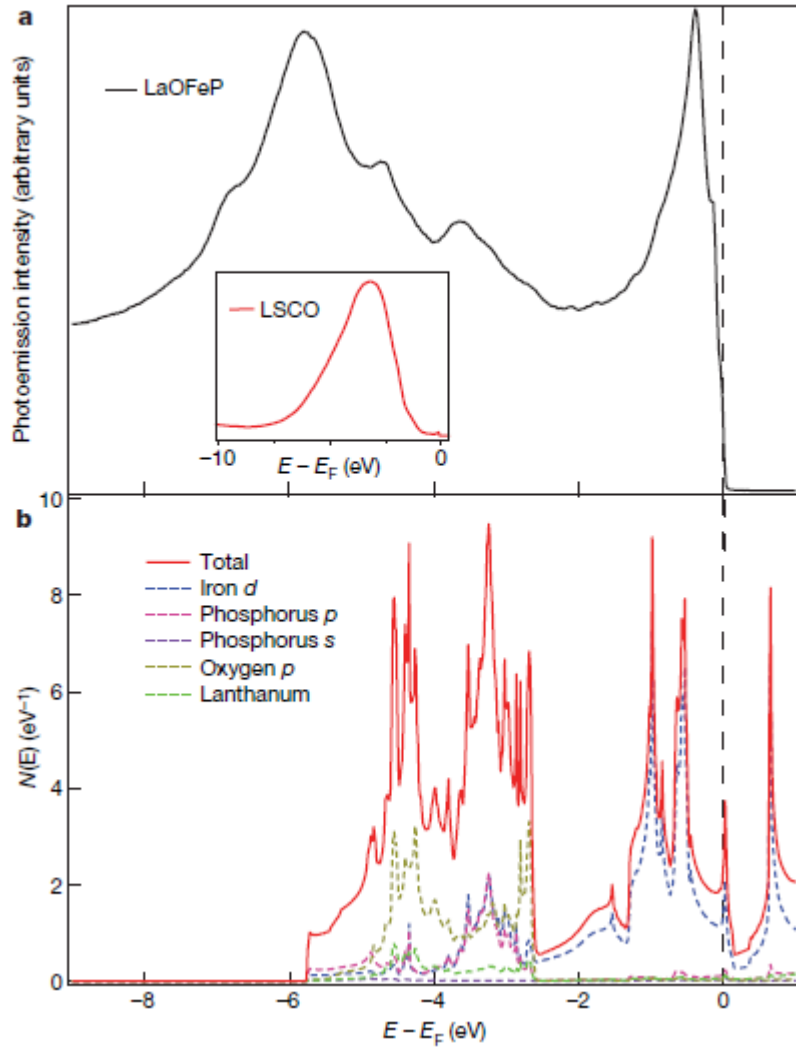


# Normal incidence



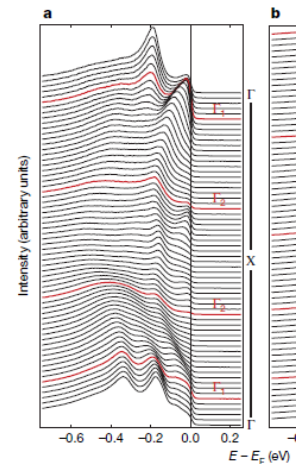
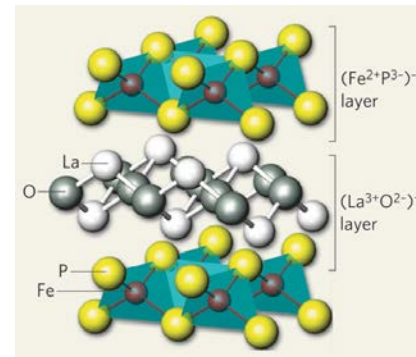
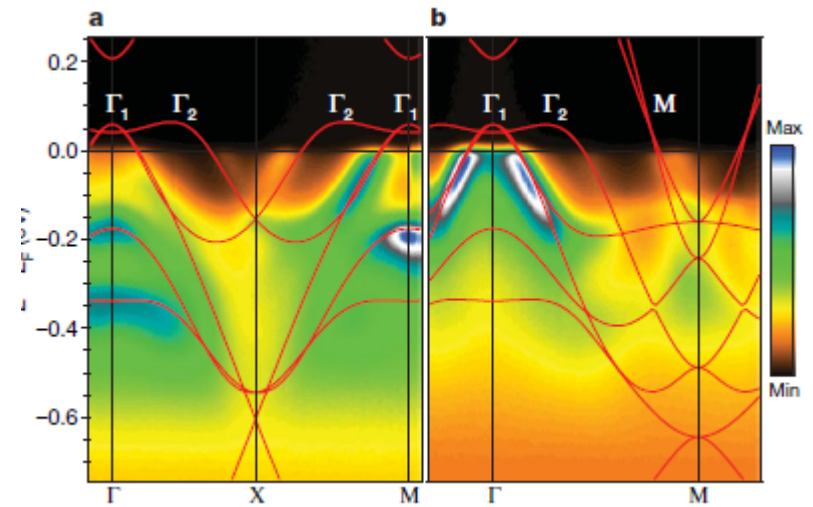
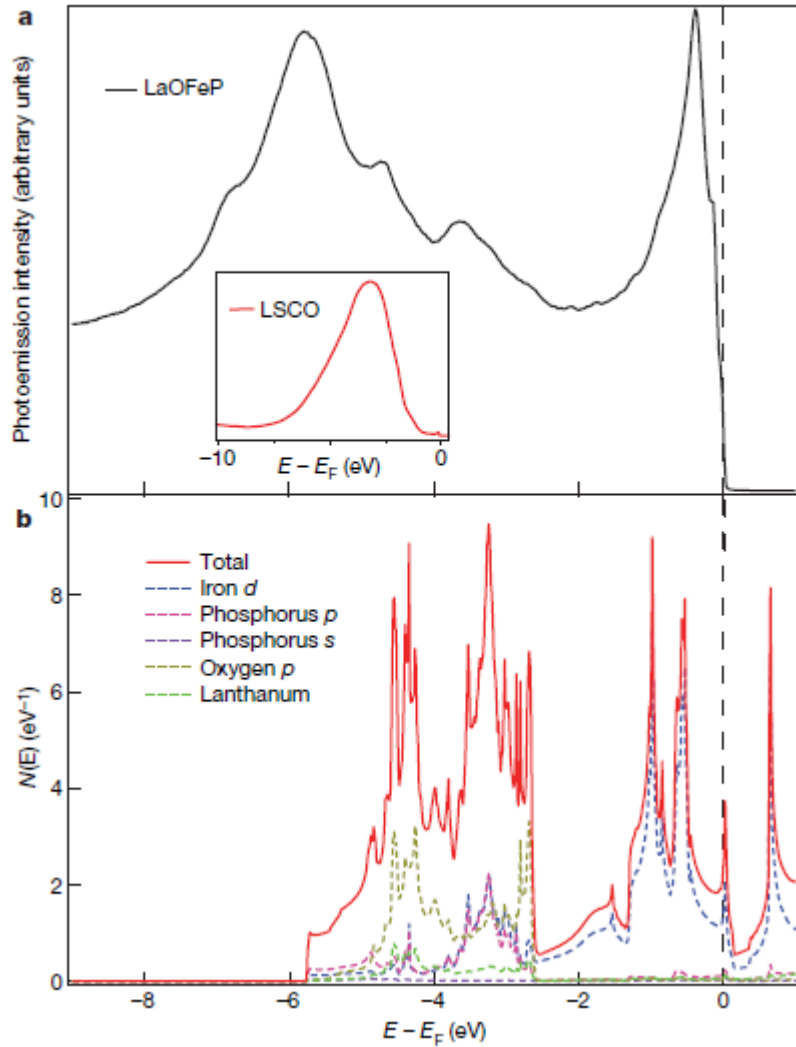


# LaOFeP



Lu, Nature 455, 81 (2008).

# LaOFeP



# Effective masses

Name	Symbol	Germanium	Silicon	Gallium Arsenide
<b>Band minimum at <math>k = 0</math></b>				
Minimum energy	$E_{g,direct}$ [eV]	0.8	3.2	1.424
Effective mass	$m_e^*/m_0$	0.041	?0.2?	0.067
<b>Band minimum not at <math>k = 0</math></b>				
Minimum energy	$E_{g,indirect}$ [eV]	0.66	1.12	1.734
Longitudinal effective mass	$m_{e,l}^*/m_0$	1.64	0.98	1.98
Transverse effective mass	$m_{e,t}^*/m_0$	0.082	0.19	0.37
Wavenumber at minimum	$k$ [1/nm]	xxx	xxx	xxx
Longitudinal direction		(111)	(100)	(111)
<b>Heavy hole valence band maximum at <math>E = k = 0</math></b>				
Effective mass	$m_{hh}^*/m_0$	0.28	0.49	0.45
<b>Light hole valence band maximum at <math>k = 0</math></b>				
Effective mass	$m_{lh}^*/m_0$	0.044	0.16	0.082
<b>Split-off hole valence band maximum at <math>k = 0</math></b>				
Split-off band valence band energy	$E_{v,so}$ [eV]	-0.028	-0.044	-0.34
Effective mass	$m_{h,so}^*/m_0$	0.084	0.29	0.154

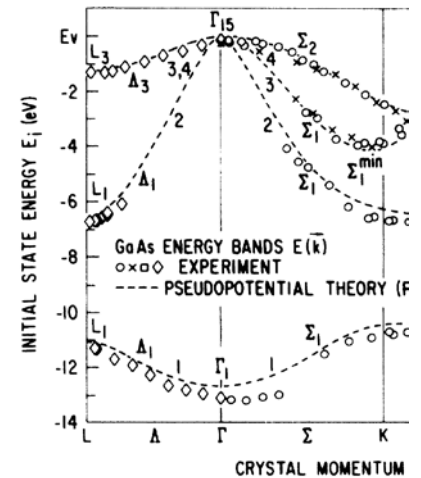
	$E_g$ (eV)	$m^*/m_0$		$\epsilon_r$
Si	1.12	long: 0.98 trans: 0.19		11.7
InP	1.34	$\Gamma$	0.082	12.5
		X	0.25	
		L	0.32	
GaAs	1.42	$\Gamma$	0.067	12.9
		X	long: 0.98 trans: 0.19	
		L	long: 0.98 trans: 0.19	
InAs	0.35	$\Gamma$	0.022	15.15
		X	0.64	
		L	0.286	
InSb	0.17	$\Gamma$	0.014	18.7
		L	0.222	

electrons

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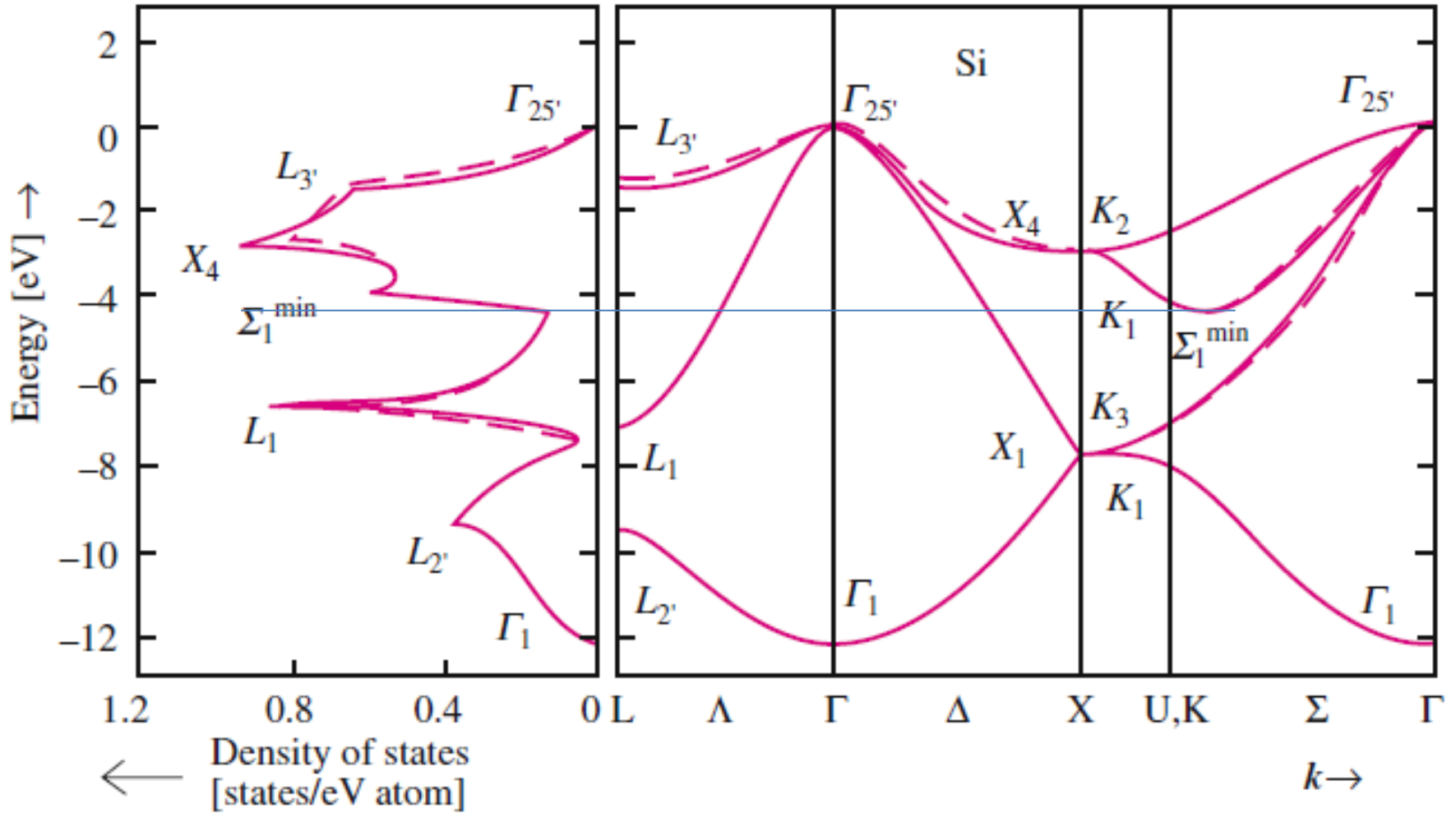
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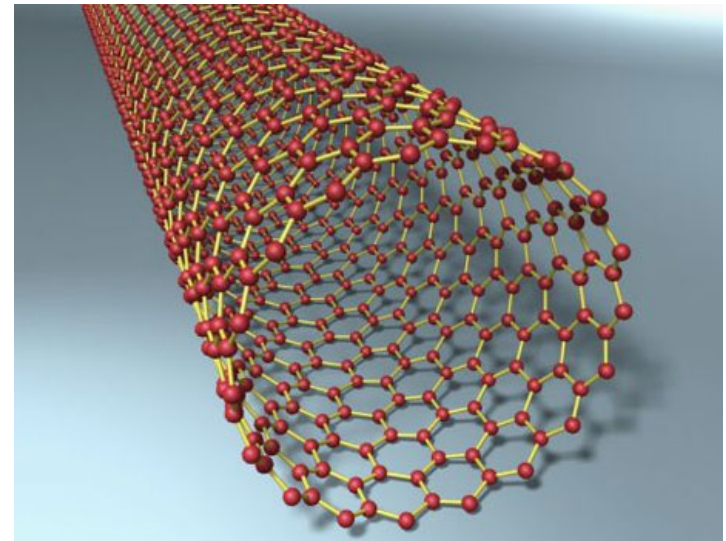
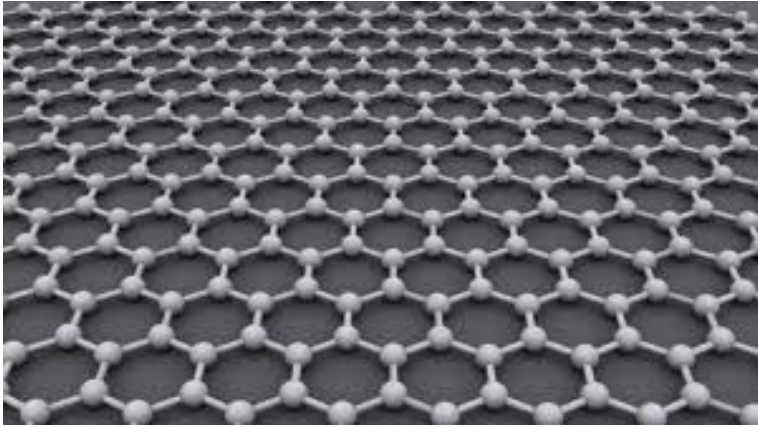
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electrons

# Density of states in Si



# Low-dimensional systems



# DOS for parabolic bands

