Condensed Matter Physics I

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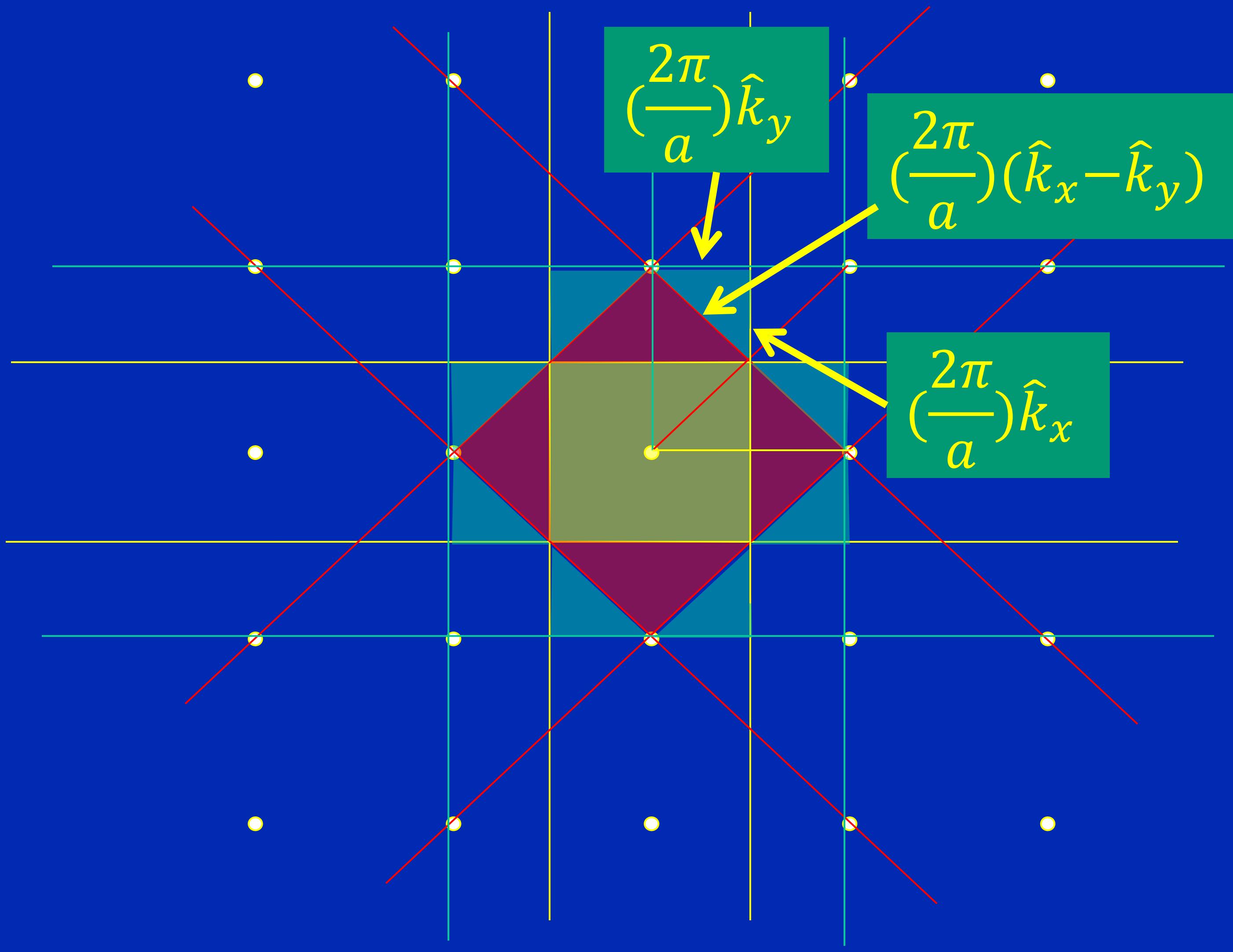
Previously

- Free electron model + perturbation
- Tight binding model + perturbation
- Tight binding in second quantization
- Fermi surfaces

Today

- Semiconductors

Brillouin zones in 2D



SEMI-CONDUCTORS

Kittel Ch. 8, Ch. 19

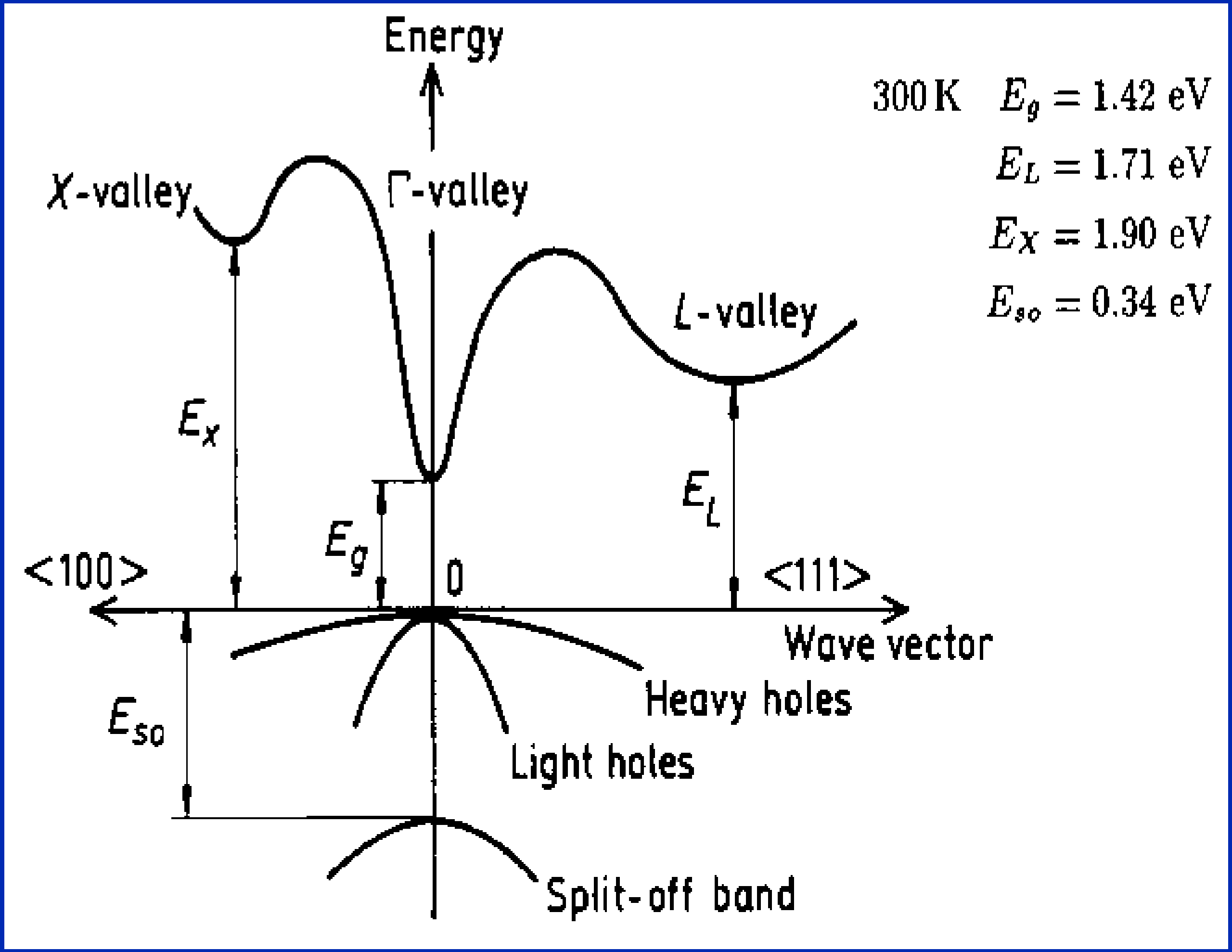
Free e^- + periodic potential

- Band structure, gaps, metals & insultators
- Effective mass $$E=\frac{\hbar^2k^2}{2m^*}\quad\rightarrow\quad m^*(k)=\hbar^2\left[\frac{\partial^2E}{\partial k^2}\right]^{-1}$$
- E.O.M. (see appendix E & pages 205-206)
- Fermi surface
    - Gap to excitations ?
    - Constant E surface for relevant electrons

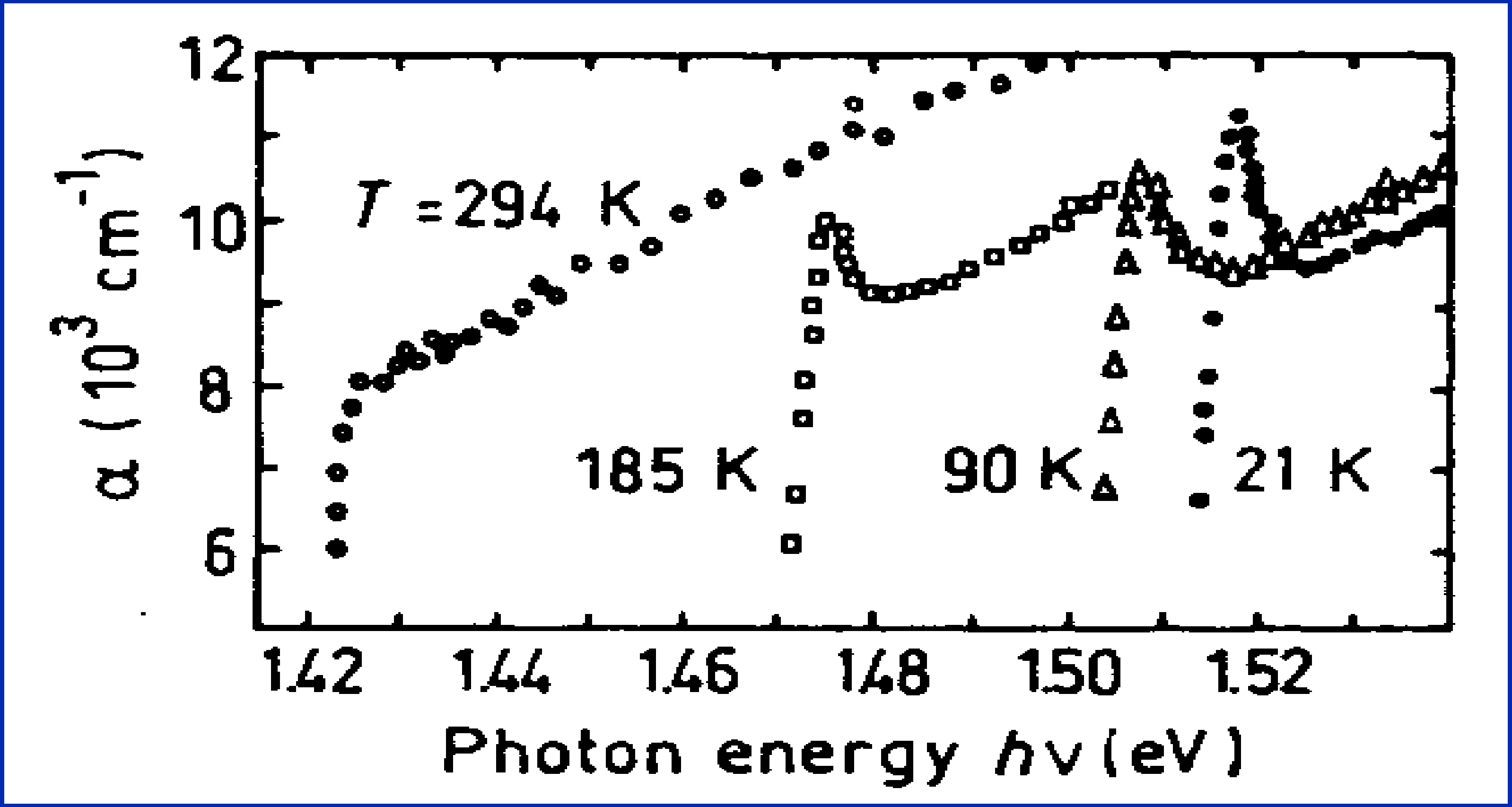
Semiconductors

Direct gap / Indirect gap
Intrinsic / Extrinsic
Homogeneous / Inhomogeneous

Direct gap: GaAs

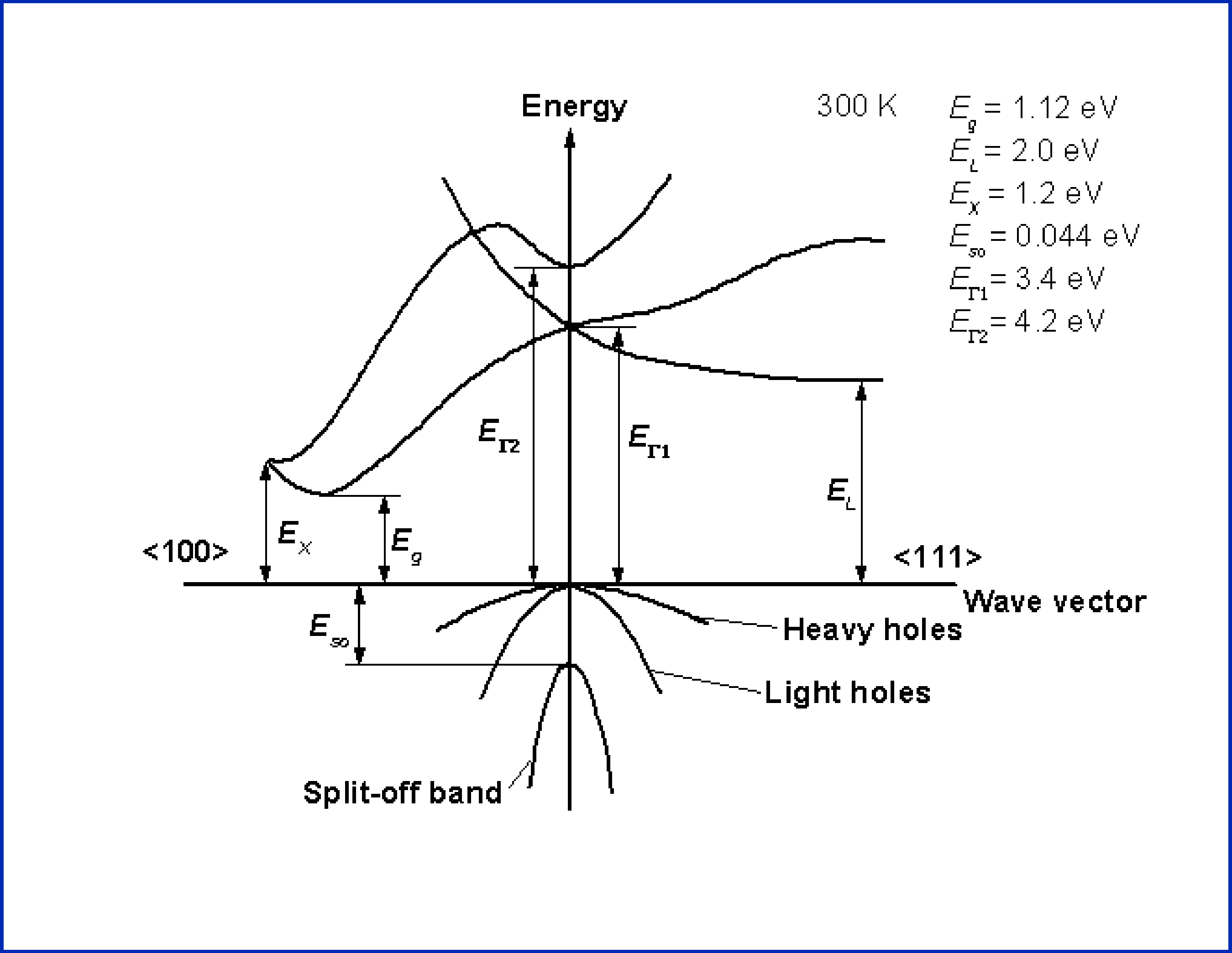


Direct gap: GaAs, absorption



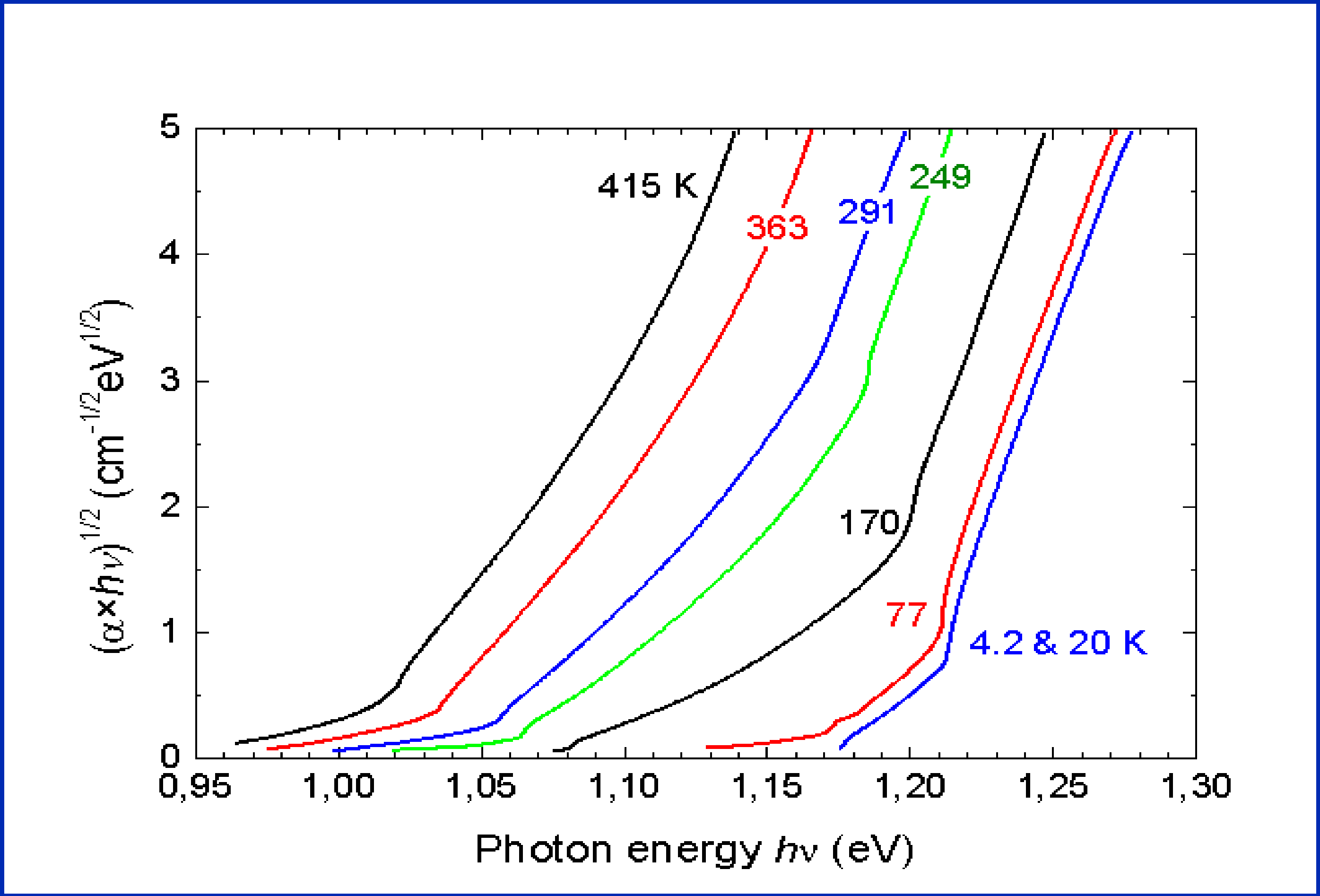
$$I(\omega) = I_0 e^{-\alpha(\omega)\cdot d}$$

Indirect gap: Silicon



PvL CMP-I
WS 14/15

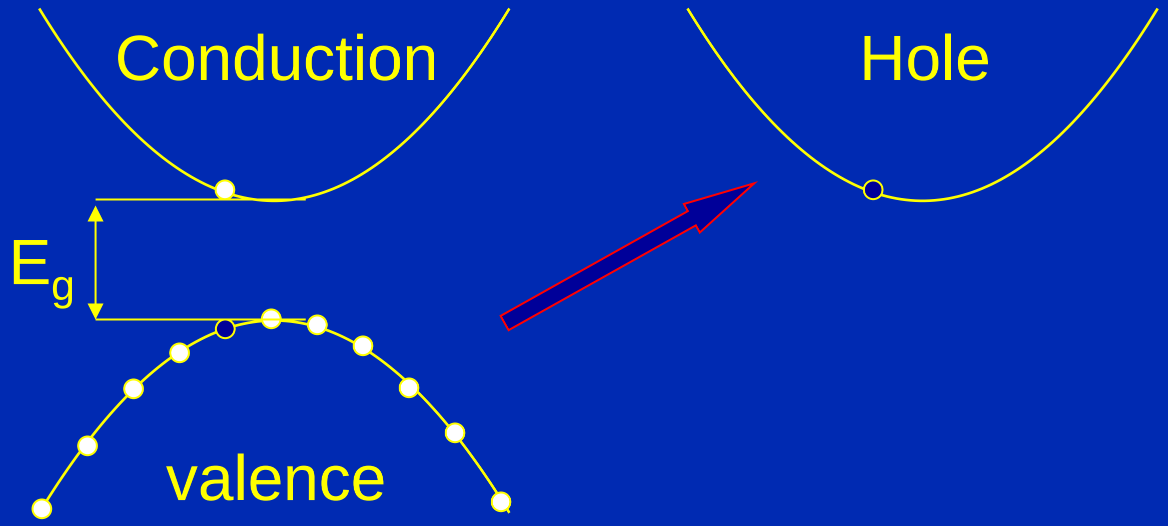
Indirect gap, Si absorption



Holes

Missing electron in a filled band
acts as a particle (*hole*) with:

- $k_h = -k_e$
- $E_h = -E_e$
- $v_h = v_e$
- $m_h = -m_e$
- $q_h = -q_e$
- $f_h = 1-f_e$



Cyclotron resonance

$$\omega_c = \frac{eB}{m^*}$$

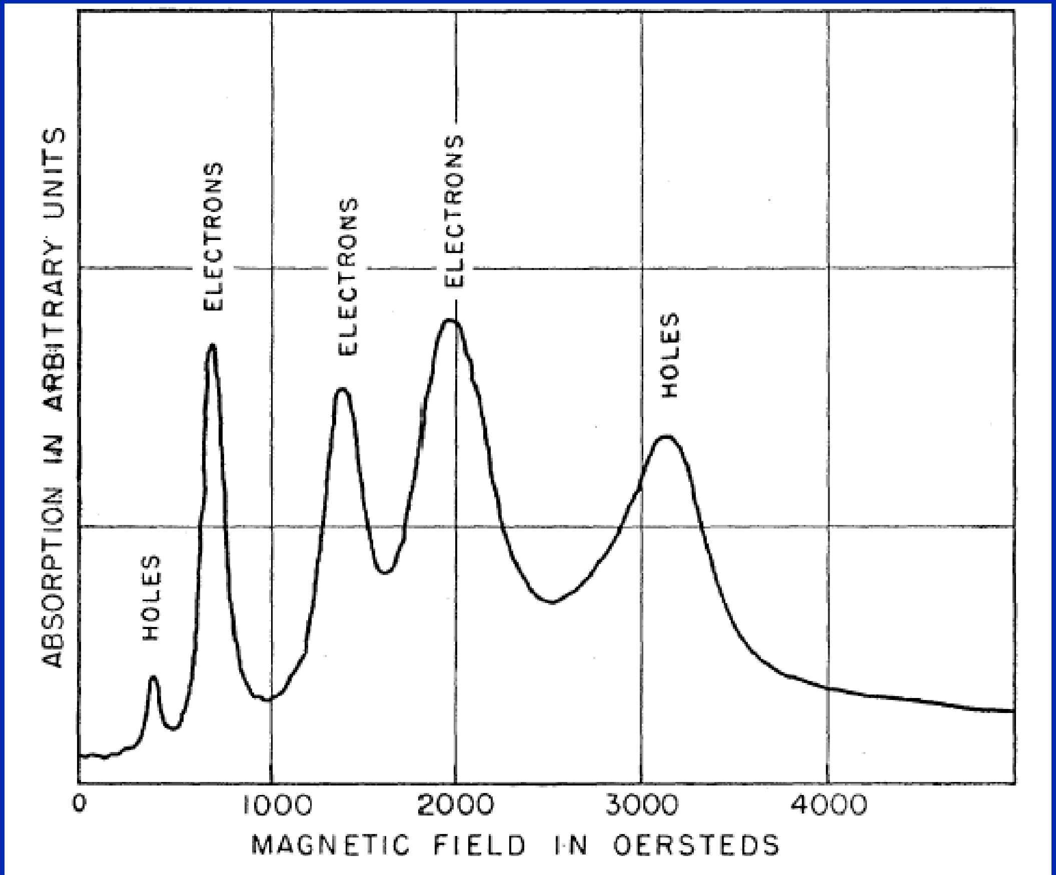
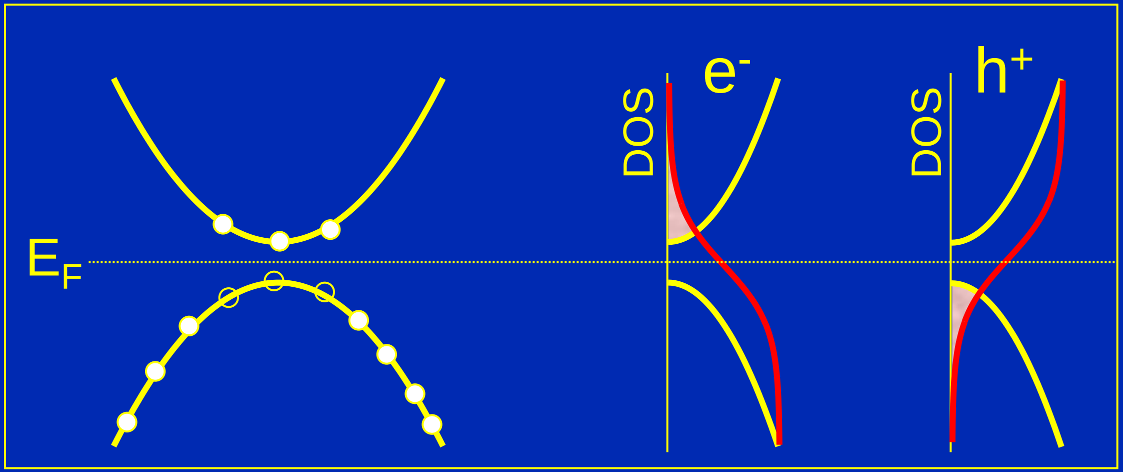


FIG. 2. Typical cyclotron resonance results in germanium near

Dresselhaus et al., Phys. Rev. **98**, 368 (1955)

Carrier density



$$n = \int_{E_c}^{\infty} dE\, D_c(E) \cdot f_e(E) = n_o \cdot e^{\frac{\mu - E_c}{k_b T}} \qquad n_o = 2\left(\frac{m_c^* k_b T}{\pi \hbar^2}\right)^{3/2}$$

$$p = \int_{-\infty}^{E_v} dE\, D_v(E) \cdot f_h(E) = p_o \cdot e^{\frac{E_v - \mu}{k_b T}} \qquad p_o = 2\left(\frac{m_v^* k_b T}{\pi \hbar^2}\right)^{3/2}$$

$$n \cdot p = n_o p_o \cdot e^{-\frac{E_g}{2 k_b T}}$$

Independent of μ or doping

Intrinsic case

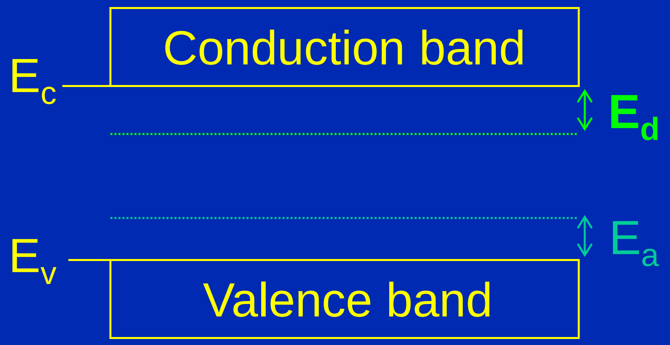
Density: $n_i \equiv p_i = \sqrt{n_o p_o} \cdot e^{-\frac{E_g}{k_b T}}$

From n = p :

$$n_o \cdot e^{\frac{\mu - E_c}{k_b T}} = p_o \cdot e^{\frac{E_v - \mu}{k_b T}}$$

$$E_F = \mu = \frac{1}{2} E_g + \frac{3}{4} k_b T \cdot \ln\left(\frac{m_h^*}{m_e^*}\right)$$ (setting E_v=0)

Extrinsic case



'H problem' with $e^2 \rightarrow e^2/\varepsilon$ & $m \rightarrow m^*$

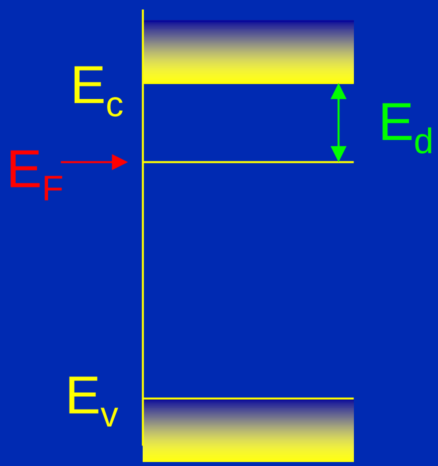
Ionization energy 1 'Ry': $E_d = \dfrac{m^* e^4}{2\hbar^2 \varepsilon^2} = \dfrac{m^*}{m_o} \dfrac{1}{\varepsilon^2} \cdot 13.6\ \text{eV}$

'Bohr' radius: $r_d = \dfrac{\hbar^2 \varepsilon}{m^* e^2} = \dfrac{m_o}{m^*} \varepsilon \cdot a_o$

Extrinsic

Donor and acceptor levels

	P	As	Sb	B	Al	Ga	In
Si	45	49	39	45	57	65	157
Ge	12	13	10	10	10	11	11



$$N_d^o = N_d \cdot \langle n \rangle = N_d \frac{e^{-(\varepsilon_d-\mu)/kT} + e^{-(\varepsilon_d-\mu)/kT}}{1+e^{-(\varepsilon_d-\mu)/kT} + e^{-(\varepsilon_d-\mu)/kT}} = N_d \frac{1}{\frac{1}{2} e^{(\varepsilon_d-\mu)/kT} + 1}$$

$$n_d = N_d - N_d^o = N_d \left(1 - \frac{2}{e^{(\varepsilon_d-\mu)/kT} + 2} \right)$$

$$\left. \begin{aligned} n_c &= p_i + n_d \\ p_i &\approx n_i \end{aligned} \right\} \rightarrow n \approx \sqrt{N_d n_0} \cdot e^{-E_d/2k_bT}$$