FoP 3B Part II

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Room 151

Lecture 2: Electrons and holes

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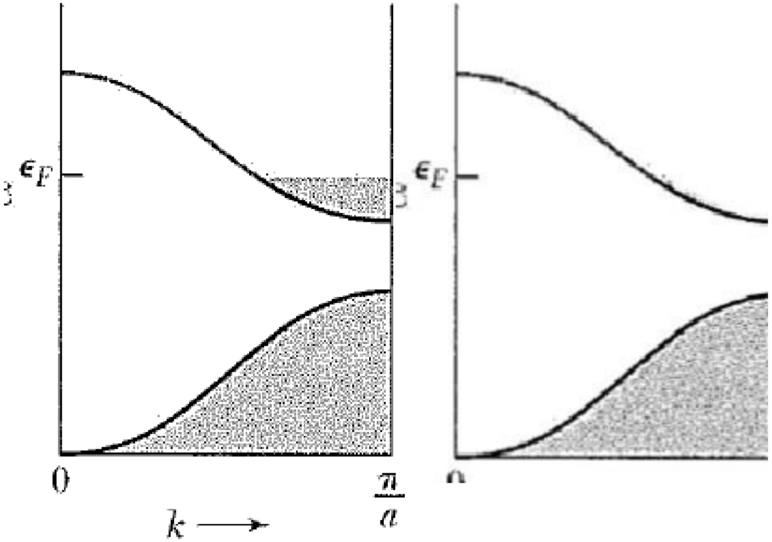
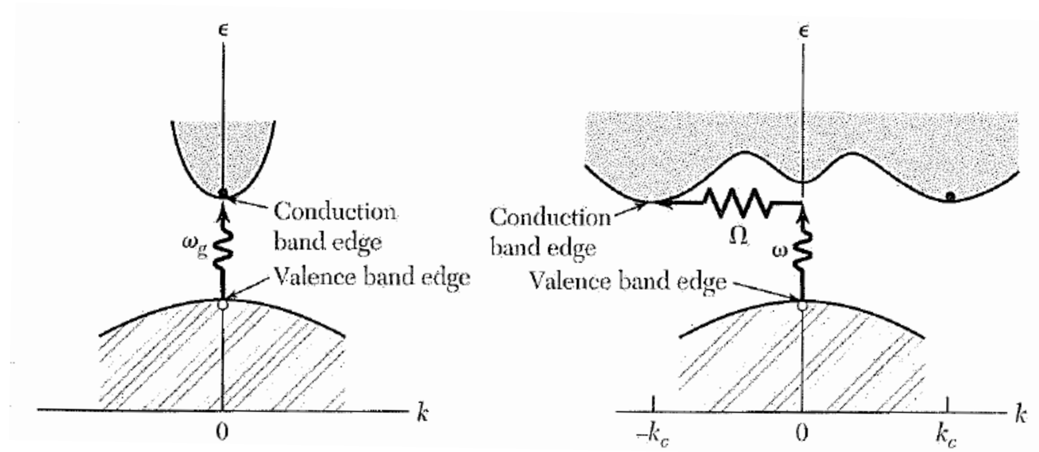
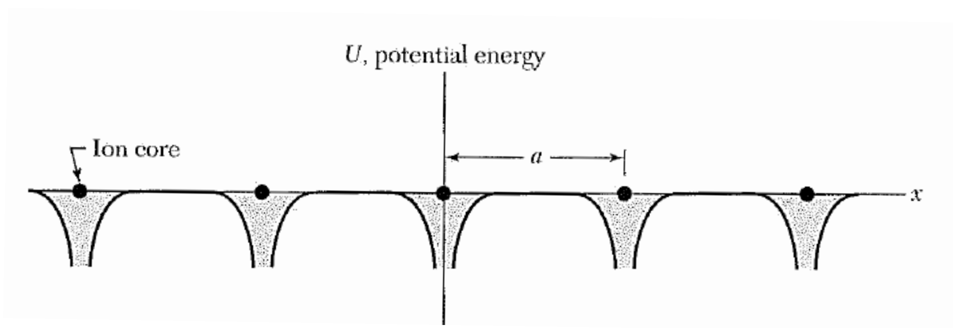
Summary of Lecture 1



Metals vs semiconductors



Direct vs indirect band gaps



Effective mass

$$\boxed{\mathbf{F} = \hbar \frac{d\mathbf{k}}{dt}}$$

$$\mathrm{v} = \frac{1}{\hbar}\frac{dE}{dk}$$

$$\boxed{m^* = \hbar^2 / \frac{d^2E}{dk^2}}$$

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Aim of today's lecture

Q: How does a material conduct electricity?

A: Electrons (nearly empty band) and holes (nearly full band)

Key concepts:

- -Conduction in a completely full band
- -Conduction in a nearly empty band (electrons)
- -Conduction in a nearly full band: concept of holes

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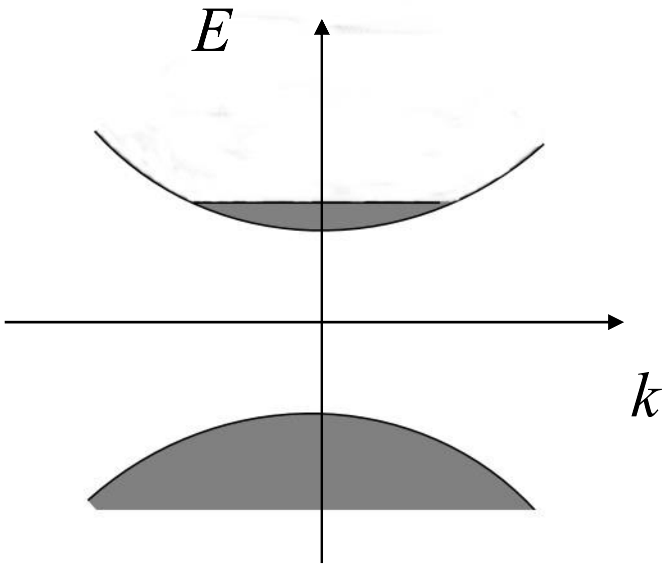
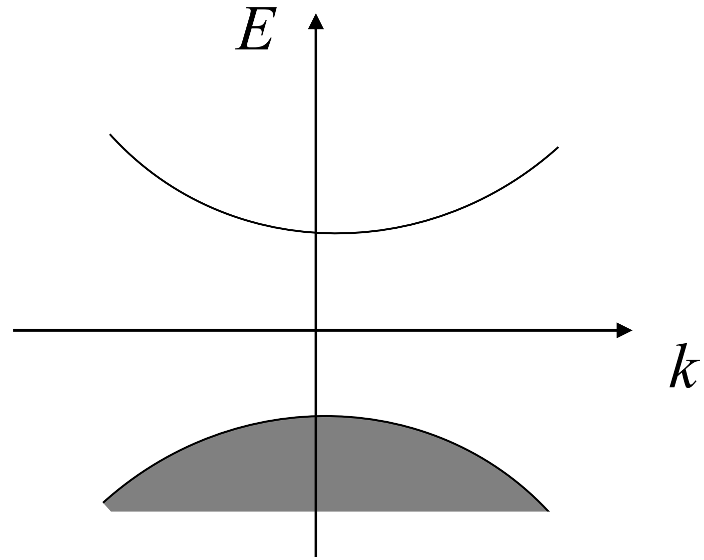
Bands at zero electric field



Metal (partially full band)



Semiconductor (full band)

From symmetry:

(i) $\sum \mathbf{k} = 0$ (no net crystal momentum)

(ii) $\sum \mathbf{v} = 0$ (no net current)

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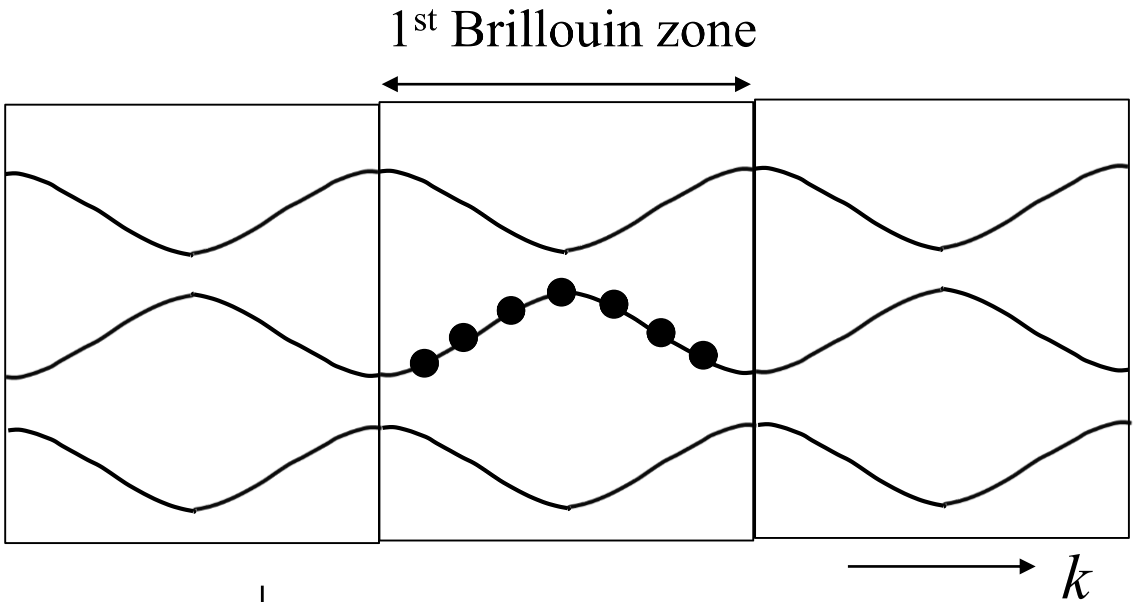
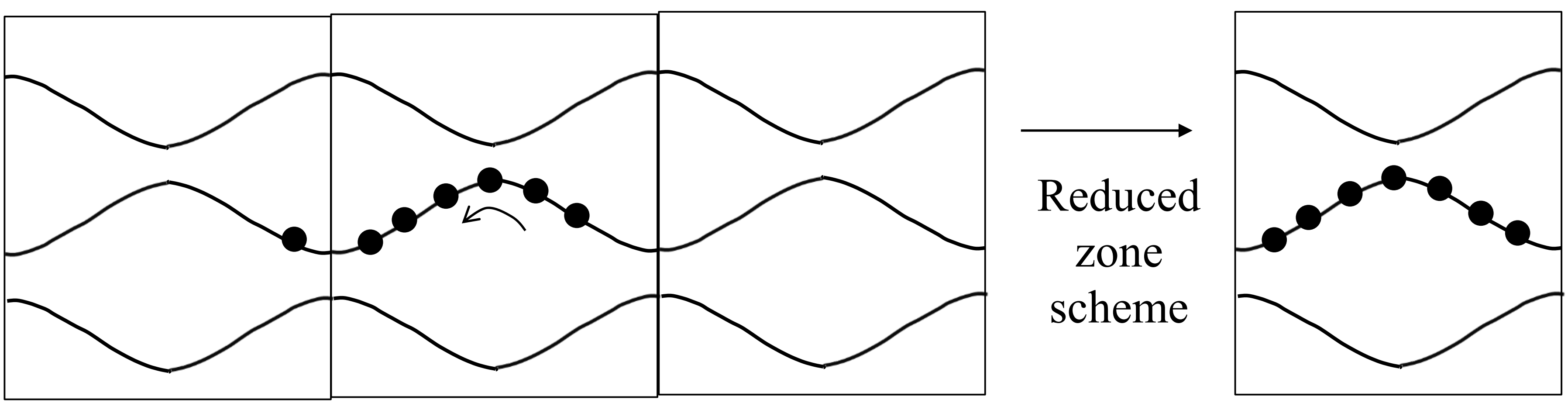
Conduction in a full band

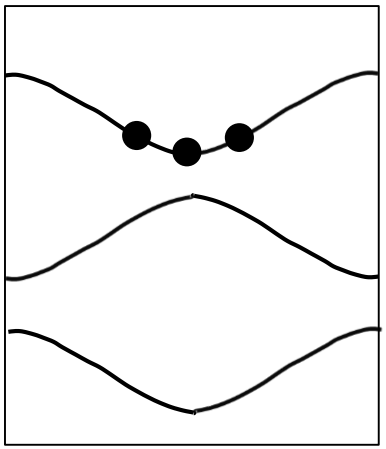
- Filled bands do not conduct electricity.
- Reason why semiconductors are insulating at 0K.



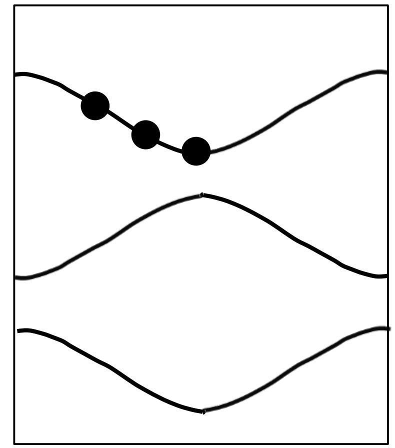
Electric field applied in $+k$ direction
and using $\boldsymbol{F} = \hbar d\mathbf{k}/dt$



Conduction in a nearly empty band (electrons)

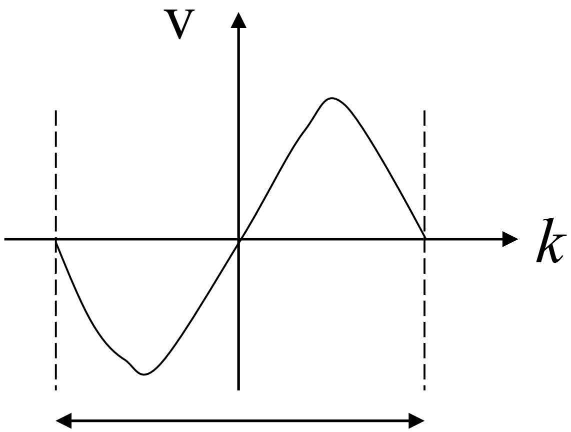


Apply electric field in $+k$ direction



-$\sum \mathbf{k}$, $\sum \mathbf{v} \neq 0$

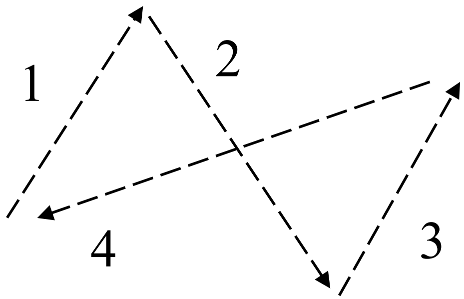
-instantaneous current in field direction



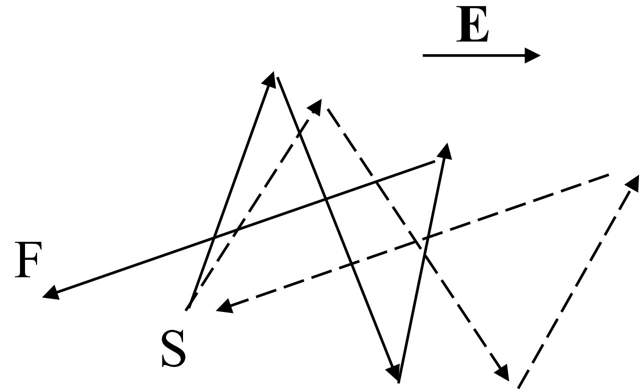
1st Brillouin zone

-The *time averaged* velocity of an electron is however zero.
-This implies that a *perfect* crystal with nearly empty band does not carry a current for any appreciable time!

Scattering in real materials (I)



Electron trajectory (no electric field)



Electron trajectory with electric field
(dashed lines- zero electric field)

Electron acquires a net *drift* velocity $\mathbf{v}_d$ given by:

$$\boxed{\mathbf{v}_d = -\mu\mathbf{E}}$$

where μ is the *mobility**.

* See supplementary notes for a derivation and Hall measurement technique (non-examinable).

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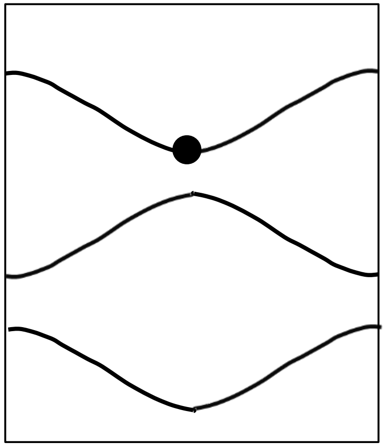
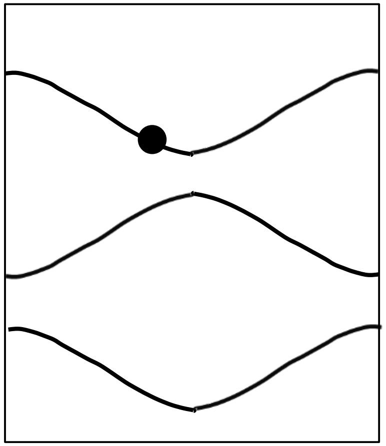
Scattering in real materials (II)

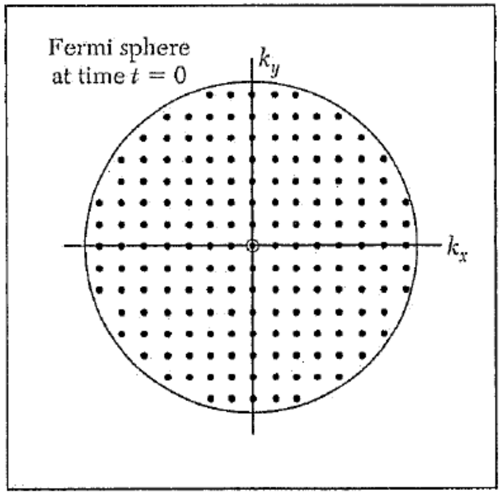


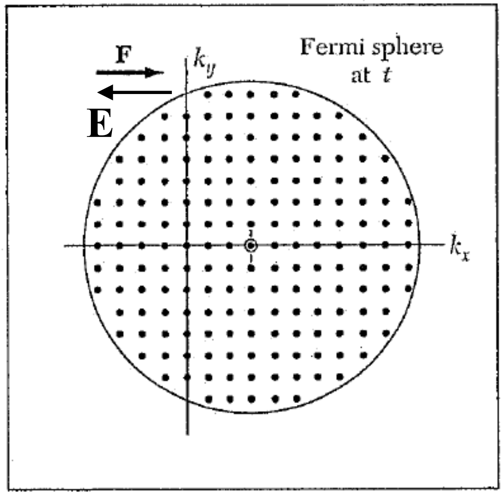
Apply electric field in $+k$ direction



Electron at bottom of conduction band before applying electric field

Time averaged state of electron in an electric field (scattering included)





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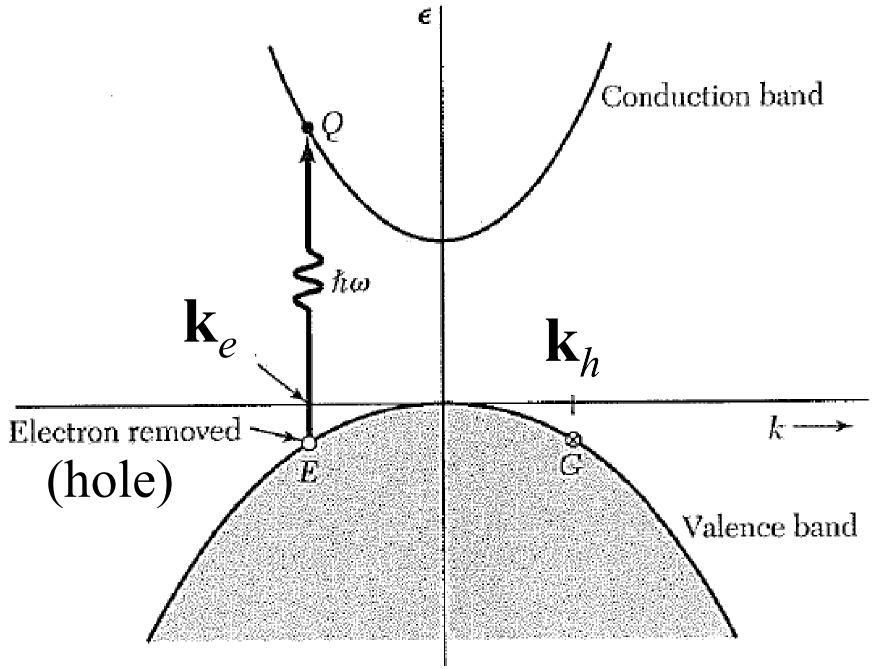
Conduction in a nearly full band (holes)- I



Semiconductors: photon/thermal excitation of valence electron into conduction band

- For a full band: $\sum \mathbf{k} = 0$
- After photon/thermal excitation: $\sum \mathbf{k} = -\mathbf{k}_e = \mathbf{k}_h$ (**k** of hole opposite to that of excited electron)

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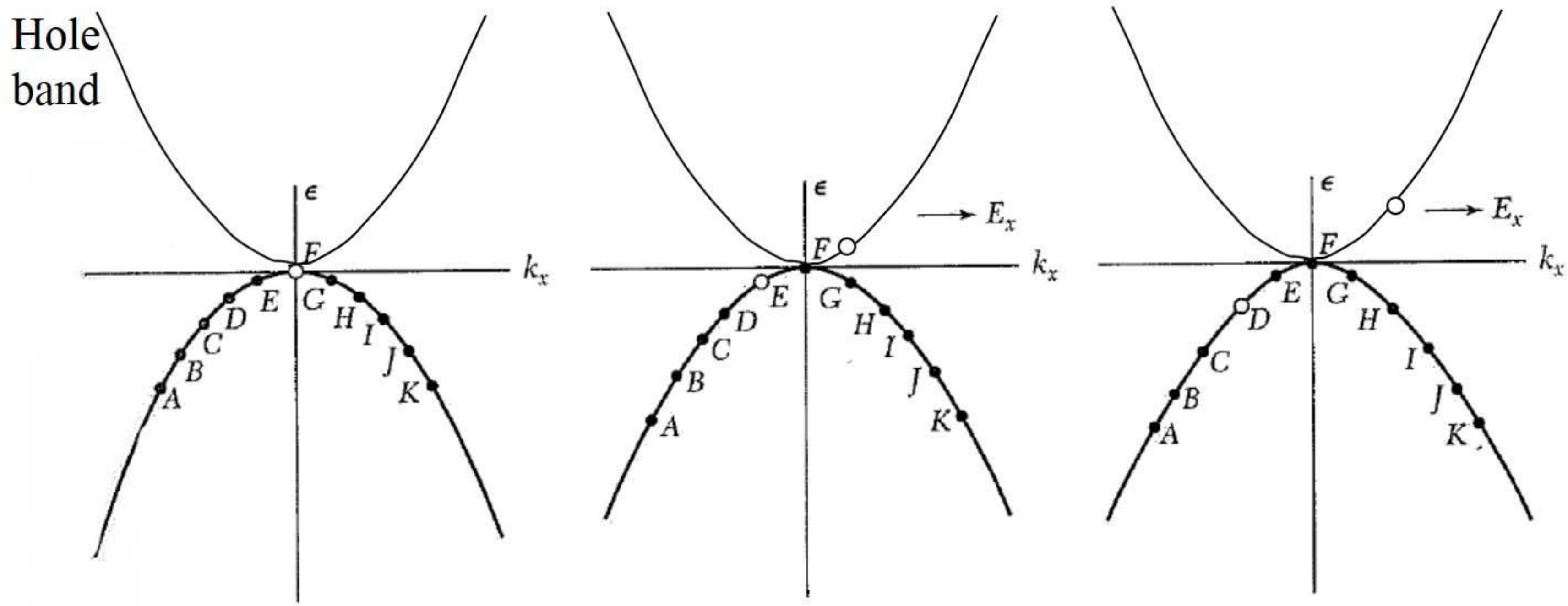
Conduction in a nearly full band (holes)- II



- Conduction of valence electrons equivalent to positively charged hole in hole band
- From the symmetry of valence and hole bands:

$$\mathbf{k}_h = -\mathbf{k}_e \text{ (}\mathbf{k}\text{ vector)}$$
$$\varepsilon_h = -\varepsilon_e \text{ (energy)}$$
$$\mathbf{v}_h = \mathbf{v}_e \text{ (velocity)}$$
$$m_h^* = -m_e^* \text{ (effective mass)}$$

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