Tasks

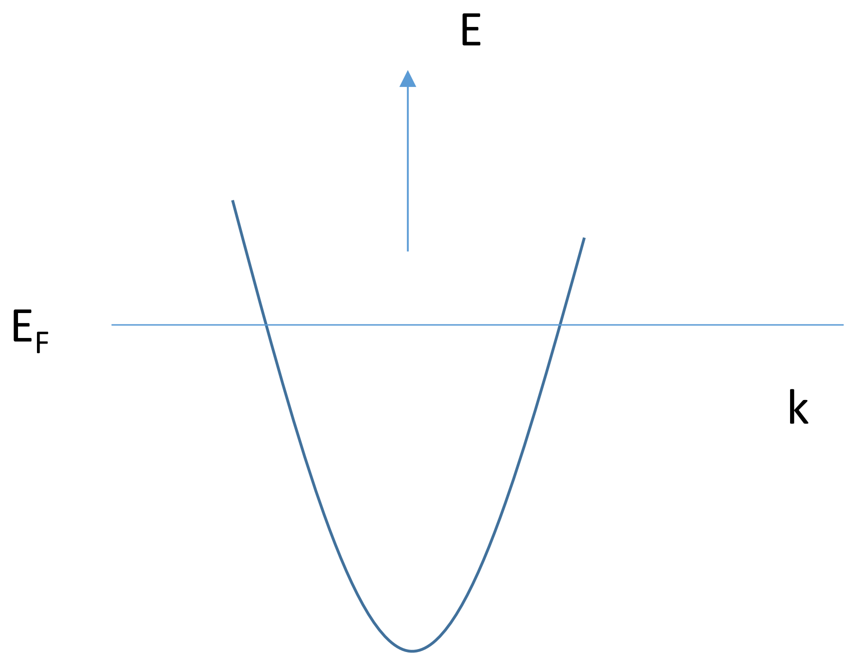
(1) Read chapter 8: Semiconductors for next week.

(2) Solve exercise sheets

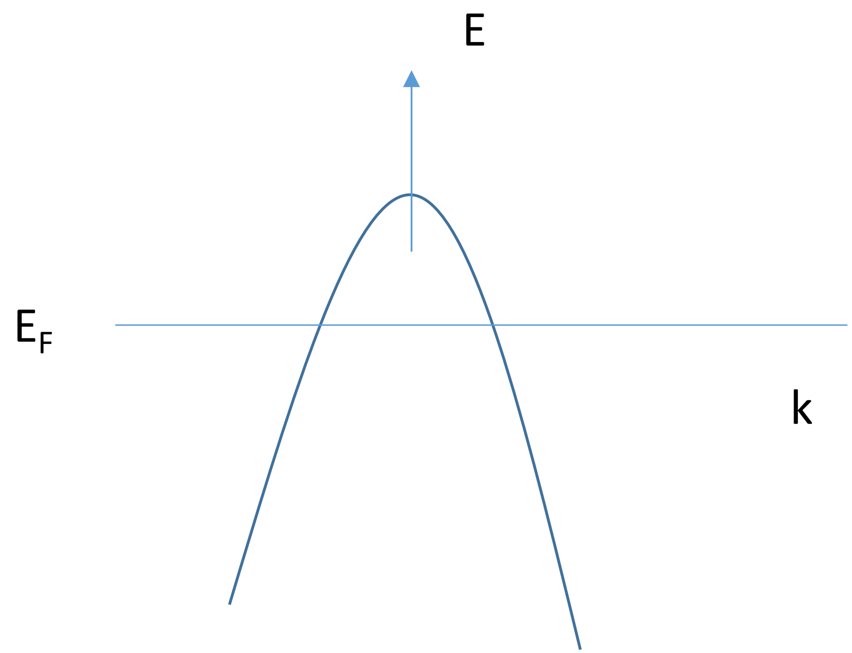
(3) Who is summarizing next week?

20 & 25th April	Chapter 6
2 & 4th May	Chapter 7
9 & 16th May	Chapter 8
18 & 23th May	Chapter 9
30th May & 1st June	Wrap-up

Electron versus Hole like bands

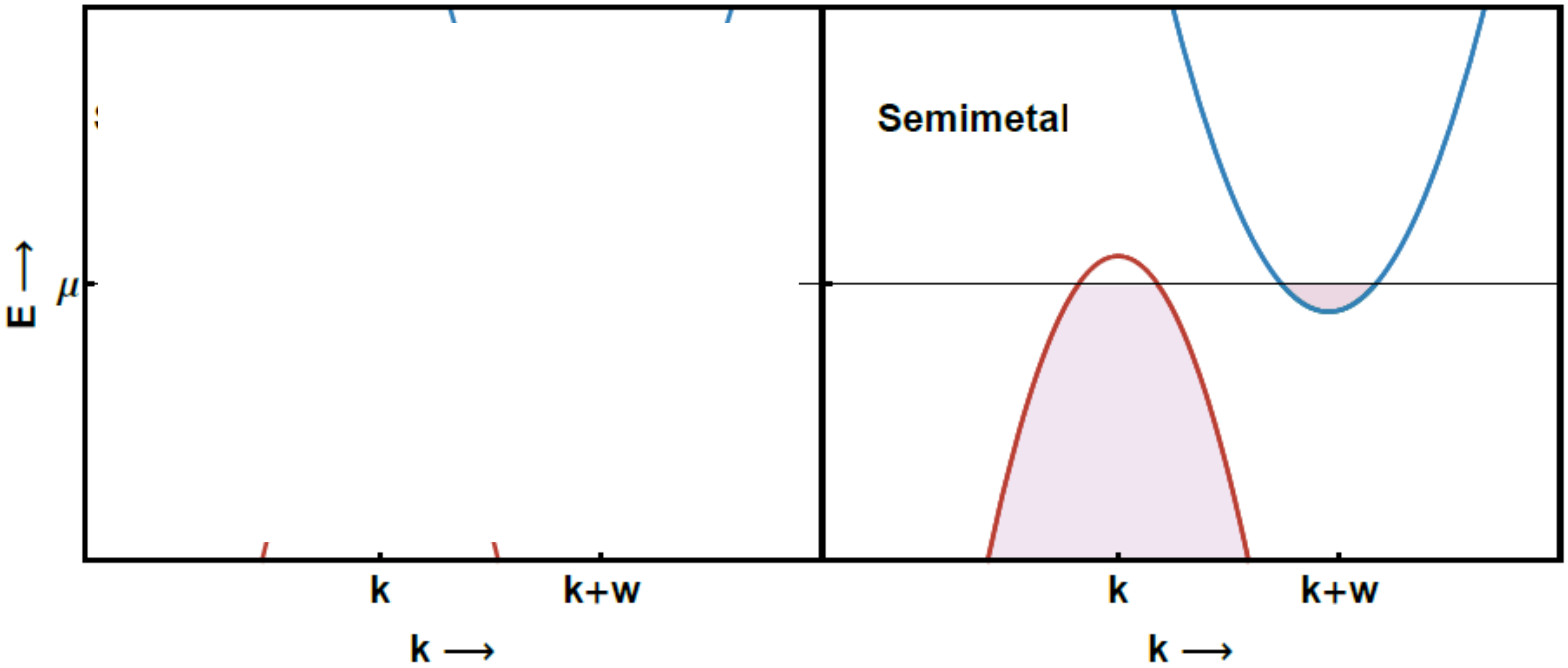


Electron-Like Band



Hole-Like Band

Consider two bands crossing the Fermi level

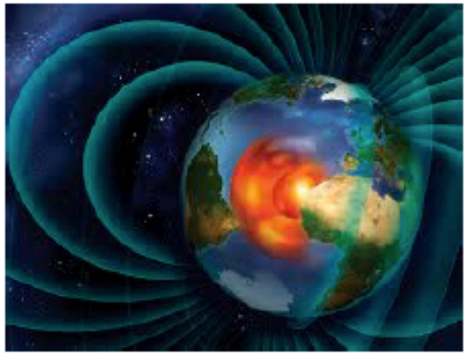


Magnetic field

Human Brain

1 nG to 10 nG

Earth

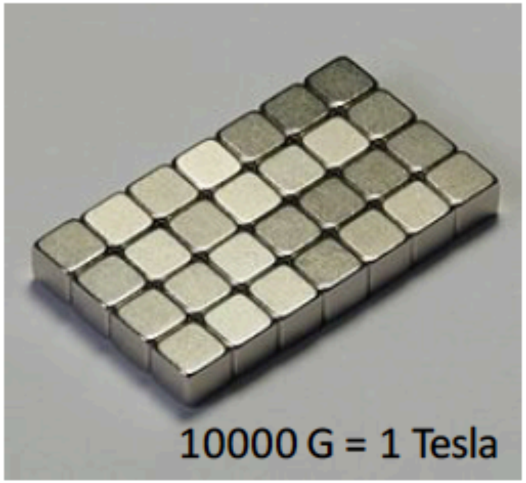


0.25 - 0.65 Gauss

Fridge Magnets

50 Gauss

Neodymium – iron – boron
$Nd_2Fe_{14}B$ Magnet



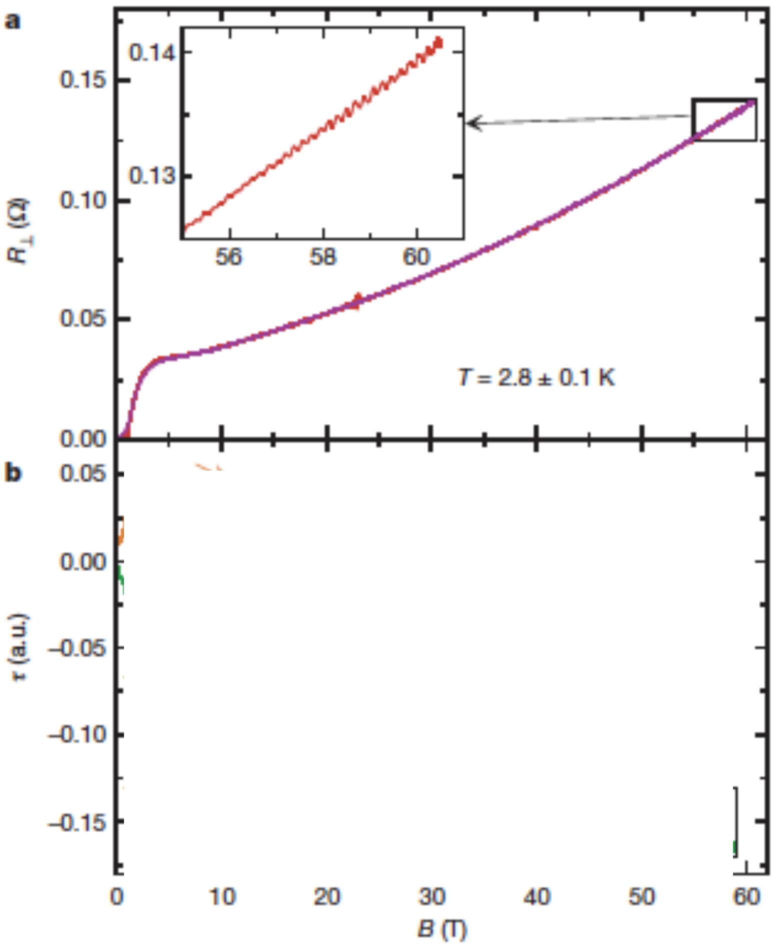
10000 G = 1 Tesla

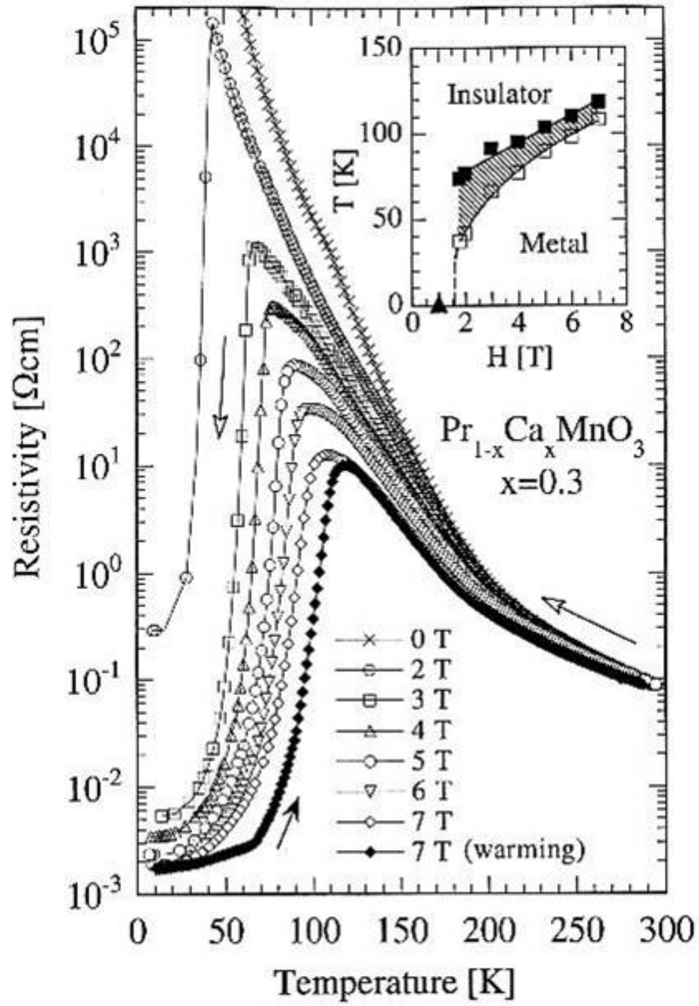
Static 45 –Tesla
Hybrid magnet

100 Tesla
Pulsed magnet

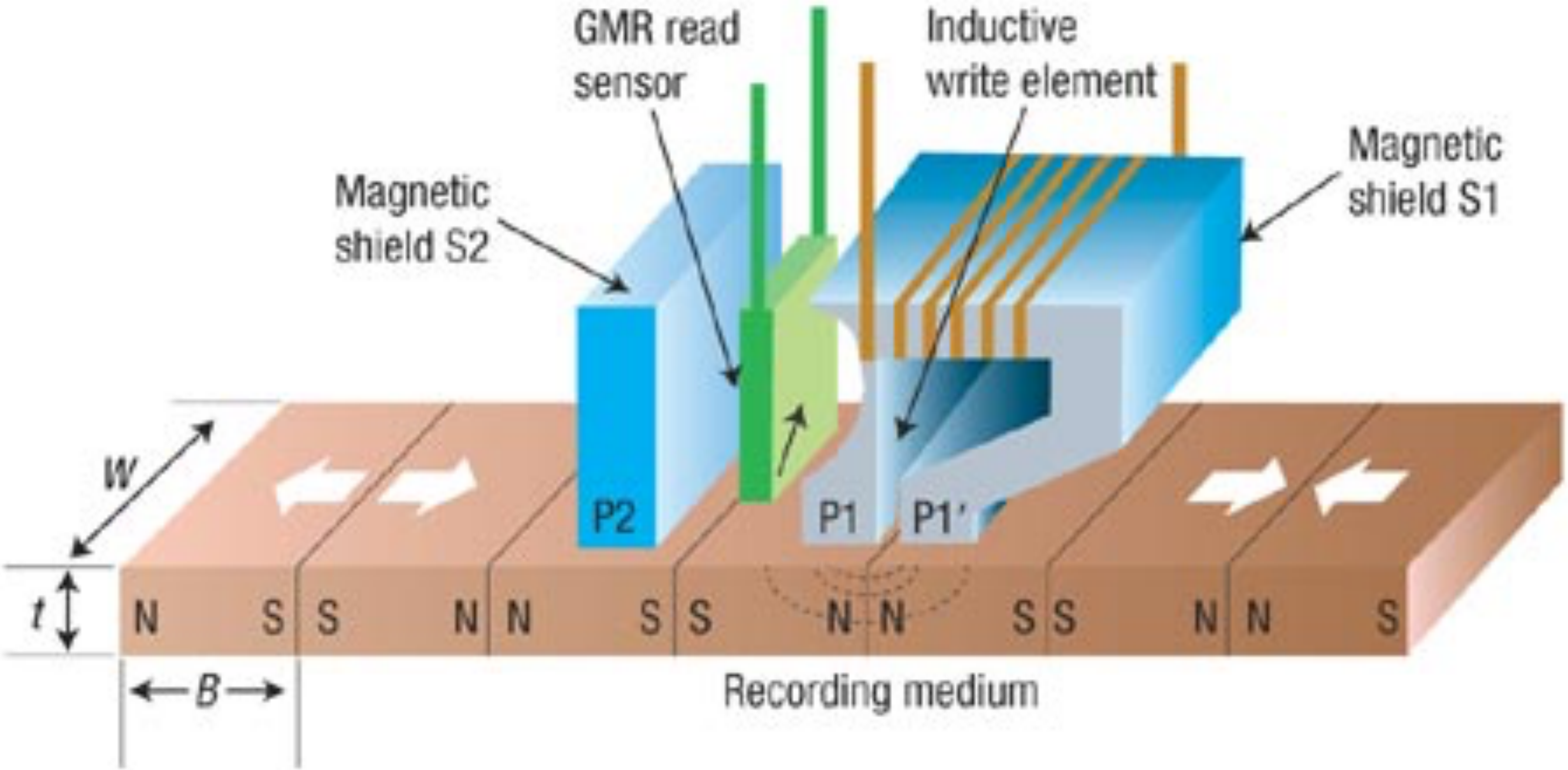
Magneto-resistance

Magnetoresistance is the tendency of a material to change the value of its electrical resistance in an externally-applied magnetic field.





Application of Magneto-resistance

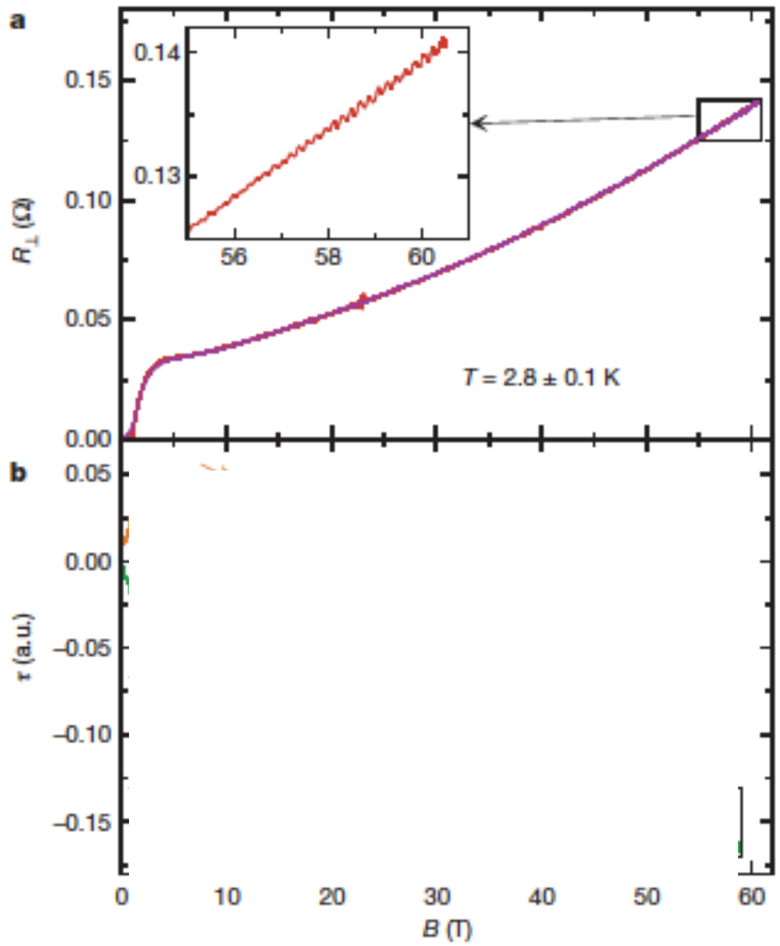


Nobel Prize 2007: Magneto-resistance

The Nobel Prize in Physics 2007 was awarded jointly to Albert Fert and Peter Grünberg *"for the discovery of Giant Magnetoresistance"*

Magneto-resistance

Magnetoresistance is the tendency of a material to change the value of its electrical resistance in an externally-applied magnetic field.



One route to Magneto-resistance

Exercise 2 *Hall effect: Multiband scenario*

In the lecture we derived single-band expressions for the resistivity $\rho = m/ne^2\tau$ and the Hall coefficient $R_{\mathrm{H}} = -1/ne$. It is convenient to write the relation between the current density $\mathbf{j}$ and the electric field $\mathbf{E}$ as $\mathbf{E} = \boldsymbol{\rho}\mathbf{j}$ where:

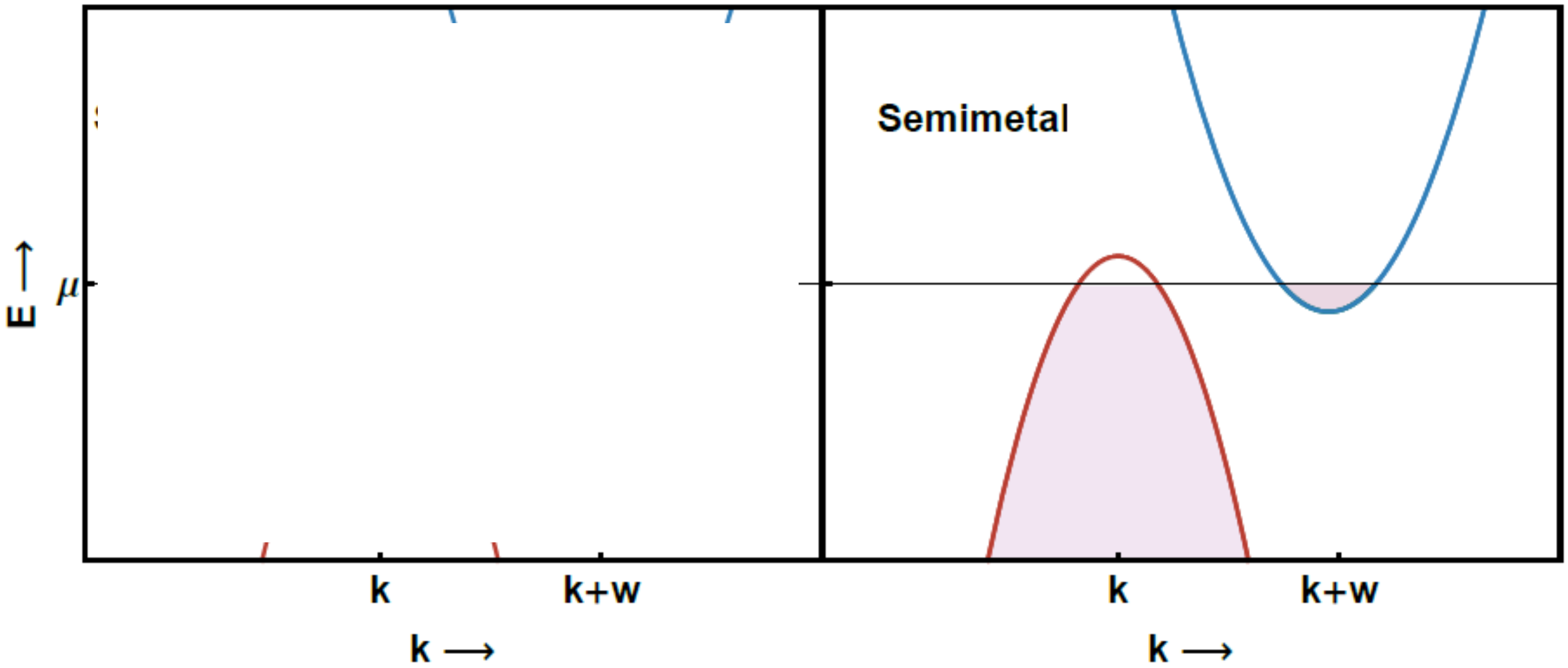
$$\boldsymbol{\rho} = \begin{pmatrix} \rho & -R_{\mathrm{H}}B \\ R_{\mathrm{H}}B & \rho \end{pmatrix} \tag{1}$$

(a) Let us consider a metal where more than one band crosses the Fermi level. When applying an electric field $\mathbf{E}$, the current $\mathbf{j}_n$ on the n^{th} band is: $\mathbf{j}_n = \boldsymbol{\rho}_n^{-1}\mathbf{E}$ where

$$\boldsymbol{\rho}_n = \begin{pmatrix} \rho_n & -R_{\mathrm{H},n}B \\ R_{\mathrm{H},n}B & \rho_n \end{pmatrix}. \tag{2}$$

Show that the total induced current $\mathbf{j}$ is given by $\mathbf{E} = \boldsymbol{\rho}\mathbf{j}$ where $\boldsymbol{\rho} = (\sum \boldsymbol{\rho}_n^{-1})^{-1}$.

Consider two bands crossing the Fermi level



One route to Magneto-resistance

(b) If only two bands are crossing the Fermi level, show that:

$$R_\mathrm{H} = \frac{R_{\mathrm{H},1}\rho_2^2 + R_{\mathrm{H},2}\rho_1^2 + R_{\mathrm{H},1}R_{\mathrm{H},2}(R_{\mathrm{H},1}+R_{\mathrm{H},2})B^2}{(\rho_1+\rho_2)^2 + (R_{\mathrm{H},1}+R_{\mathrm{H},2})^2B^2} \tag{3}$$

$$\rho = \frac{\rho_1\rho_2(\rho_1+\rho_2) + (\rho_1 R_{\mathrm{H},2}^2 + \rho_2 R_{\mathrm{H},1}^2)B^2}{(\rho_1+\rho_2)^2 + (R_{\mathrm{H},1}+R_{\mathrm{H},2})^2B^2} \tag{4}$$

Hint: It is allowed to use Mathematica. If you do so, print out the code and the output.

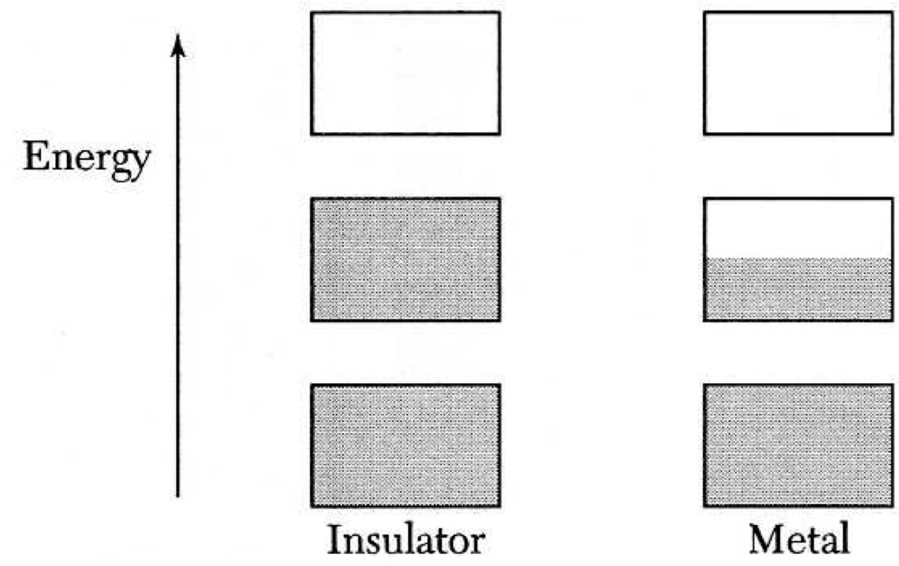
(c) Magnetic field dependence of resistivity is called magneto-resistance. If the two-band system has both electron-like and hole-like carries so that $|R_{\mathrm{H},1}| \approx |R_{\mathrm{H},2}|$, what is the field dependence of ρ.

(d) The mobility can be expressed as $\mu = e\tau/m$. Use the low-field limits of equations 3 and 4 to derive the following two expressions:

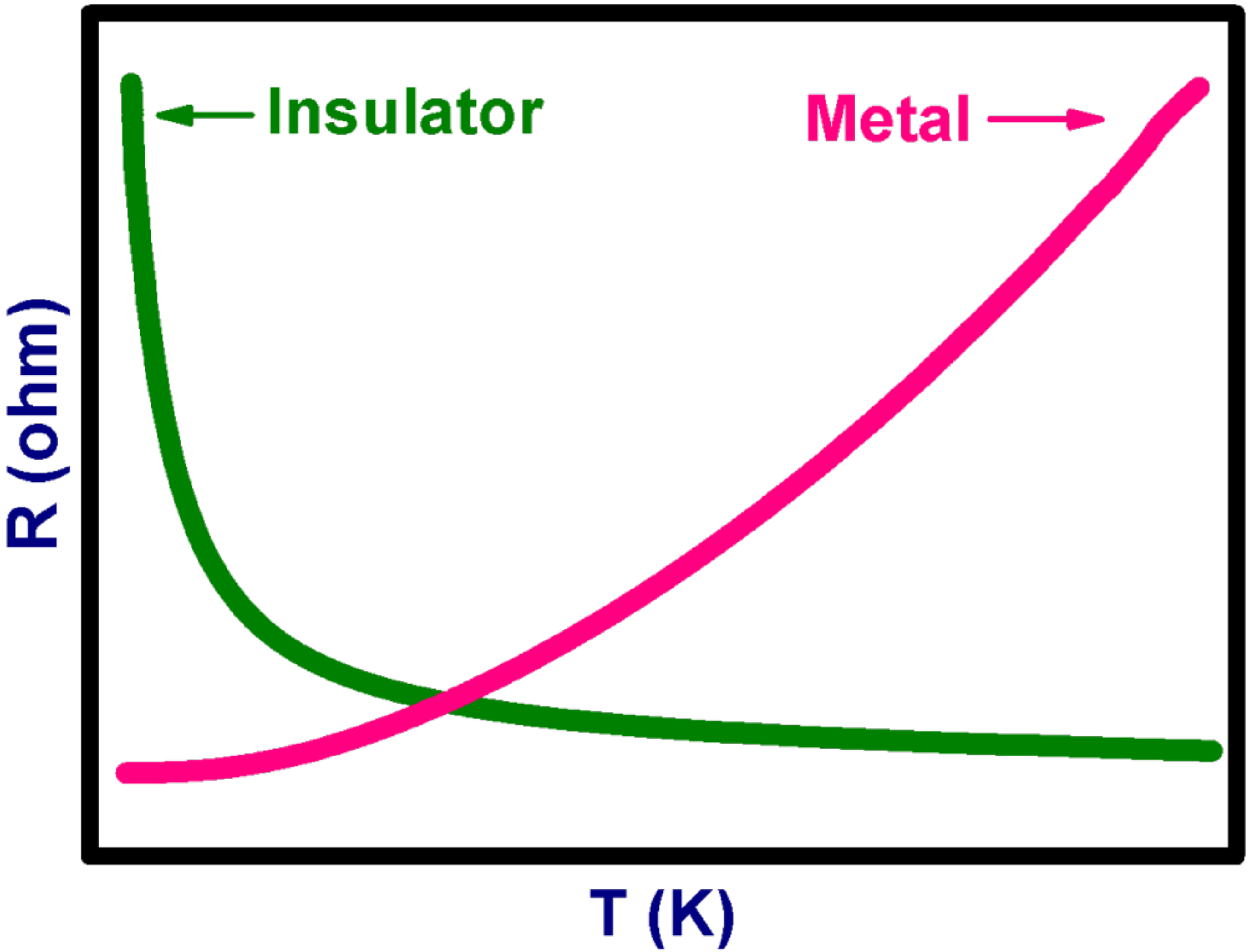
$$\sigma = ne\mu_\mathrm{e} + pe\mu_\mathrm{h} \tag{5}$$

$$R_\mathrm{H} = \frac{p\mu_\mathrm{h}^2 - n\mu_\mathrm{e}^2}{e(p\mu_\mathrm{h} + n\mu_\mathrm{e})^2}. \tag{6}$$

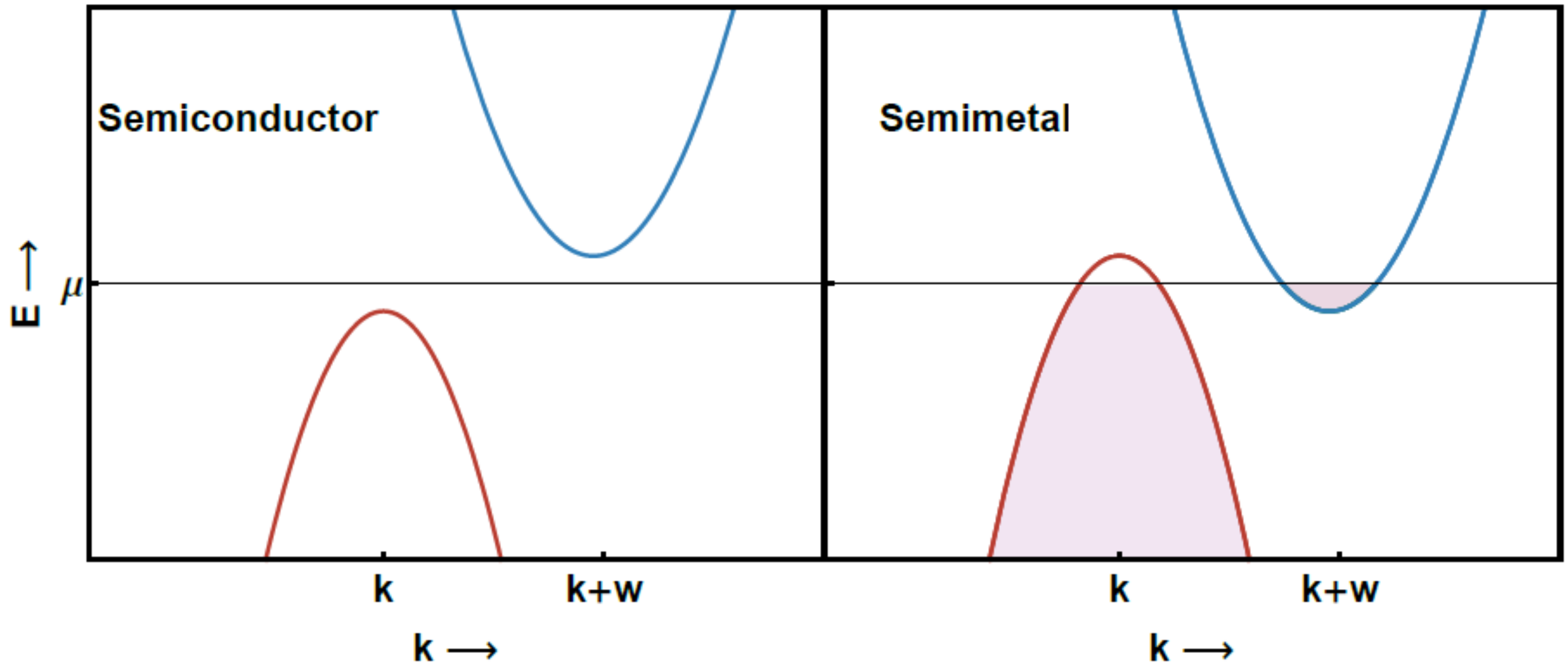
Metals & Insulators



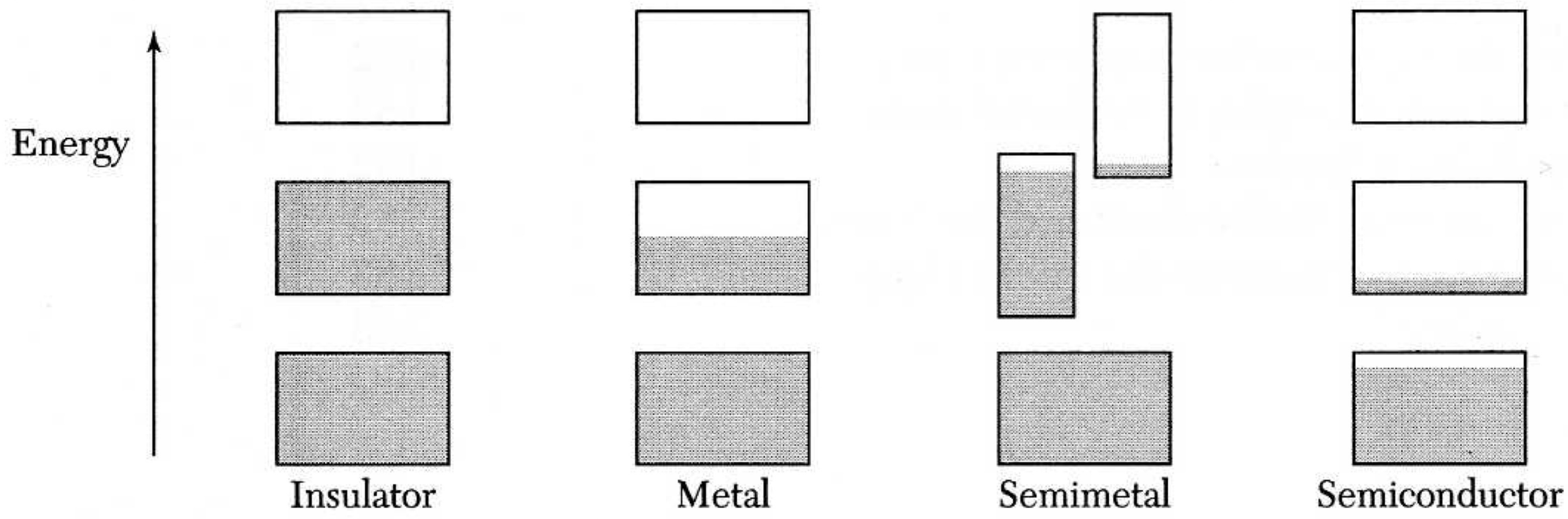
Metals and insulators: Resistivity



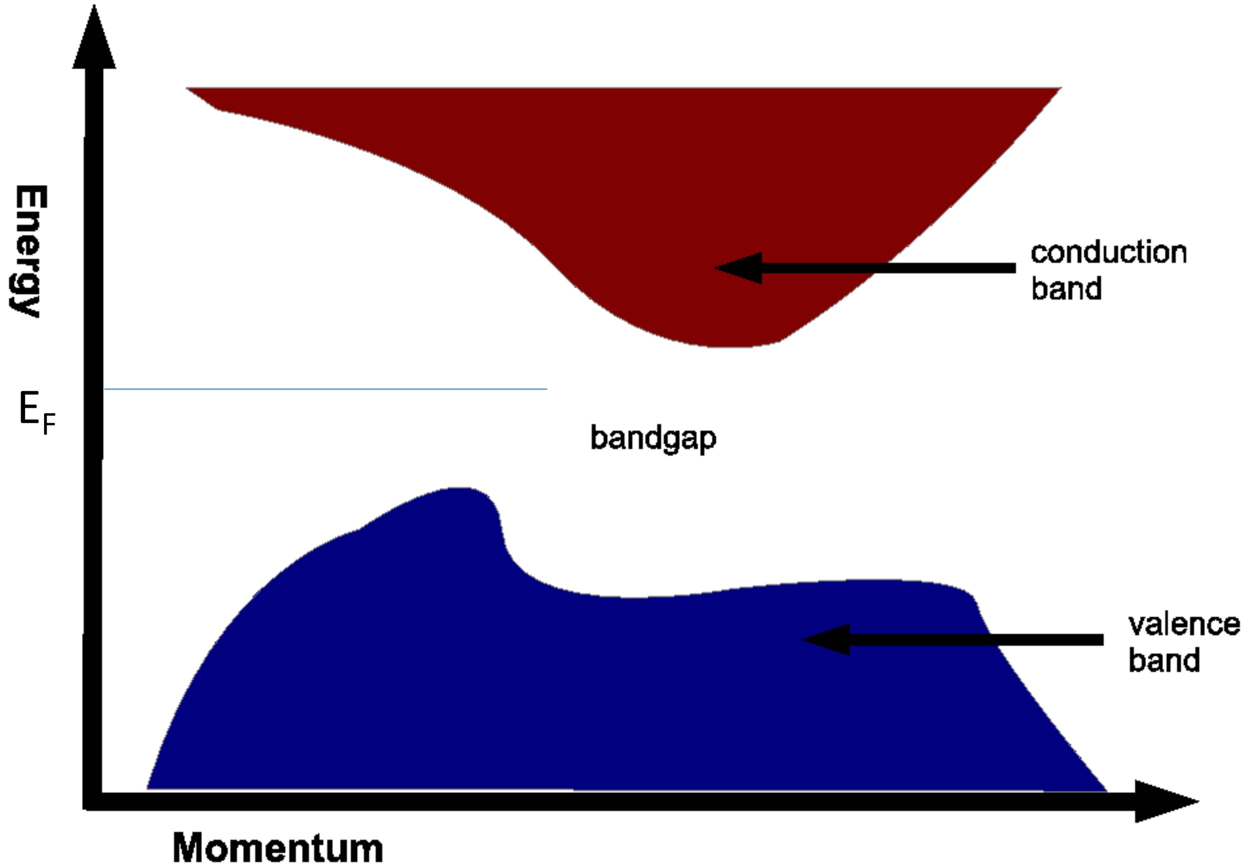
Semimetals & Semiconductors



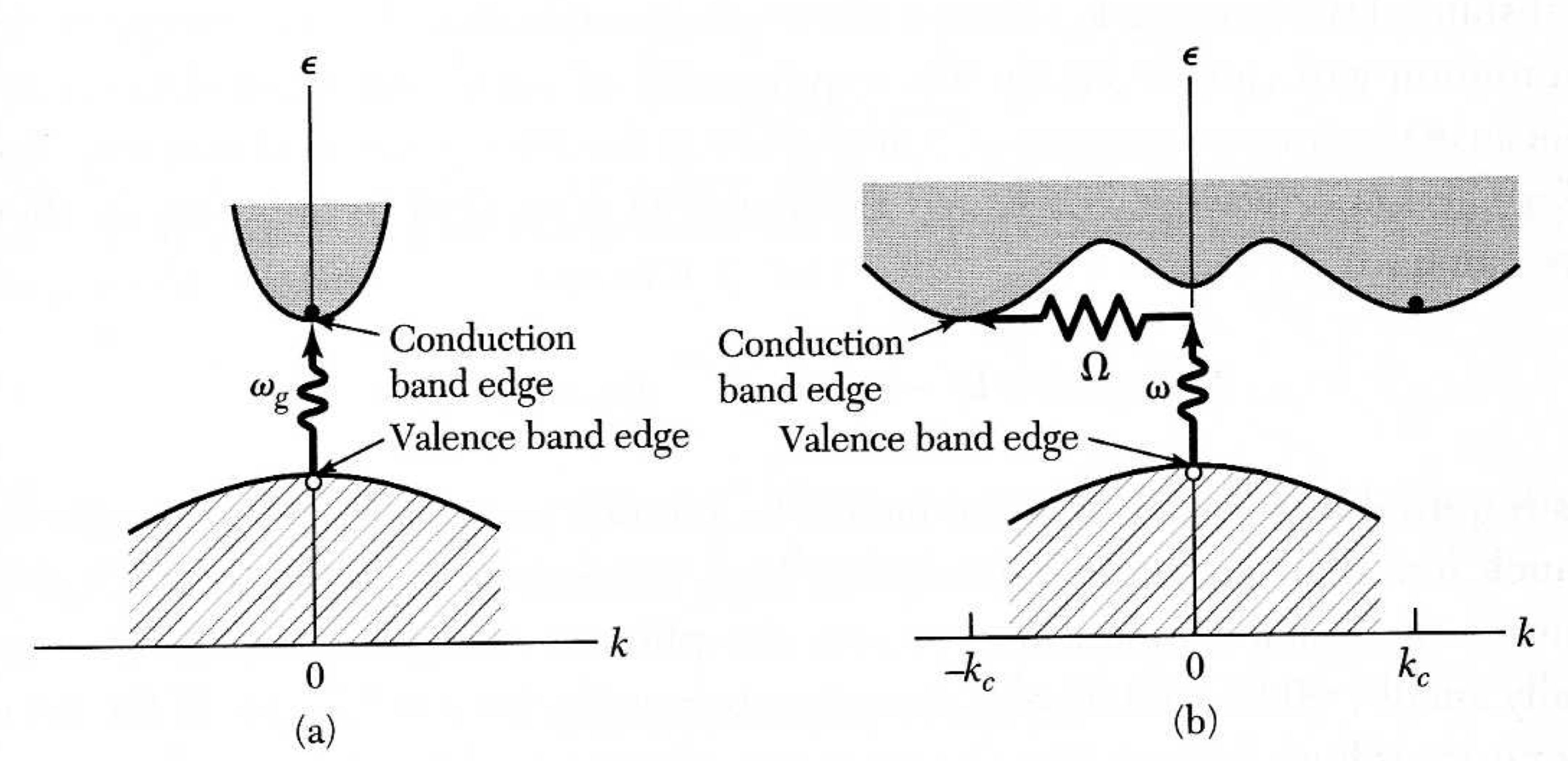
Semimetals & Semiconductors



Valence and conduction band



Direct and indirect gap



Semiconductor gaps versus k_BT

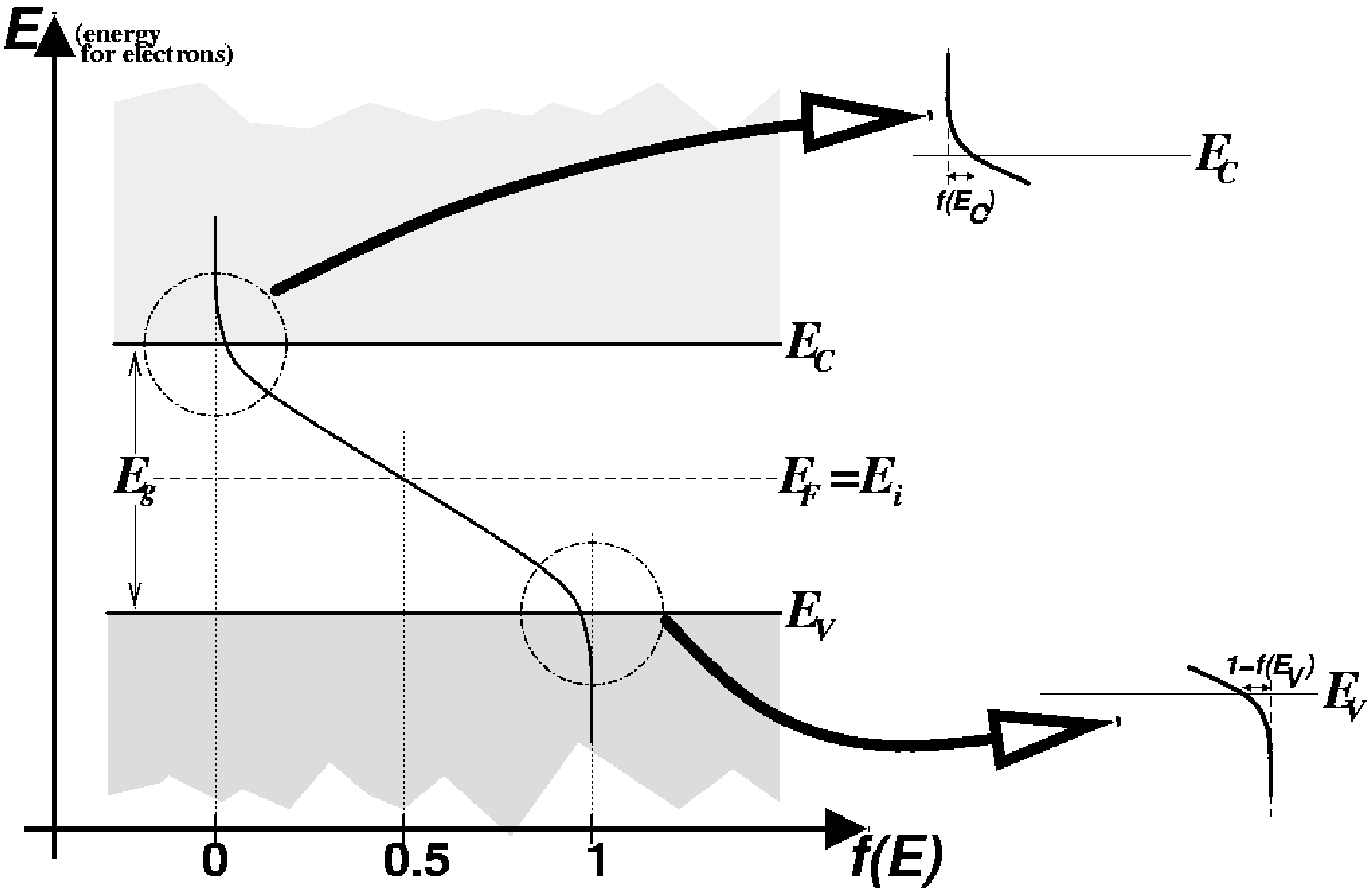
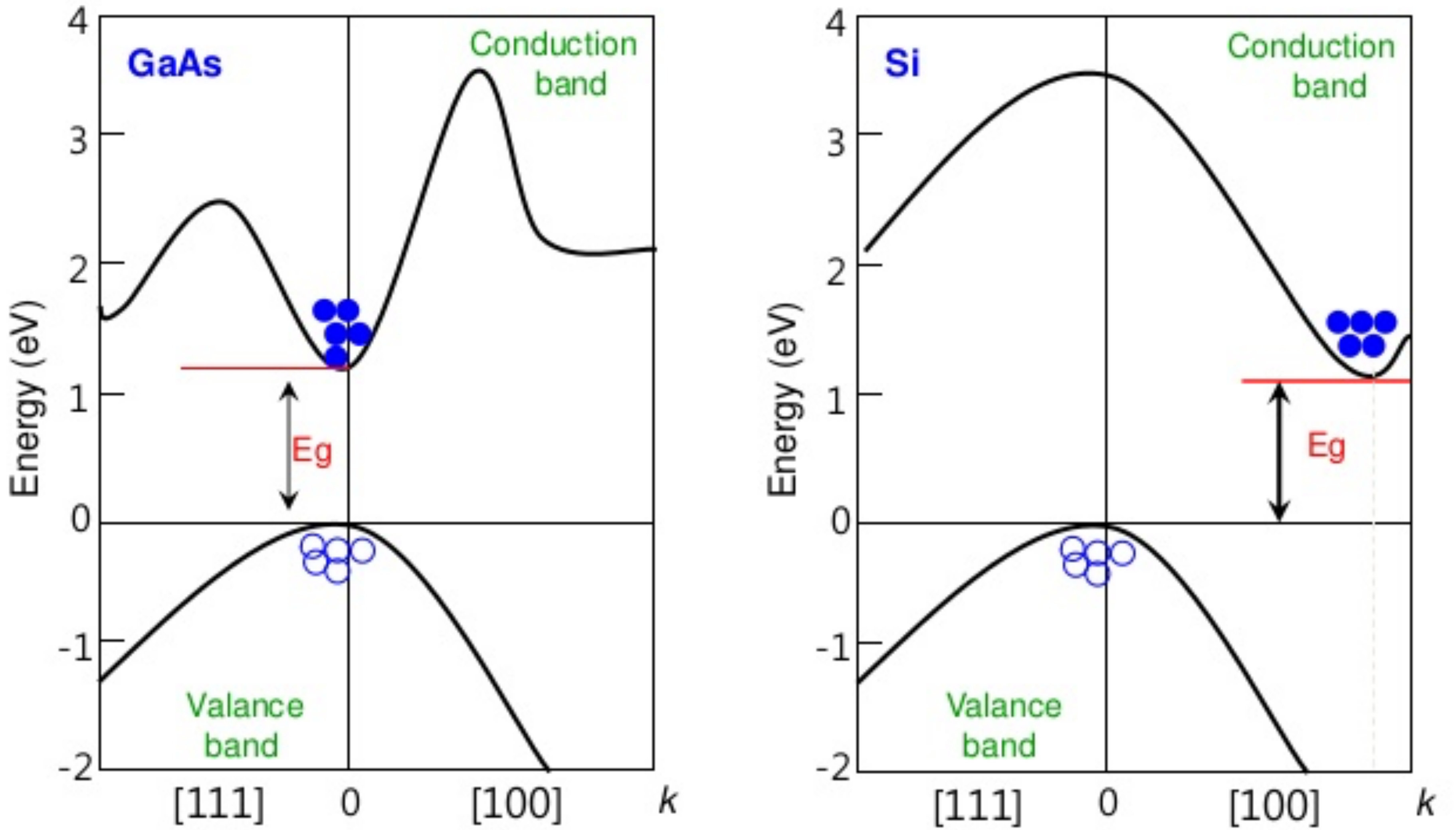


Figure 4:

Band Structure of Semiconductors



Energy band structures of *GaAs* and *Si*

Semiconductor gaps

Table 1 Energy gap between the valence and conduction bands
(*i* = indirect gap; *d* = direct gap)

		E_g, eV				E_g, eV	
Crystal	Gap	0 K	300 K	Crystal	Gap	0 K	300 K
Diamond	*i*	5.4		SiC(hex)	*i*	3.0	—
Si	*i*	1.17	1.11	Te	*d*	0.33	—
Ge	*i*	0.744	0.66	HgTe[a]	*d*	−0.30	
αSn	*d*	0.00	0.00	PbS	*d*	0.286	0.34–0.37
InSb	*d*	0.23	0.17	PbSe	*i*	0.165	0.27
InAs	*d*	0.43	0.36	PbTe	*i*	0.190	0.29
InP	*d*	1.42	1.27	CdS	*d*	2.582	2.42
GaP	*i*	2.32	2.25	CdSe	*d*	1.840	1.74
GaAs	*d*	1.52	1.43	CdTe	*d*	1.607	1.44
GaSb	*d*	0.81	0.68	SnTe	*d*	0.3	0.18
AlSb	*i*	1.65	1.6	Cu_2O	*d*	2.172	—

[a]HgTe is a semimetal; the bands overlap.

Electronic masses

Crystal	Electron m_e/m
InSb	0.015
InAs	0.026
InP	0.073
GaSb	0.047
GaAs	0.066
Cu_2O	0.99

Reading Kittel carefully,
following notation is adopted.
m = is the free electron mass.
m_e = effective crystal electron mass

Conduction Electron Concentration

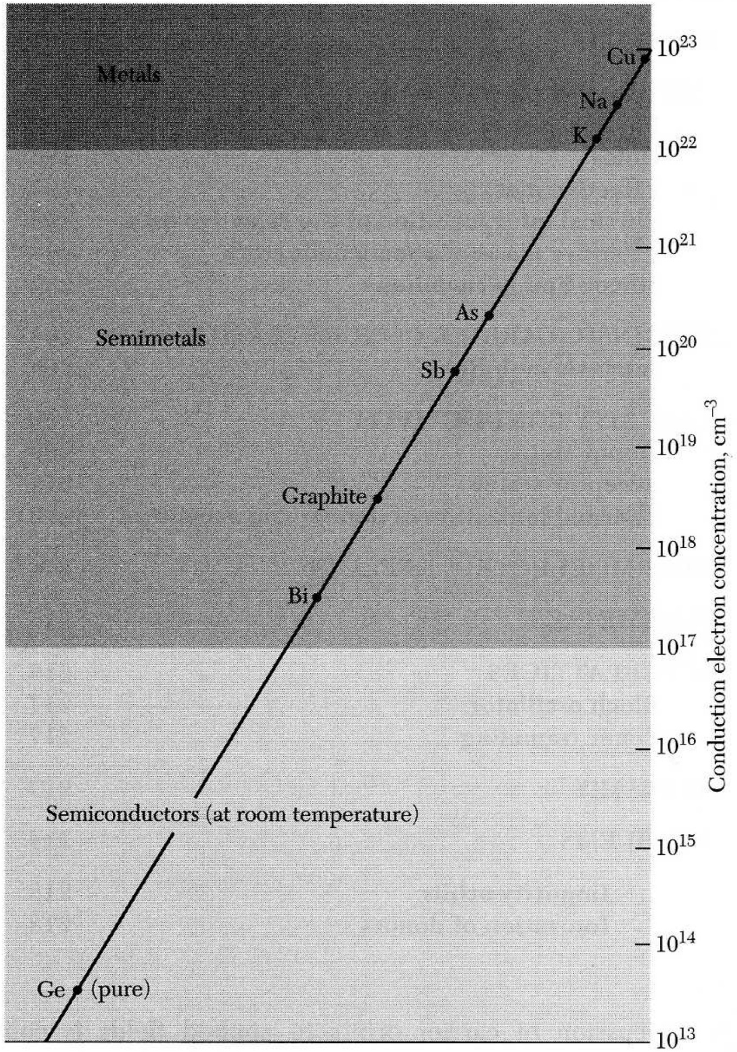


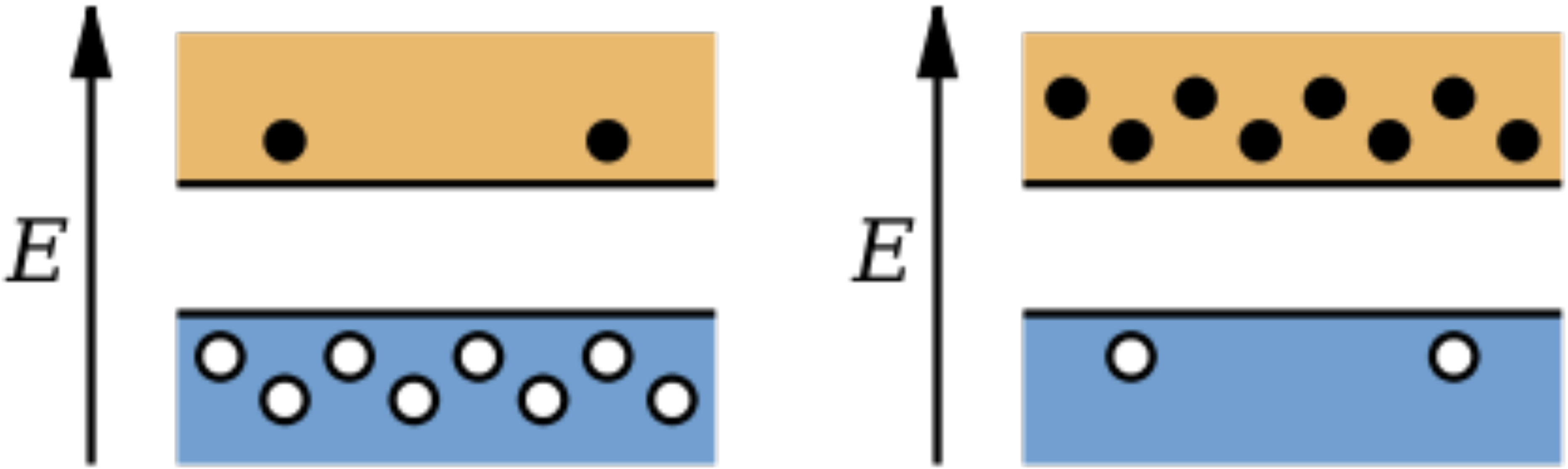
Figure 1 Carrier concentrations for metals, semimetals, and semiconductors. The semiconductor range may be extended upward by increasing the impurity concentration, and the range can be extended downward to merge eventually with the insulator range.

Electronic mobility

Table 3 Carrier mobilities at room temperature, in $cm^2/V\text{-}s$

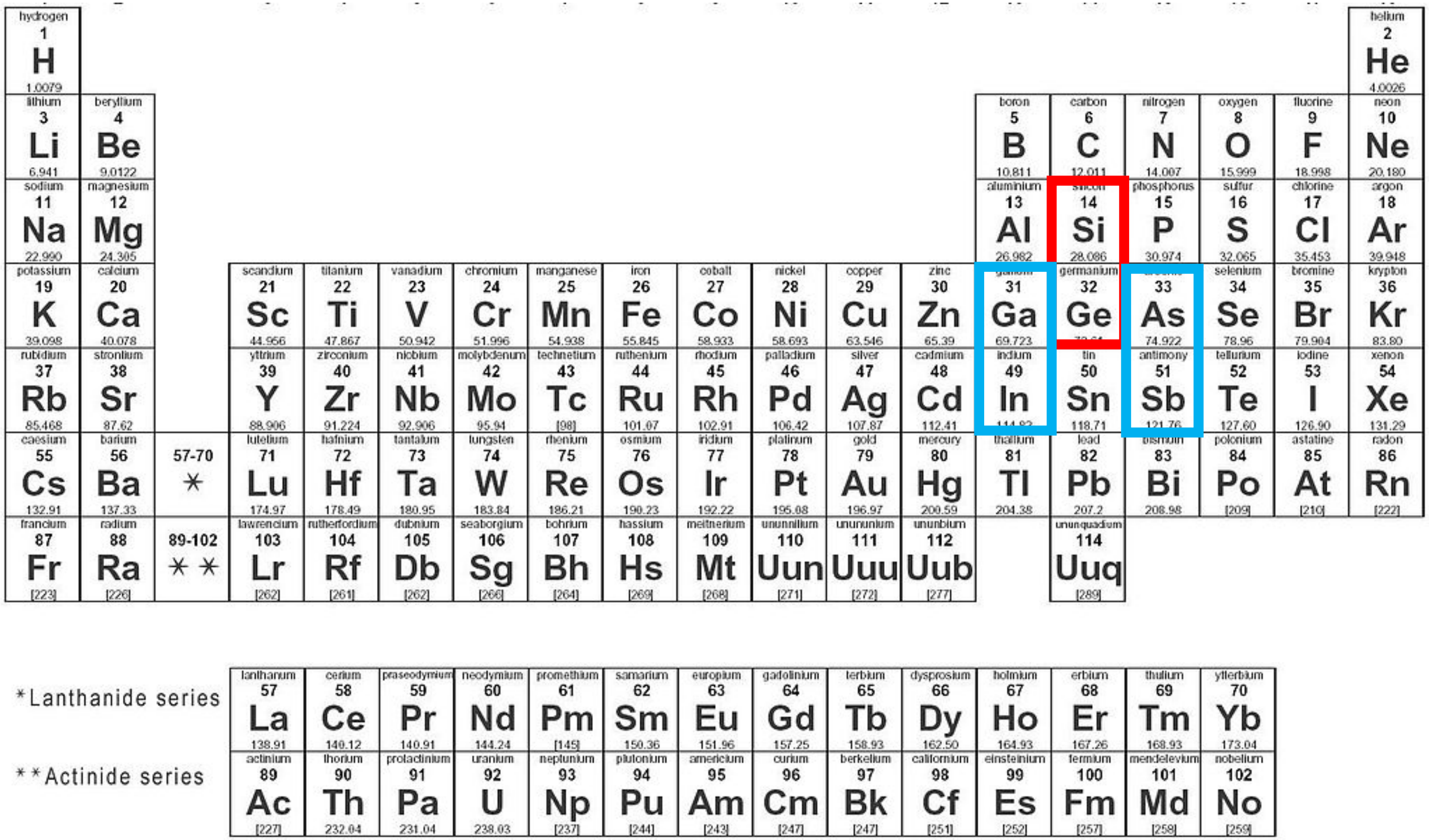
Crystal	Electrons	Holes	Crystal	Electrons	Holes
Diamond	1800	1200	GaAs	8000	300
Si	1350	480	GaSb	5000	1000
Ge	3600	1800	PbS	550	600
InSb	800	450	PbSe	1020	930
InAs	30000	450	PbTe	2500	1000
InP	4500	100	AgCl	50	—
AlAs	280	—	KBr (100 K)	100	—
AlSb	900	400	SiC	100	10–20

n- and p-type semiconductors



Doping – Performance Enhancement

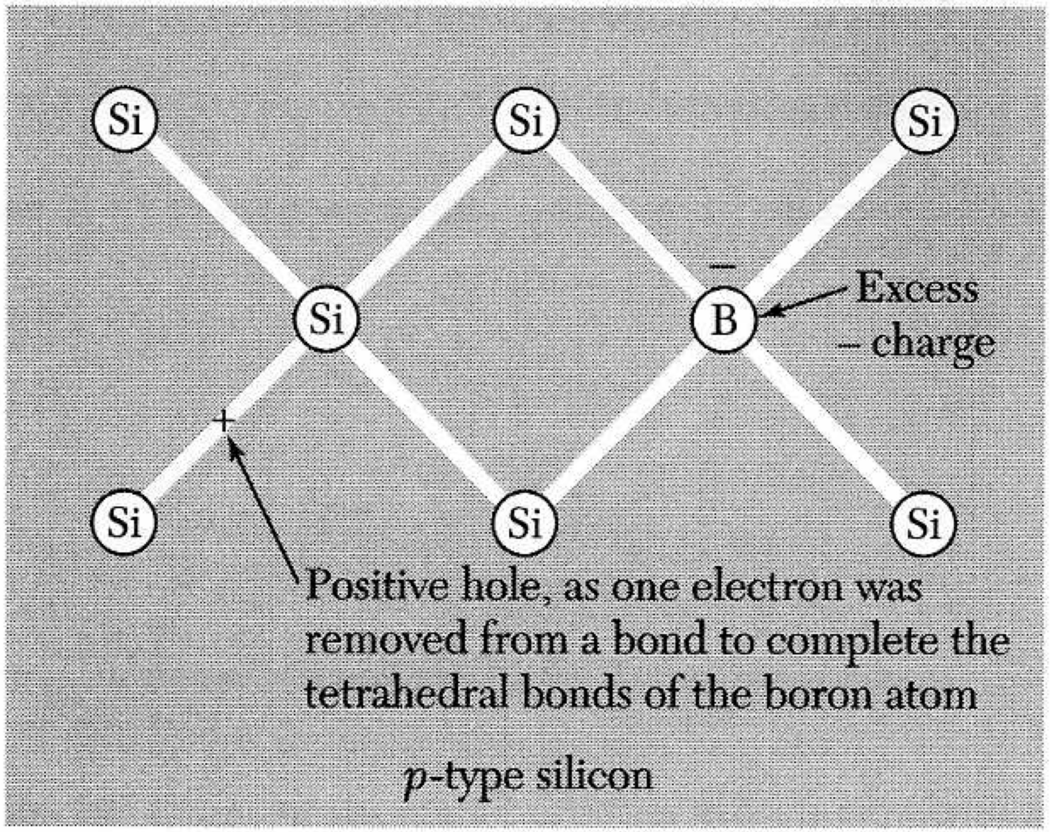
Semiconductor Materials

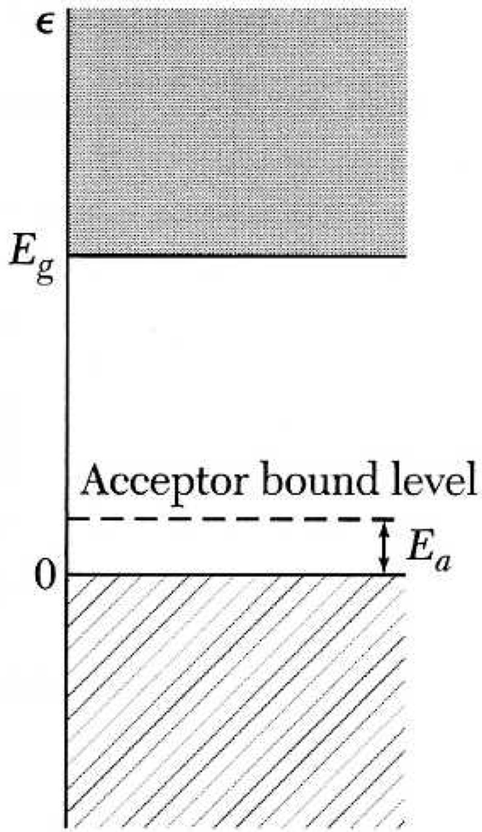


Diamond-type semiconductors

III – V compounds (GaAs, InSb)

Hole - doping



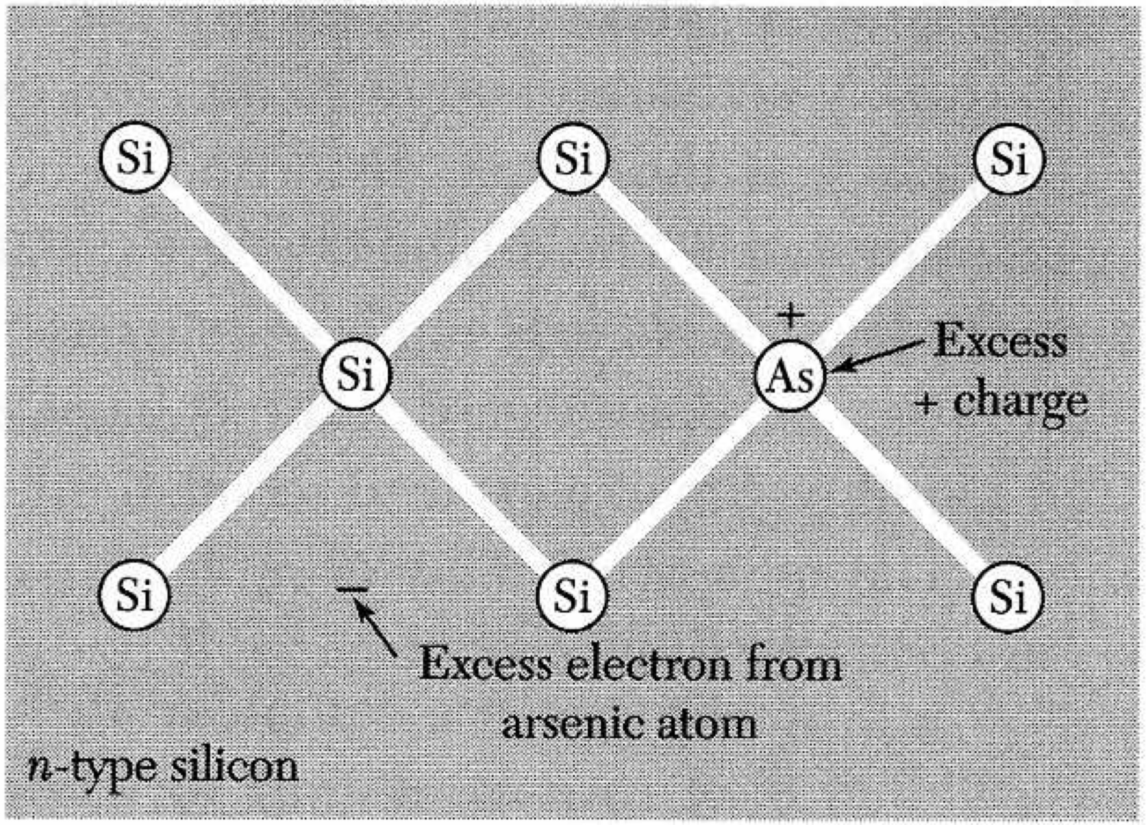


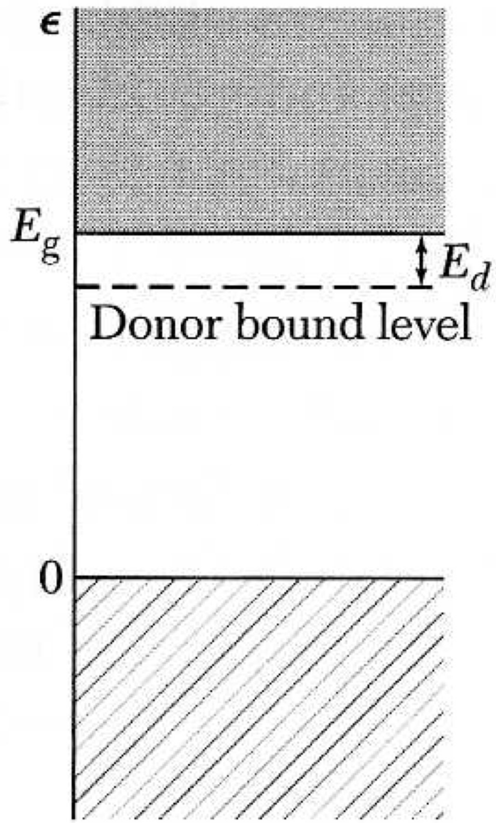
Si^{4+}

B^{3+}

From Kittel

Electron - doping





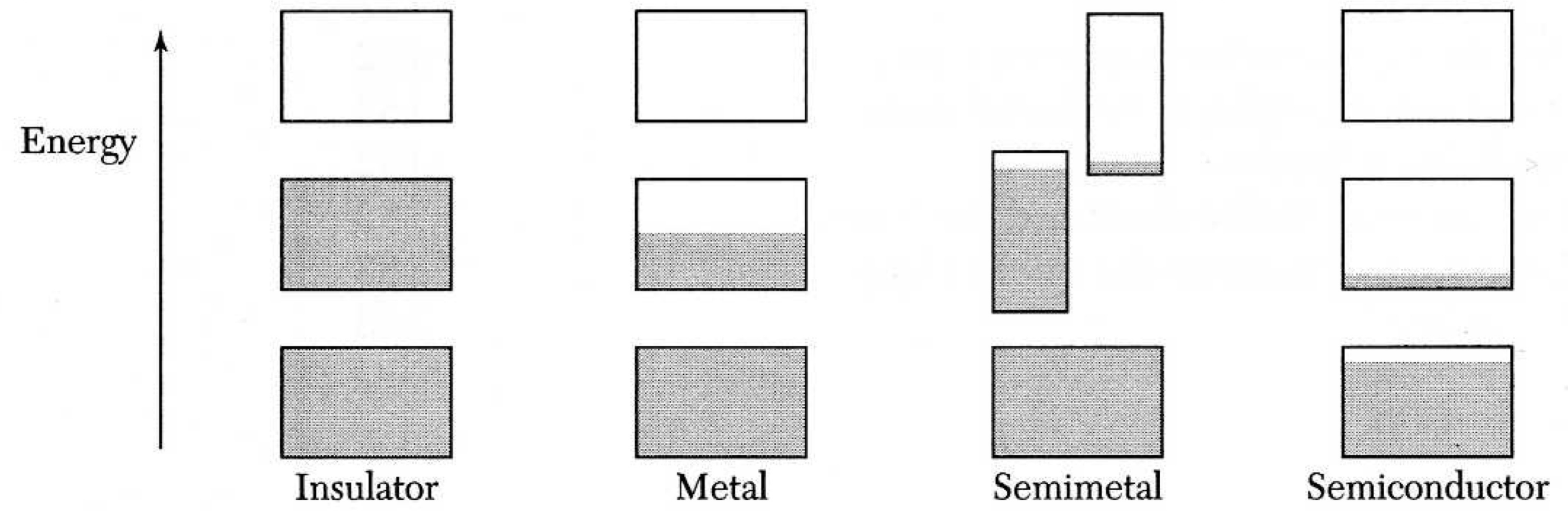
Si^{4+}

As^{5+}

From Kittel

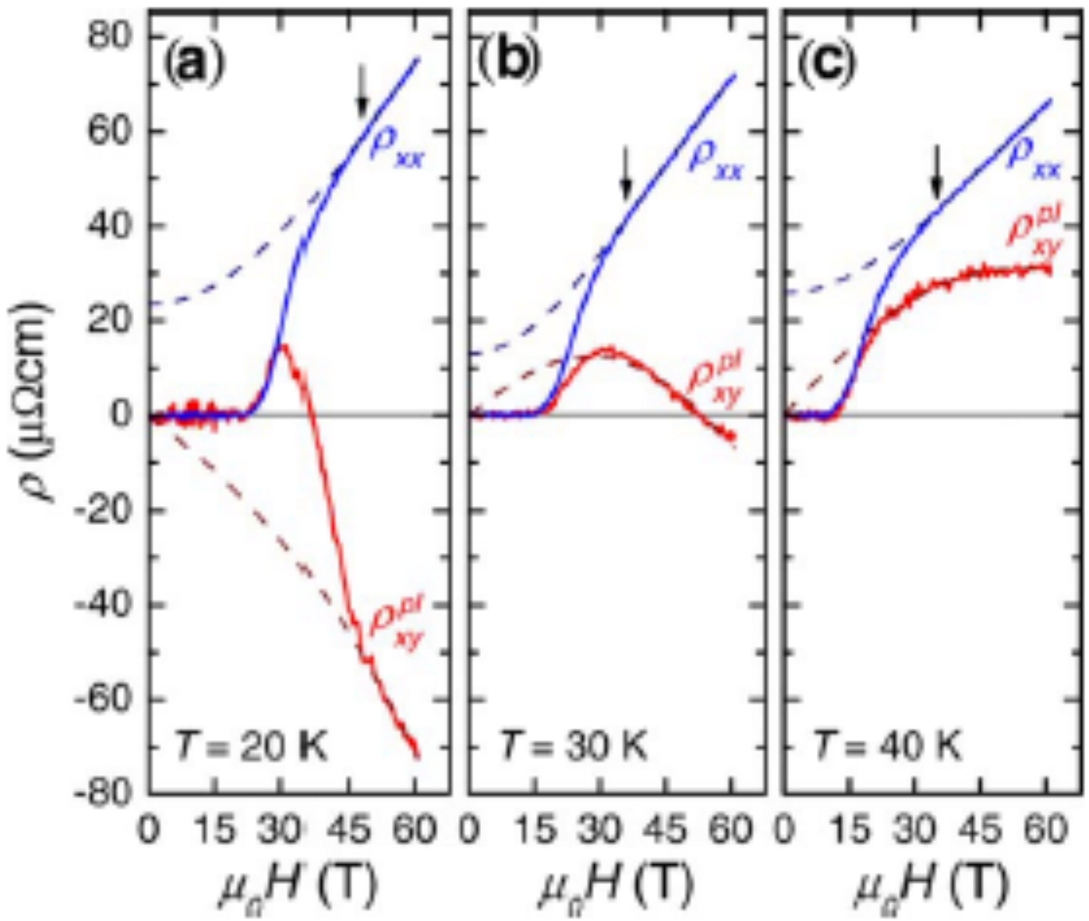
Concluding quiz

Does a semiconductor have a Fermi surface? (yes/no)



Does a semimetal have a Fermi surface? (yes/no)

Magneto-resistance



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