

# Tasks

- (1) Read chapter 8: Semiconductors for next week.**
- (2) Solve exercise sheets**
- (3) Who is summarizing next week?**

20 & 25<sup>th</sup> April

2 & 4<sup>th</sup> May

9 & 16<sup>th</sup> May

18 & 23<sup>th</sup> May

30<sup>th</sup> May & 1<sup>st</sup> June

Chapter 6

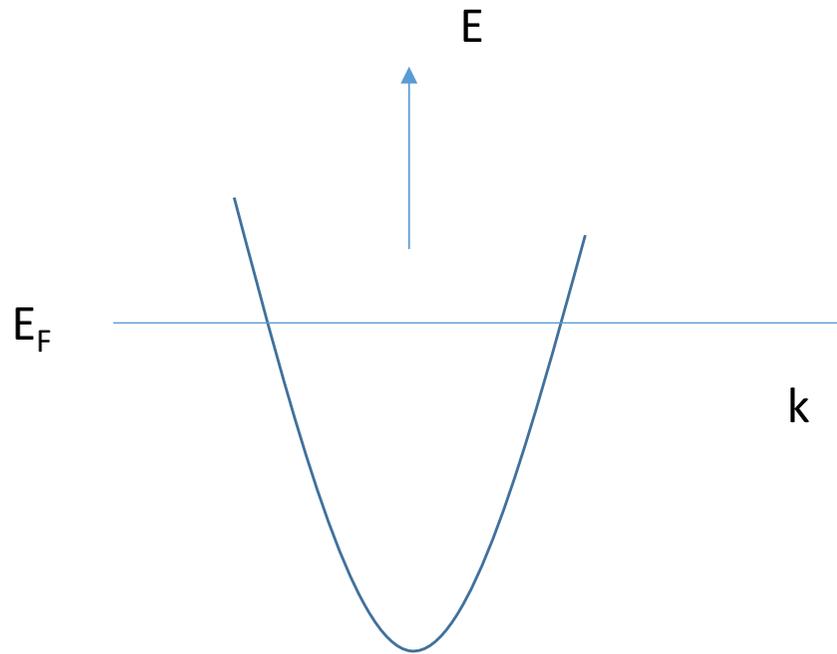
Chapter 7

Chapter 8

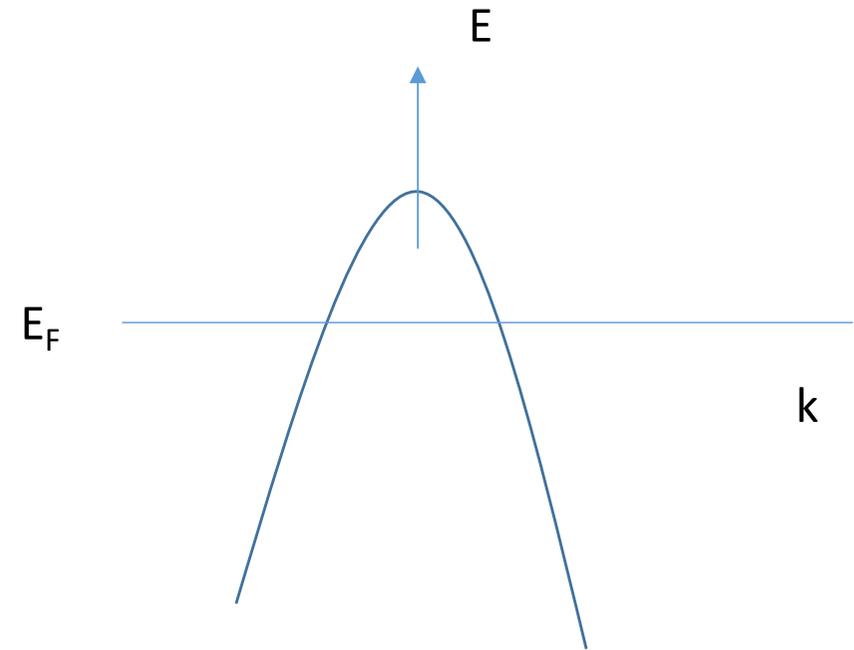
Chapter 9

Wrap-up

# Electron versus Hole like bands

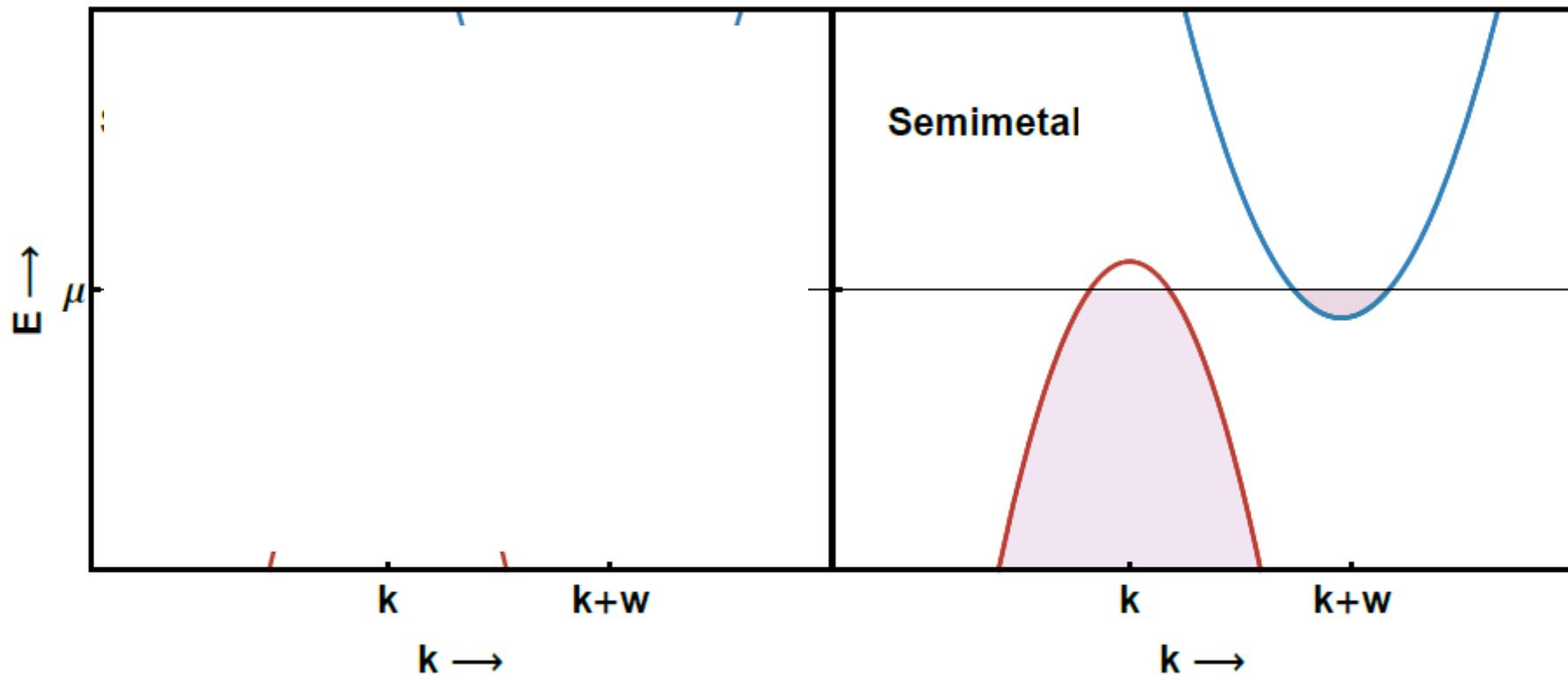


**Electron-Like Band**



**Hole-Like Band**

# Consider two bands crossing the Fermi level



# Magnetic field

Human Brain

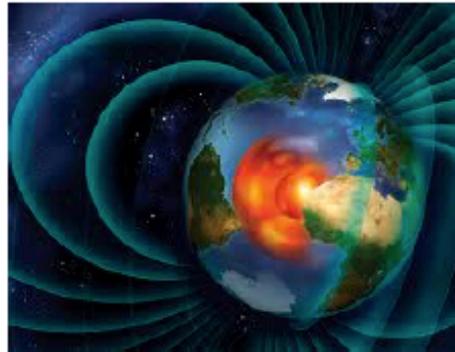


1 nG to 10 nG

Neodymium – iron – boron  
 $\text{Nd}_2\text{Fe}_{14}\text{B}$  Magnet



Earth



0.25 - 0.65 Gauss

Static 45 –Tesla  
Hybrid magnet



Fridge Magnets



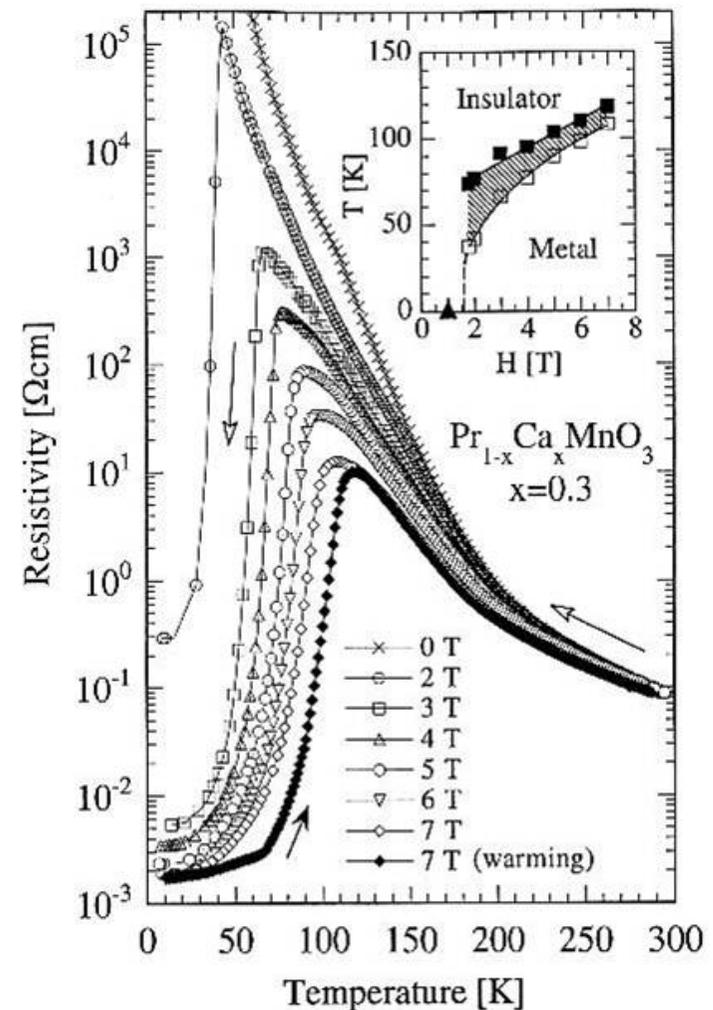
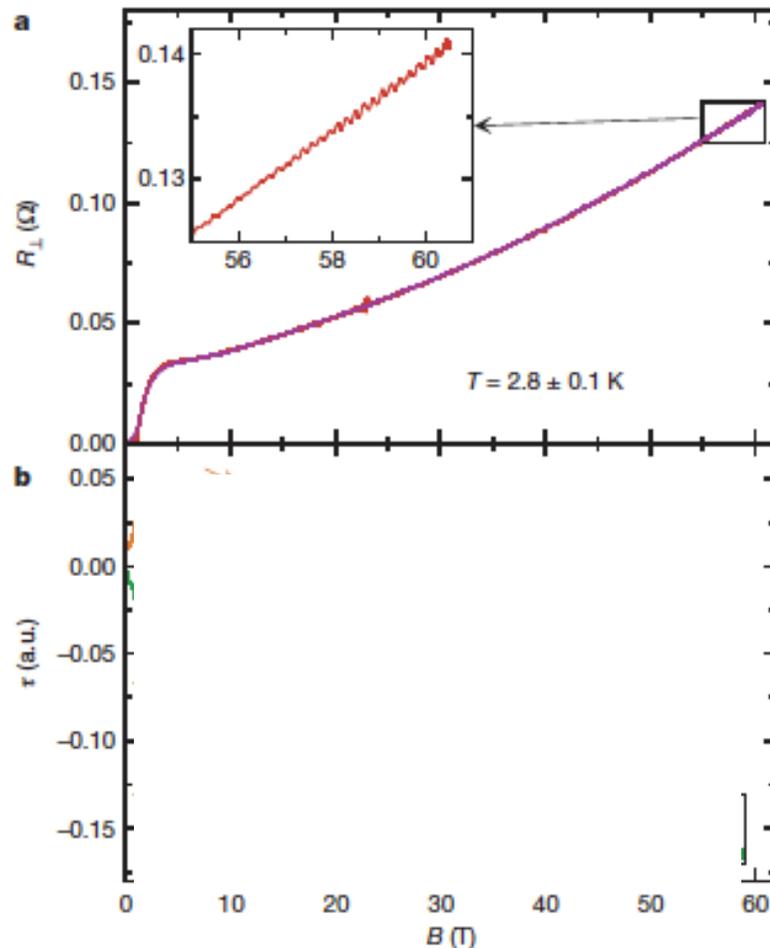
50 Gauss

100 Tesla  
Pulsed magnet

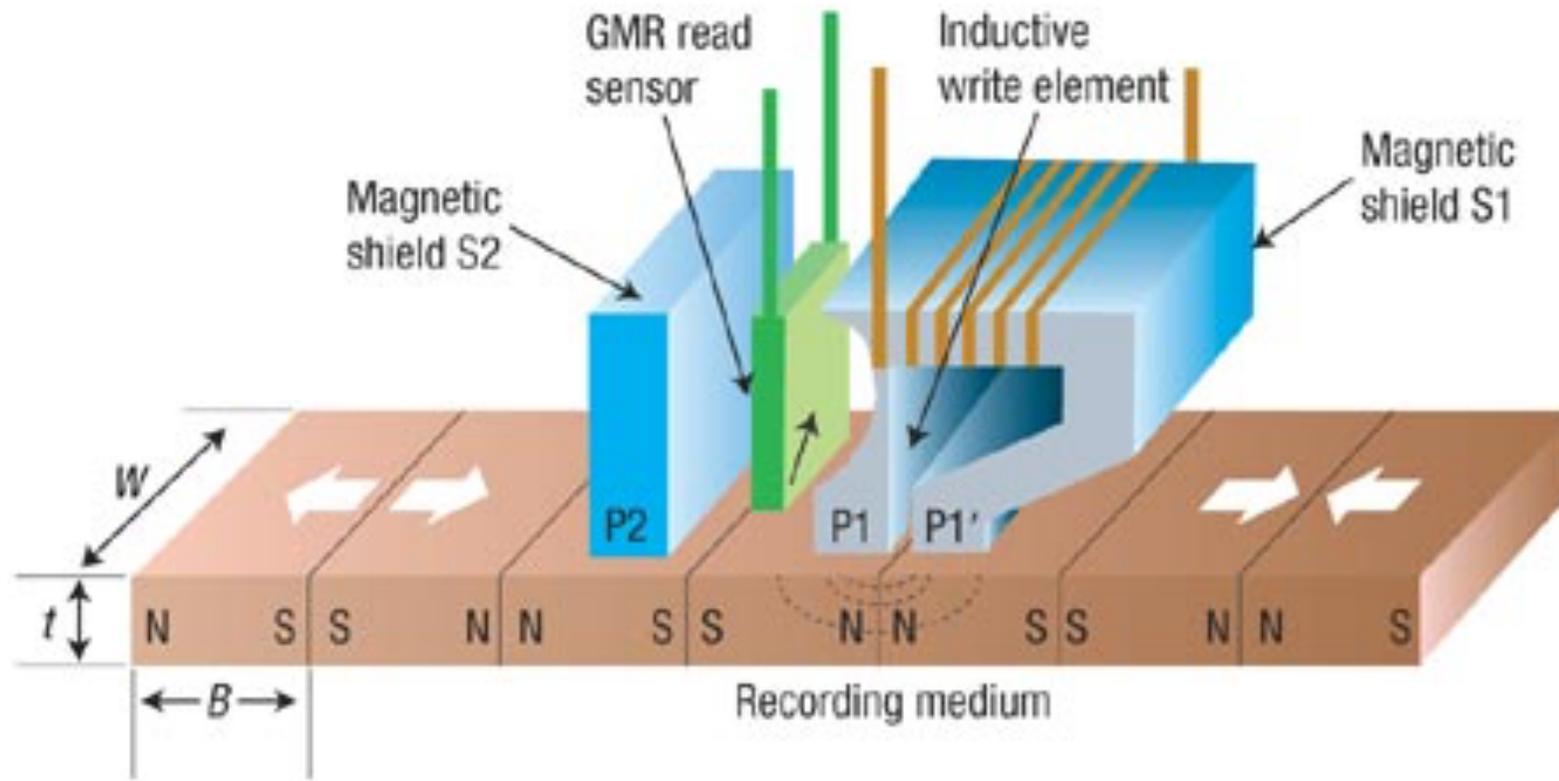


# Magneto-resistance

**Magneto-resistance** is the tendency of a material to change the value of its [electrical resistance](#) in an externally-applied [magnetic field](#).



# Application of Magneto-resistance



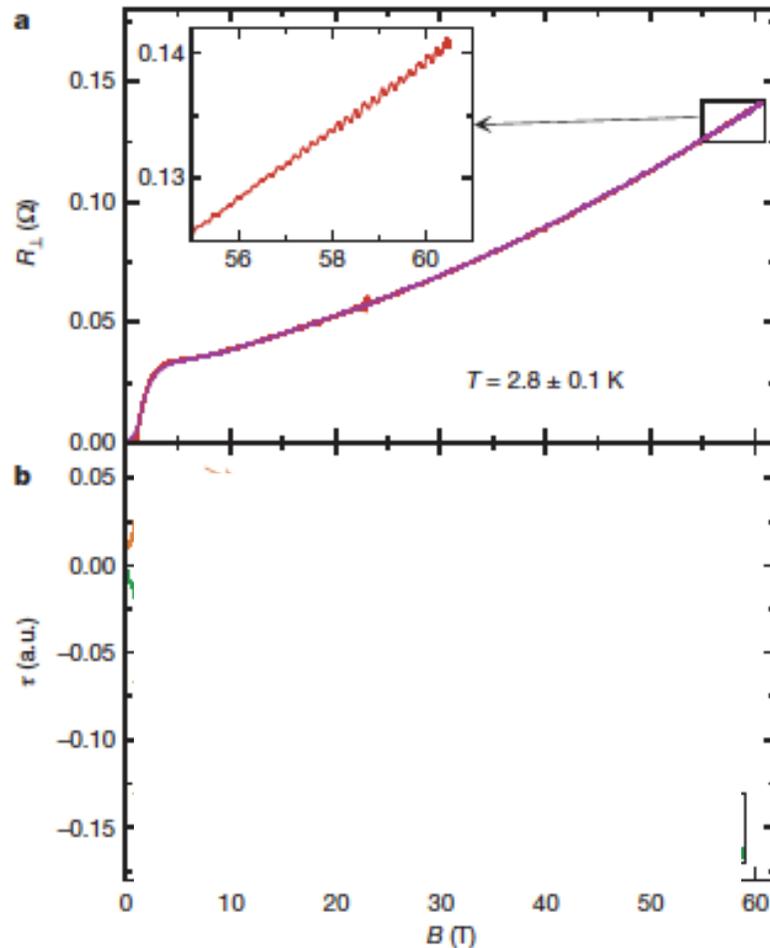
# Nobel Prize 2007: Magneto-resistance

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



# Magneto-resistance

**Magneto-resistance** 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  $R_H = -1/ne$ . 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:

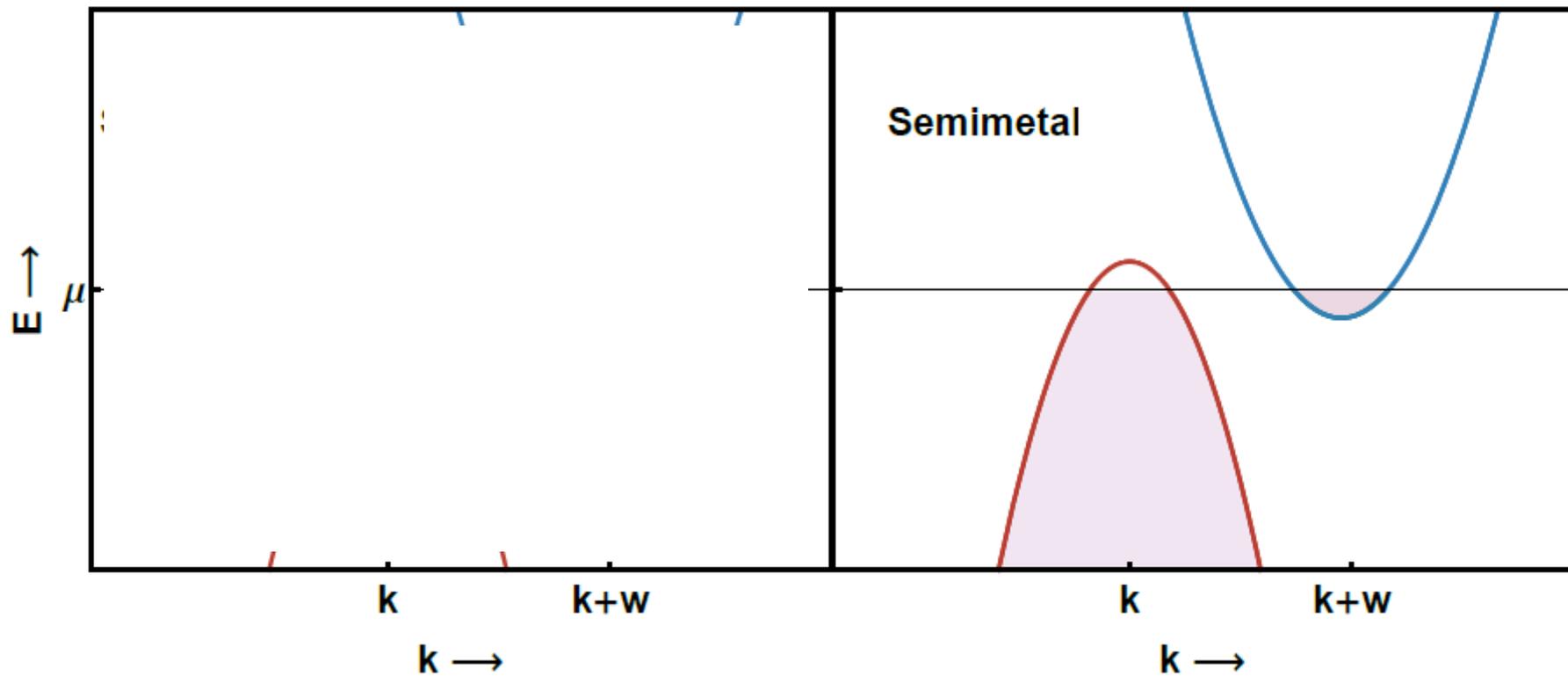
$$\boldsymbol{\rho} = \begin{pmatrix} \rho & -R_H B \\ R_H B & \rho \end{pmatrix} \quad (1)$$

(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  $n^{\text{th}}$  band is:  $\mathbf{j}_n = \boldsymbol{\rho}_n^{-1}\mathbf{E}$  where

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

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:

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

$$\rho = \frac{\rho_1\rho_2(\rho_1 + \rho_2) + (\rho_1R_{H,2}^2 + \rho_2R_{H,1}^2)B^2}{(\rho_1 + \rho_2)^2 + (R_{H,1} + R_{H,2})^2B^2} \quad (4)$$

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

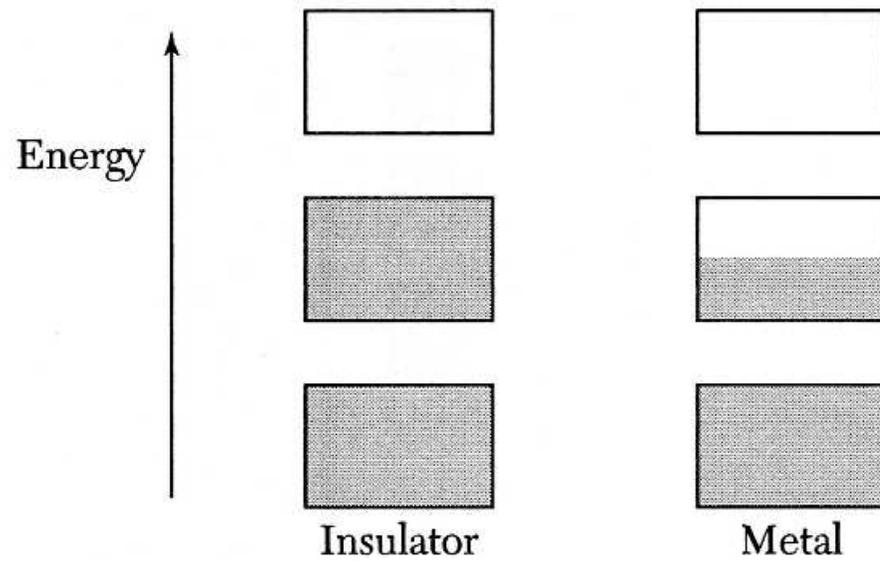
(c) Magnetic field dependence of resistivity is called magneto-resistance. If the two-band system has both electron-like and hole-like carriers so that  $|R_{H,1}| \approx |R_{H,2}|$ , what is the field dependence of  $\rho$ .

(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:

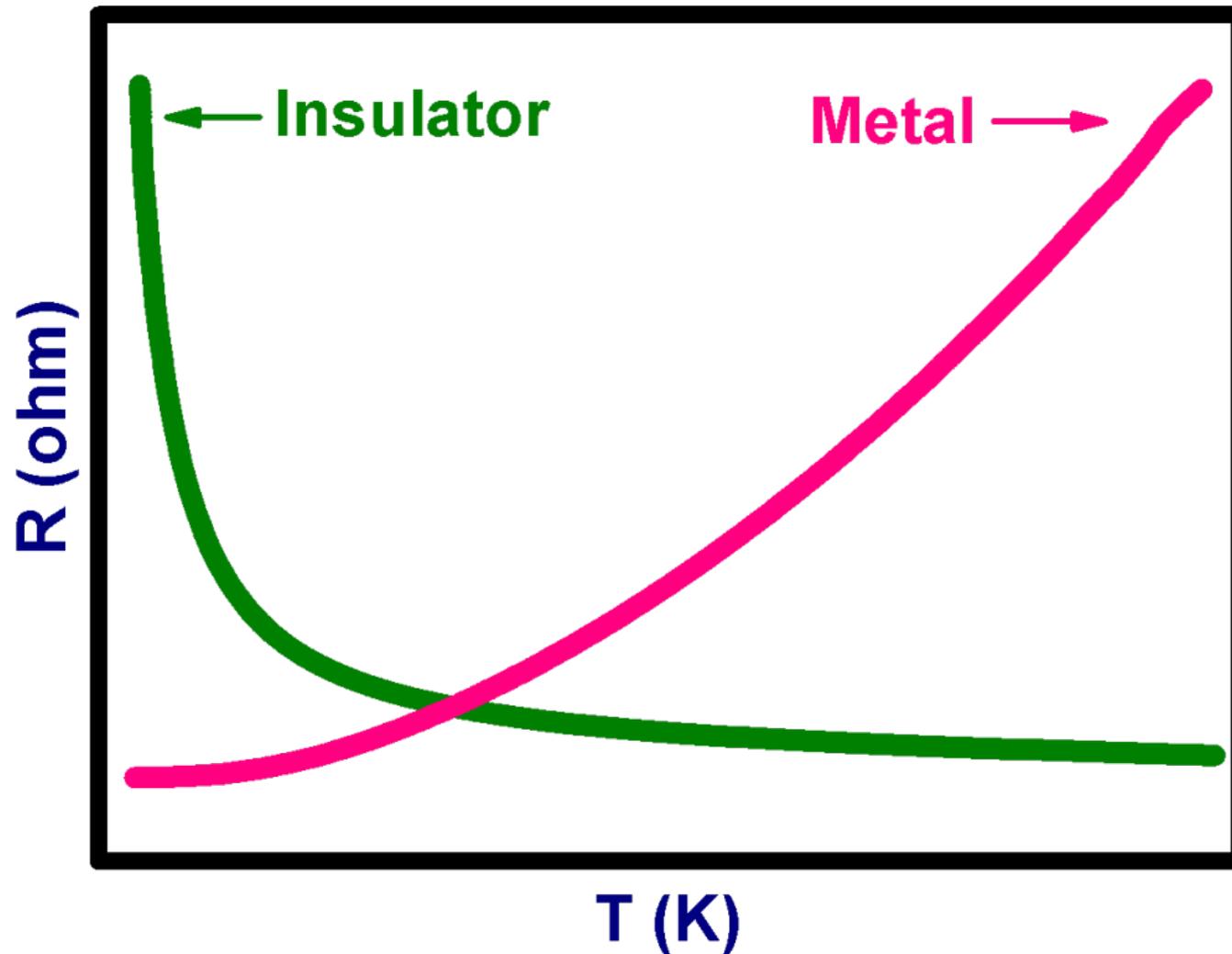
$$\sigma = ne\mu_e + pe\mu_h \quad (5)$$

$$R_H = \frac{p\mu_h^2 - n\mu_e^2}{e(p\mu_h + n\mu_e)^2}. \quad (6)$$

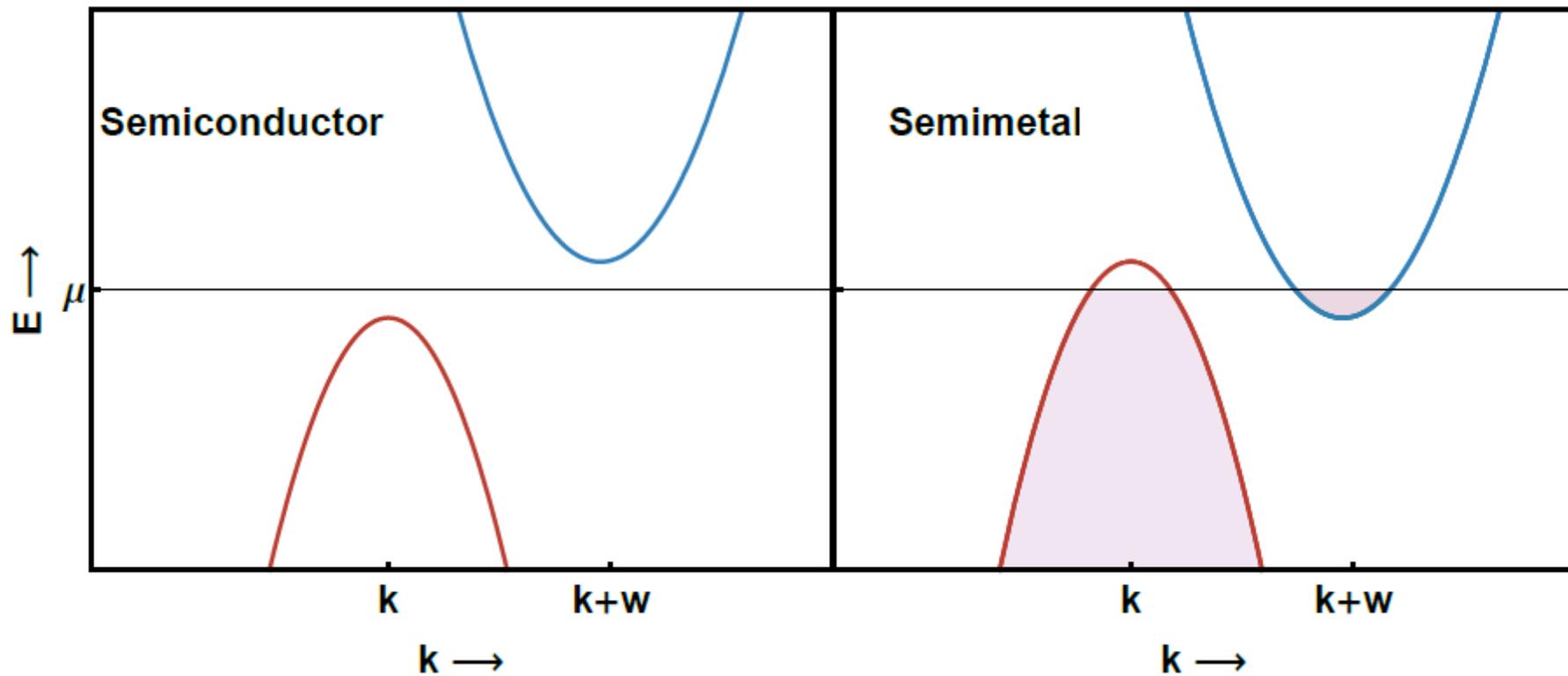
# Metals & Insulators



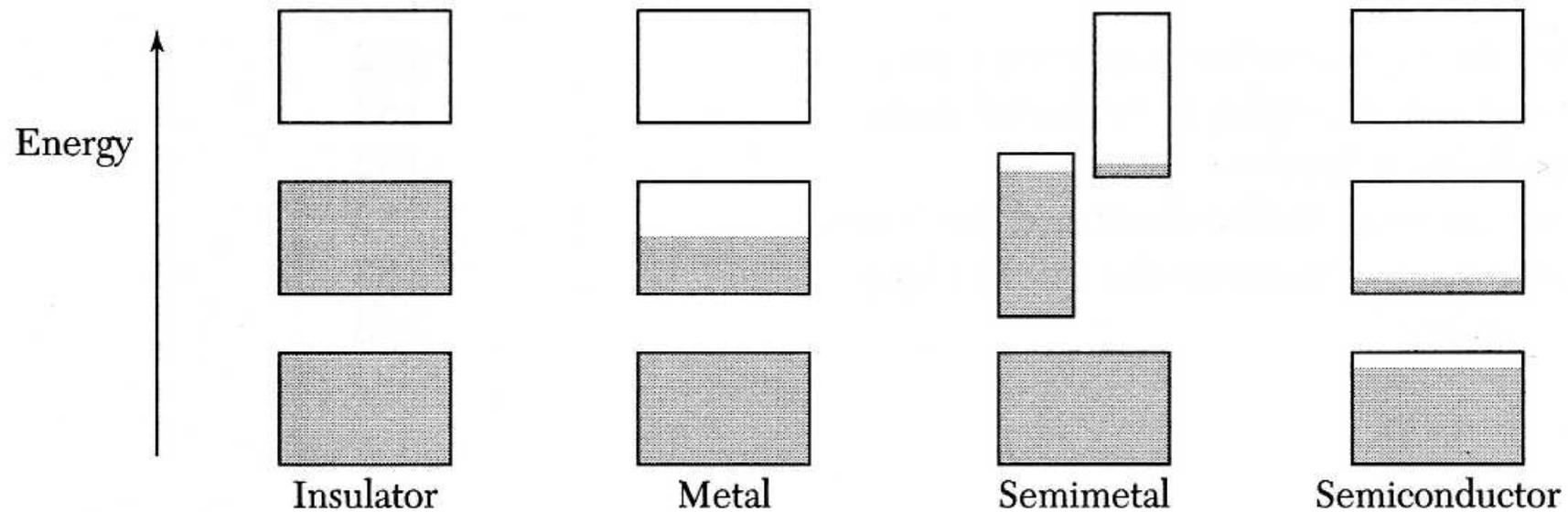
# Metals and insulators: Resistivity



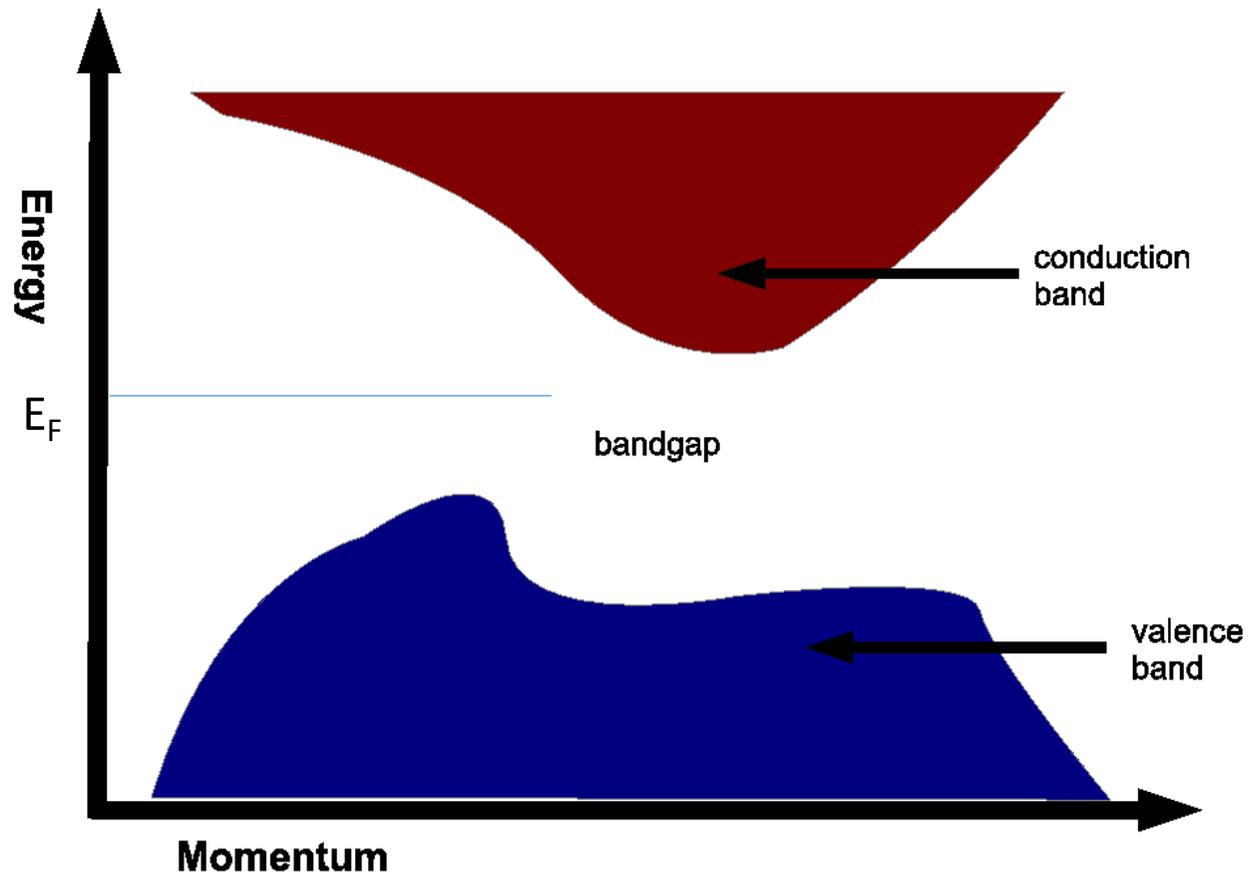
# Semimetals & Semiconductors



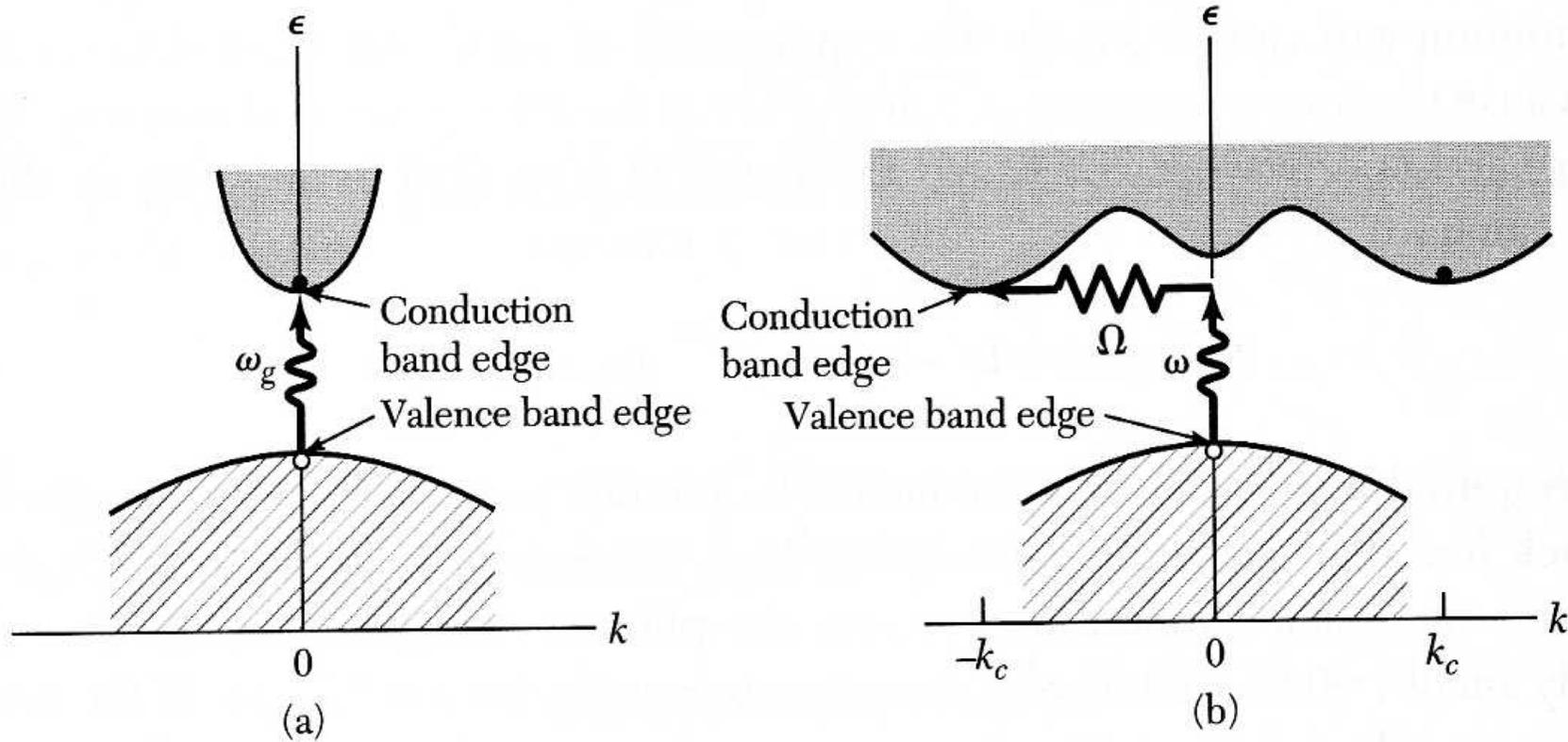
# Semimetals & Semiconductors



# Valence and conduction band



# Direct and indirect gap



# Semiconductor gaps versus $k_B T$

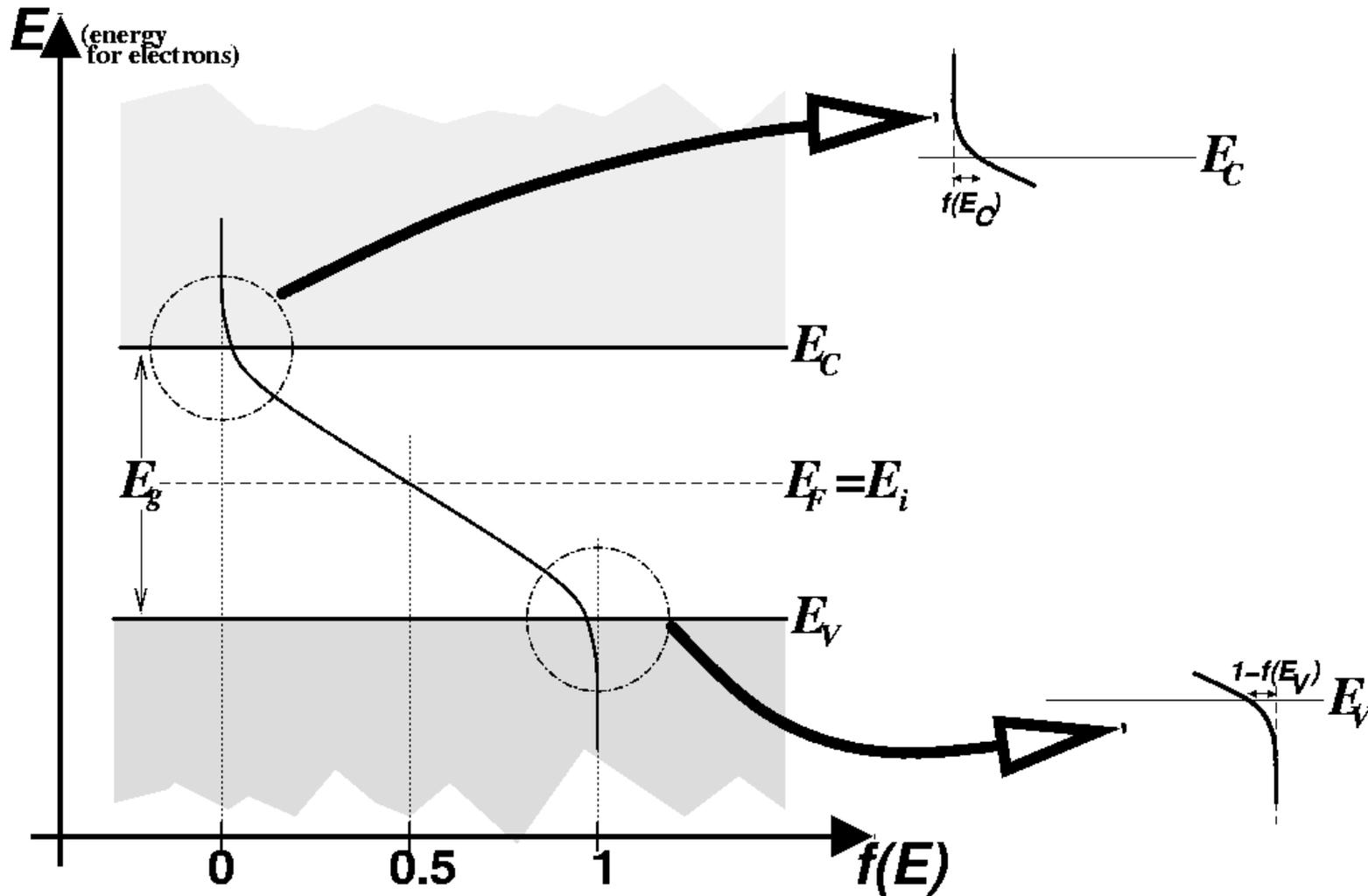
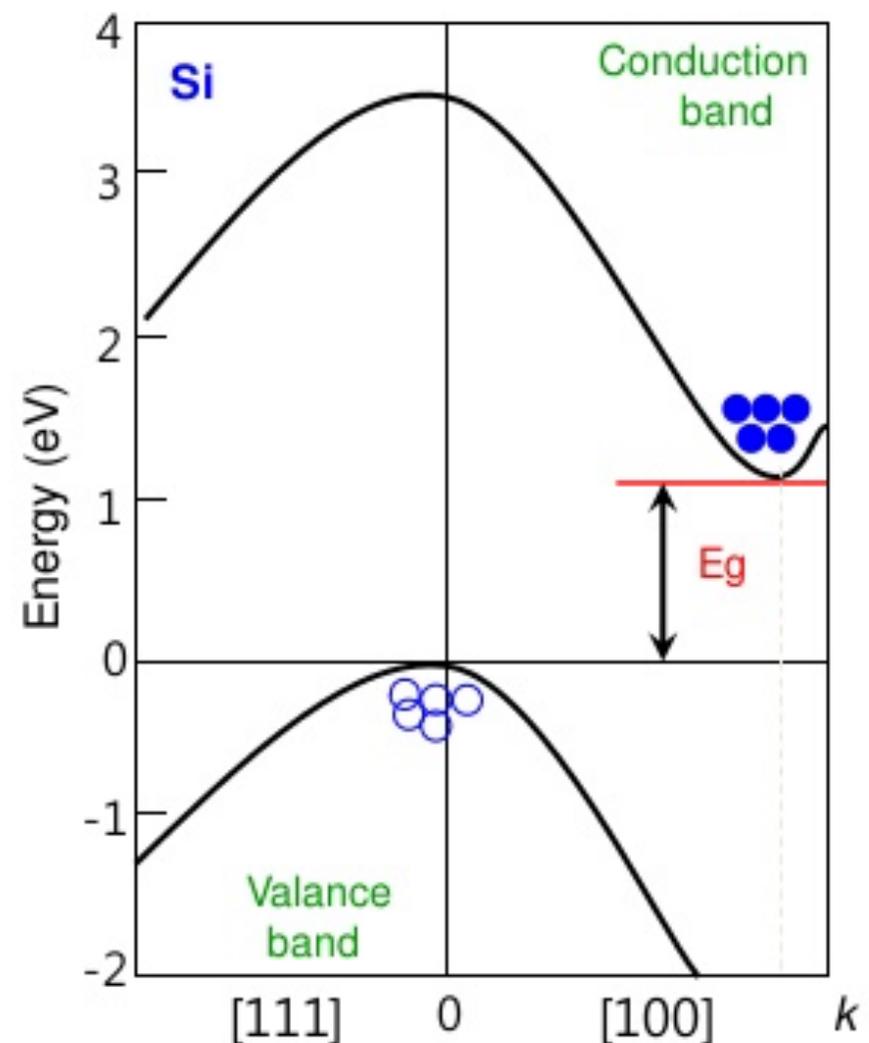
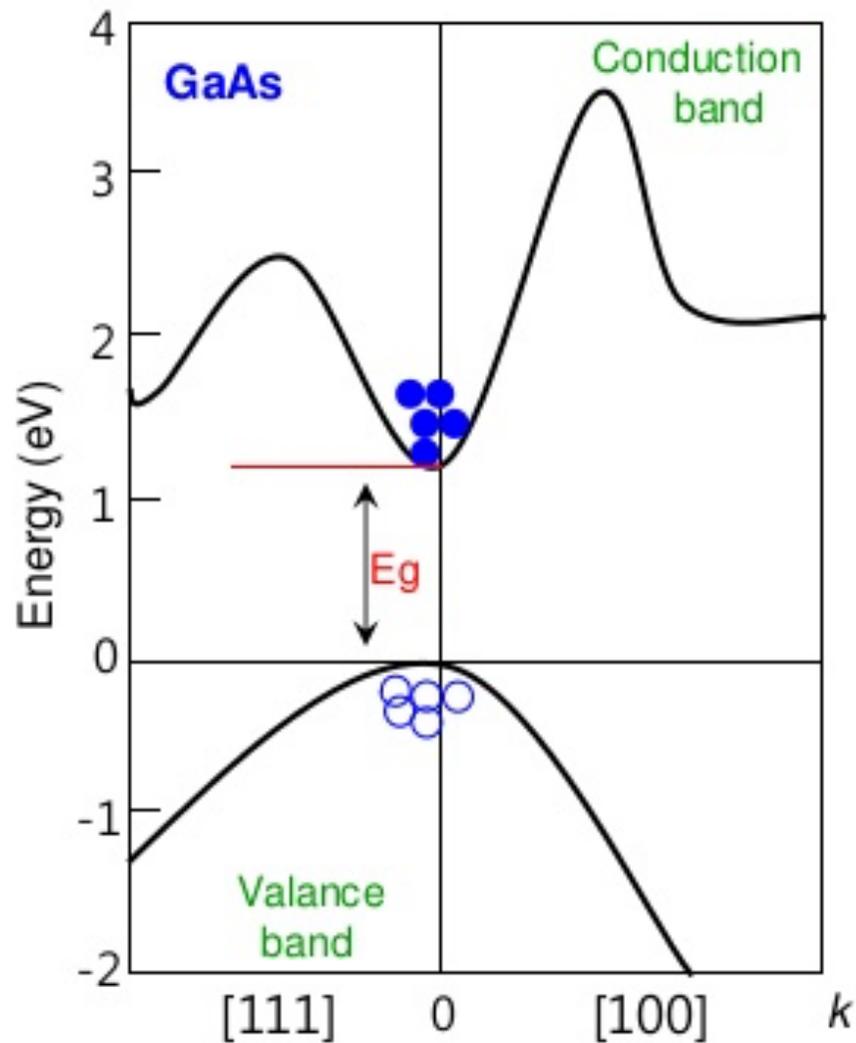


Figure 4:

## 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)

Crystal	Gap	$E_g$ , eV		Crystal	Gap	$E_g$ , eV	
		0 K	300 K			0 K	300 K
Diamond	<i>i</i>	5.4		SiC(hex)	<i>i</i>	3.0	—
Si	<i>i</i>	1.17	1.11	Te	<i>d</i>	0.33	—
Ge	<i>i</i>	0.744	0.66	HgTe <sup>a</sup>	<i>d</i>	-0.30	
$\alpha$ Sn	<i>d</i>	0.00	0.00	PbS	<i>d</i>	0.286	0.34–0.37
InSb	<i>d</i>	0.23	0.17	PbSe	<i>i</i>	0.165	0.27
InAs	<i>d</i>	0.43	0.36	PbTe	<i>i</i>	0.190	0.29
InP	<i>d</i>	1.42	1.27	CdS	<i>d</i>	2.582	2.42
GaP	<i>i</i>	2.32	2.25	CdSe	<i>d</i>	1.840	1.74
GaAs	<i>d</i>	1.52	1.43	CdTe	<i>d</i>	1.607	1.44
GaSb	<i>d</i>	0.81	0.68	SnTe	<i>d</i>	0.3	0.18
AlSb	<i>i</i>	1.65	1.6	Cu <sub>2</sub> O	<i>d</i>	2.172	—

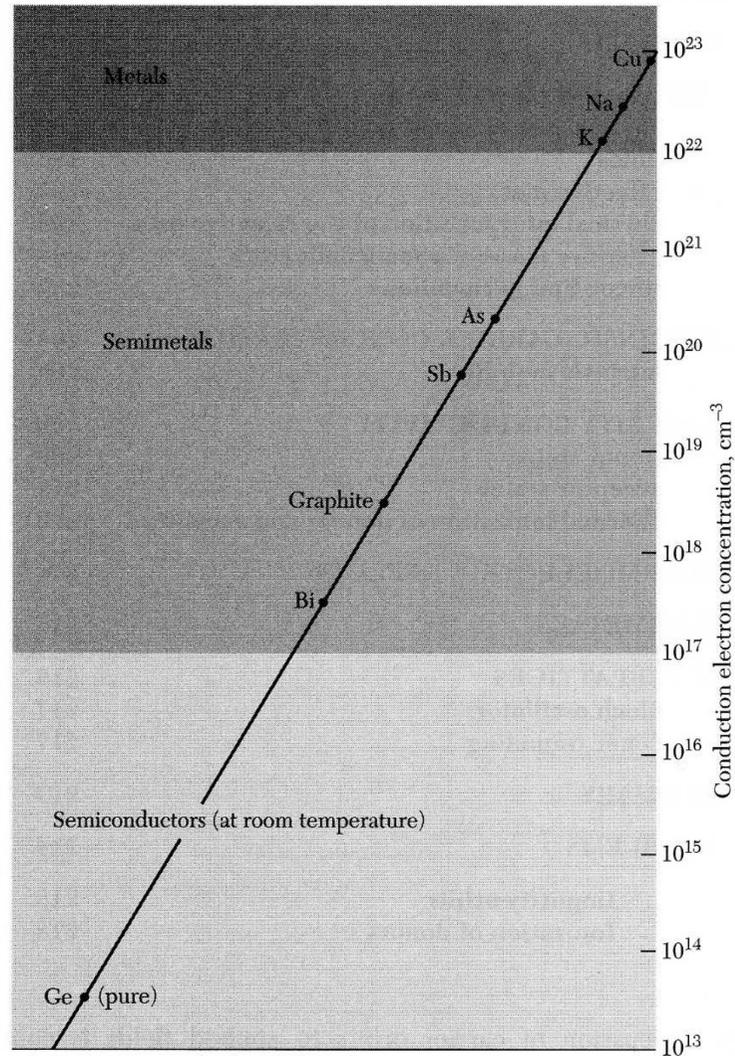
<sup>a</sup>HgTe is a semimetal; the bands overlap.

# Electronic masses

Crystal	Electron $m_e/m$
InSb	0.015
InAs	0.026
InP	0.073
GaSb	0.047
GaAs	0.066
Cu <sub>2</sub> O	0.99

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

# Conduction Electron Concentration



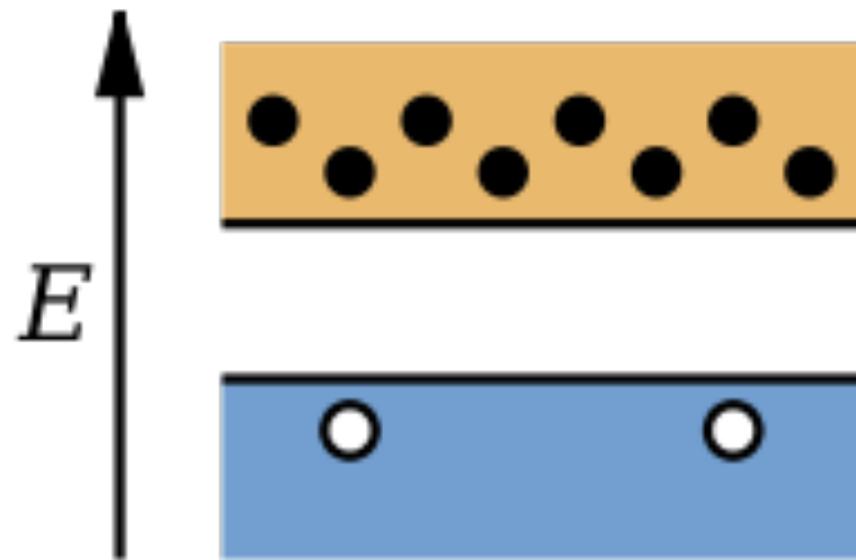
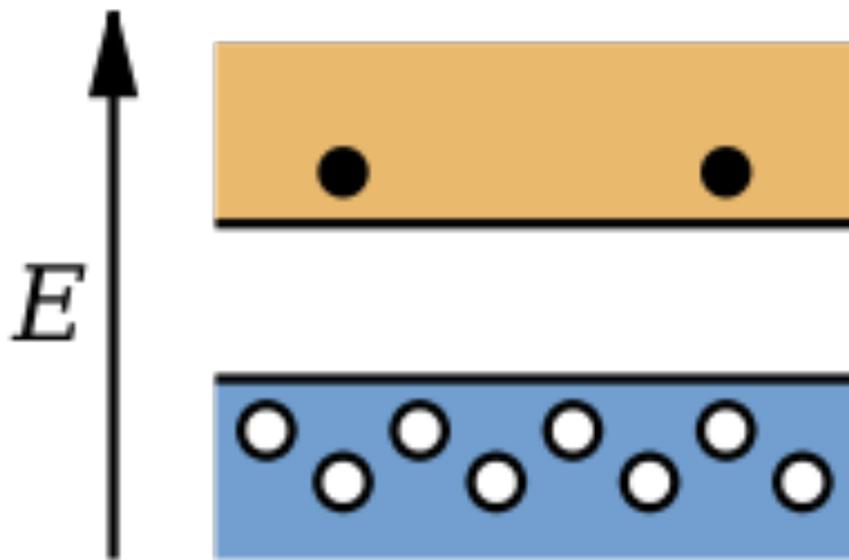
**Figure 1** Carrier concentrations for metals, semimetals, and semiconductors. The semiconductor range may be extended upward by increasing the impurity concentration, and the range can be extended downward to merge eventually with the insulator range.

# Electronic mobility

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

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

hydrogen 1 <b>H</b> 1.0079																			helium 2 <b>He</b> 4.0026
lithium 3 <b>Li</b> 6.941	beryllium 4 <b>Be</b> 9.0122													boron 5 <b>B</b> 10.811	carbon 6 <b>C</b> 12.011	nitrogen 7 <b>N</b> 14.007	oxygen 8 <b>O</b> 15.999	fluorine 9 <b>F</b> 18.998	neon 10 <b>Ne</b> 20.180
sodium 11 <b>Na</b> 22.990	magnesium 12 <b>Mg</b> 24.305												aluminium 13 <b>Al</b> 26.982	silicon 14 <b>Si</b> 28.086	phosphorus 15 <b>P</b> 30.974	sulfur 16 <b>S</b> 32.065	chlorine 17 <b>Cl</b> 35.453	argon 18 <b>Ar</b> 39.948	
potassium 19 <b>K</b> 39.098	calcium 20 <b>Ca</b> 40.078	scandium 21 <b>Sc</b> 44.956	titanium 22 <b>Ti</b> 47.867	vanadium 23 <b>V</b> 50.942	chromium 24 <b>Cr</b> 51.996	manganese 25 <b>Mn</b> 54.938	iron 26 <b>Fe</b> 55.845	cobalt 27 <b>Co</b> 58.933	nickel 28 <b>Ni</b> 58.693	copper 29 <b>Cu</b> 63.546	zinc 30 <b>Zn</b> 65.39	gallium 31 <b>Ga</b> 69.723	germanium 32 <b>Ge</b> 72.64	arsenic 33 <b>As</b> 74.922	selenium 34 <b>Se</b> 78.96	bromine 35 <b>Br</b> 79.904	krypton 36 <b>Kr</b> 83.80		
rubidium 37 <b>Rb</b> 85.468	strontium 38 <b>Sr</b> 87.62	yttrium 39 <b>Y</b> 88.906	zirconium 40 <b>Zr</b> 91.224	niobium 41 <b>Nb</b> 92.906	molybdenum 42 <b>Mo</b> 95.94	technetium 43 <b>Tc</b> [98]	ruthenium 44 <b>Ru</b> 101.07	rhodium 45 <b>Rh</b> 102.91	palladium 46 <b>Pd</b> 106.42	silver 47 <b>Ag</b> 107.87	cadmium 48 <b>Cd</b> 112.41	indium 49 <b>In</b> 114.82	tin 50 <b>Sn</b> 118.71	antimony 51 <b>Sb</b> 121.76	tellurium 52 <b>Te</b> 127.60	iodine 53 <b>I</b> 126.90	xenon 54 <b>Xe</b> 131.29		
caesium 55 <b>Cs</b> 132.91	barium 56 <b>Ba</b> 137.33	lanthanum 57 <b>La</b> 174.97	hafnium 72 <b>Hf</b> 178.49	tantalum 73 <b>Ta</b> 180.95	wolfram 74 <b>W</b> 183.84	rhenium 75 <b>Re</b> 186.21	osmium 76 <b>Os</b> 190.23	iridium 77 <b>Ir</b> 192.22	platinum 78 <b>Pt</b> 195.08	gold 79 <b>Au</b> 196.97	mercury 80 <b>Hg</b> 200.59	thallium 81 <b>Tl</b> 204.38	lead 82 <b>Pb</b> 207.2	bismuth 83 <b>Bi</b> 208.98	polonium 84 <b>Po</b> [209]	astatine 85 <b>At</b> [210]	radon 86 <b>Rn</b> [222]		
francium 87 <b>Fr</b> [223]	radium 88 <b>Ra</b> [226]	actinide series 89-102 * *	rutherfordium 104 <b>Rf</b> [261]	dubnium 105 <b>Db</b> [262]	seaborgium 106 <b>Sg</b> [266]	bohrium 107 <b>Bh</b> [264]	hassium 108 <b>Hs</b> [269]	meitnerium 109 <b>Mt</b> [268]	ununnilium 110 <b>Uun</b> [271]	unununium 111 <b>Uuu</b> [272]	ununbium 112 <b>Uub</b> [277]		ununquadium 114 <b>Uuq</b> [289]						

\* Lanthanide series

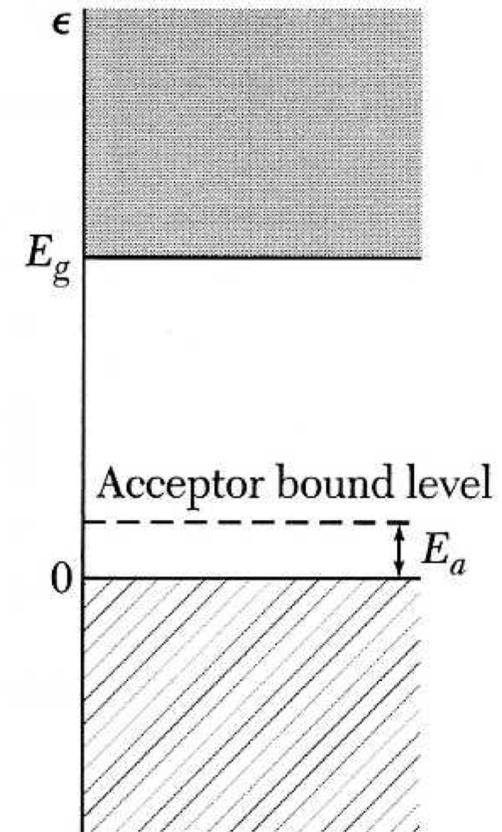
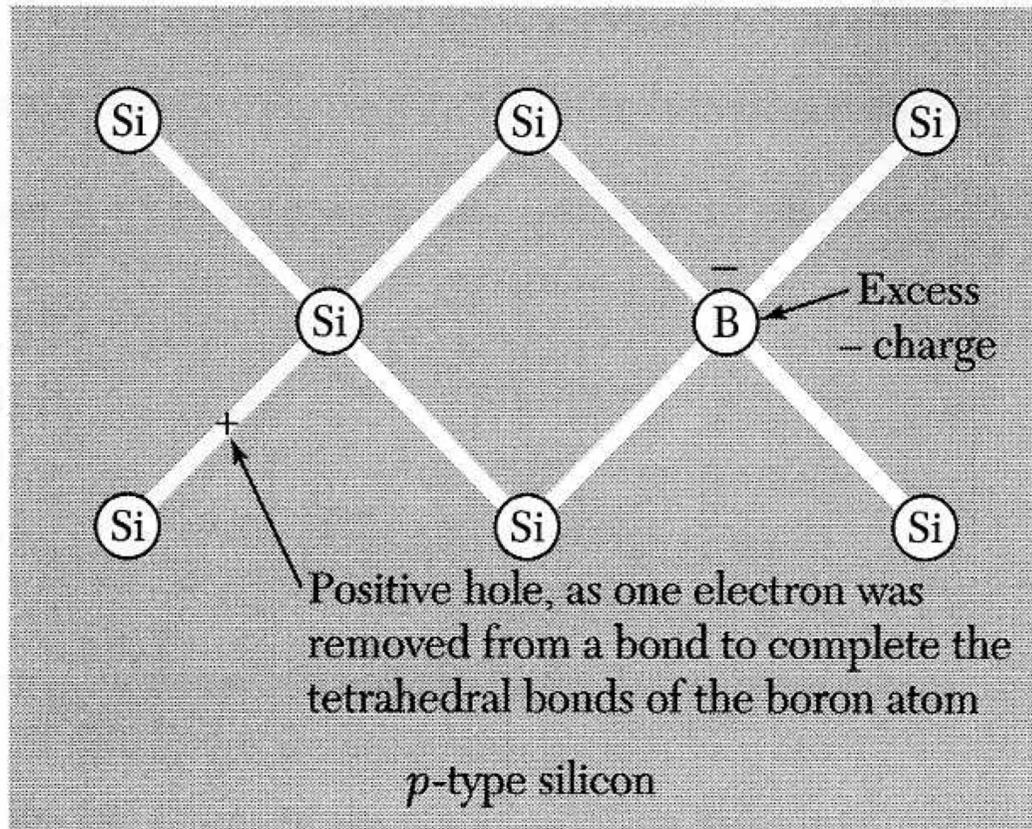
lanthanum 57 <b>La</b> 138.91	cerium 58 <b>Ce</b> 140.12	praseodymium 59 <b>Pr</b> 140.91	neodymium 60 <b>Nd</b> 144.24	promethium 61 <b>Pm</b> [145]	samarium 62 <b>Sm</b> 150.36	europium 63 <b>Eu</b> 151.96	gadolinium 64 <b>Gd</b> 157.25	terbium 65 <b>Tb</b> 158.93	dysprosium 66 <b>Dy</b> 162.50	holmium 67 <b>Ho</b> 164.93	erbium 68 <b>Er</b> 167.26	thulium 69 <b>Tm</b> 168.93	ytterbium 70 <b>Yb</b> 173.04
actinium 89 <b>Ac</b> [227]	thorium 90 <b>Th</b> 232.04	protactinium 91 <b>Pa</b> 231.04	uranium 92 <b>U</b> 238.03	neptunium 93 <b>Np</b> [237]	plutonium 94 <b>Pu</b> [244]	americium 95 <b>Am</b> [243]	curium 96 <b>Cm</b> [247]	berkelium 97 <b>Bk</b> [247]	californium 98 <b>Cf</b> [251]	einsteinium 99 <b>Es</b> [252]	fermium 100 <b>Fm</b> [257]	mendelevium 101 <b>Md</b> [258]	nobelium 102 <b>No</b> [259]

\*\* Actinide series

Diamond-type semiconductors

III – V compounds (GaAs, InSb)

# Hole - doping

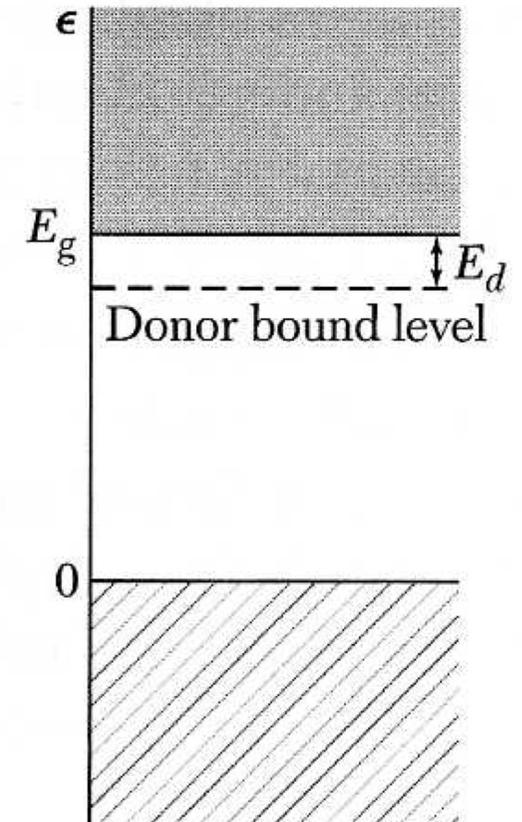
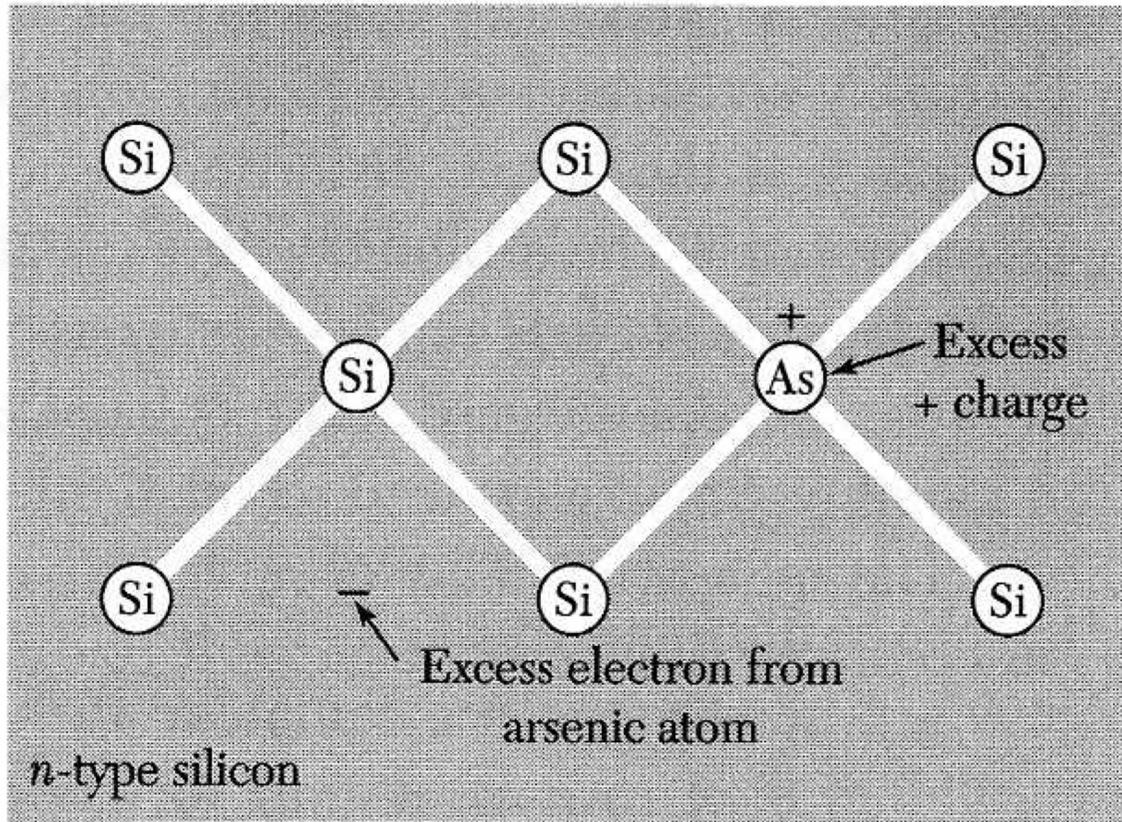


$\text{Si}^{4+}$

$\text{B}^{3+}$

From Kittel

# Electron - doping

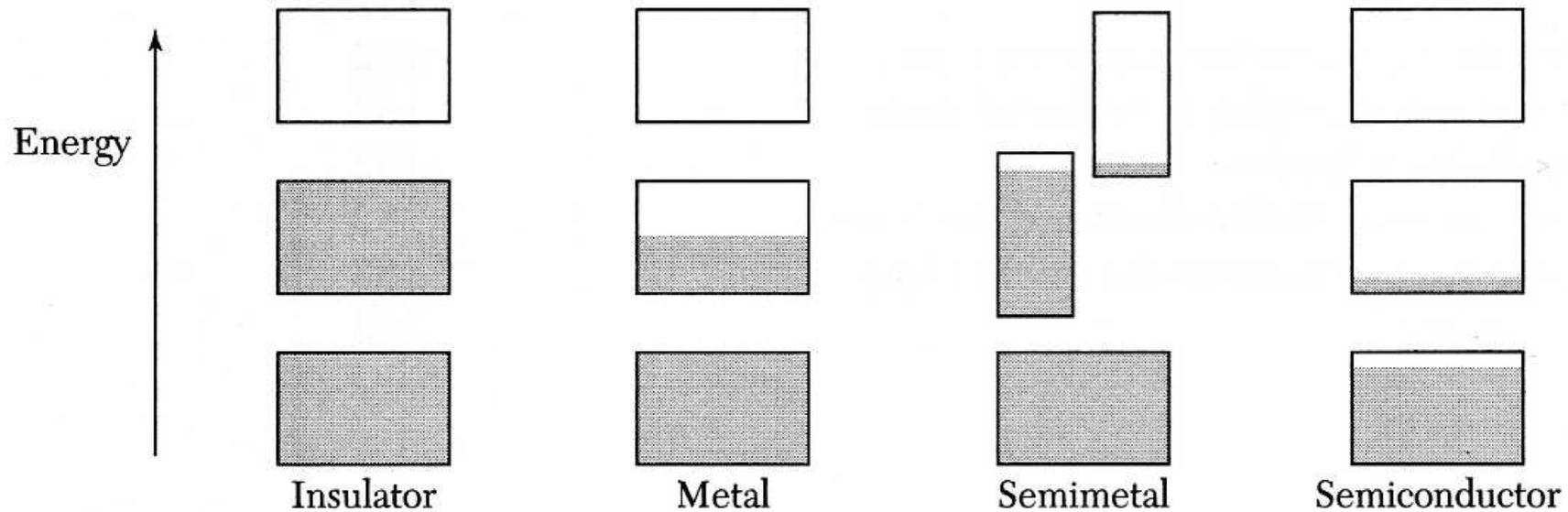


$\text{Si}^{4+}$

$\text{As}^{5+}$

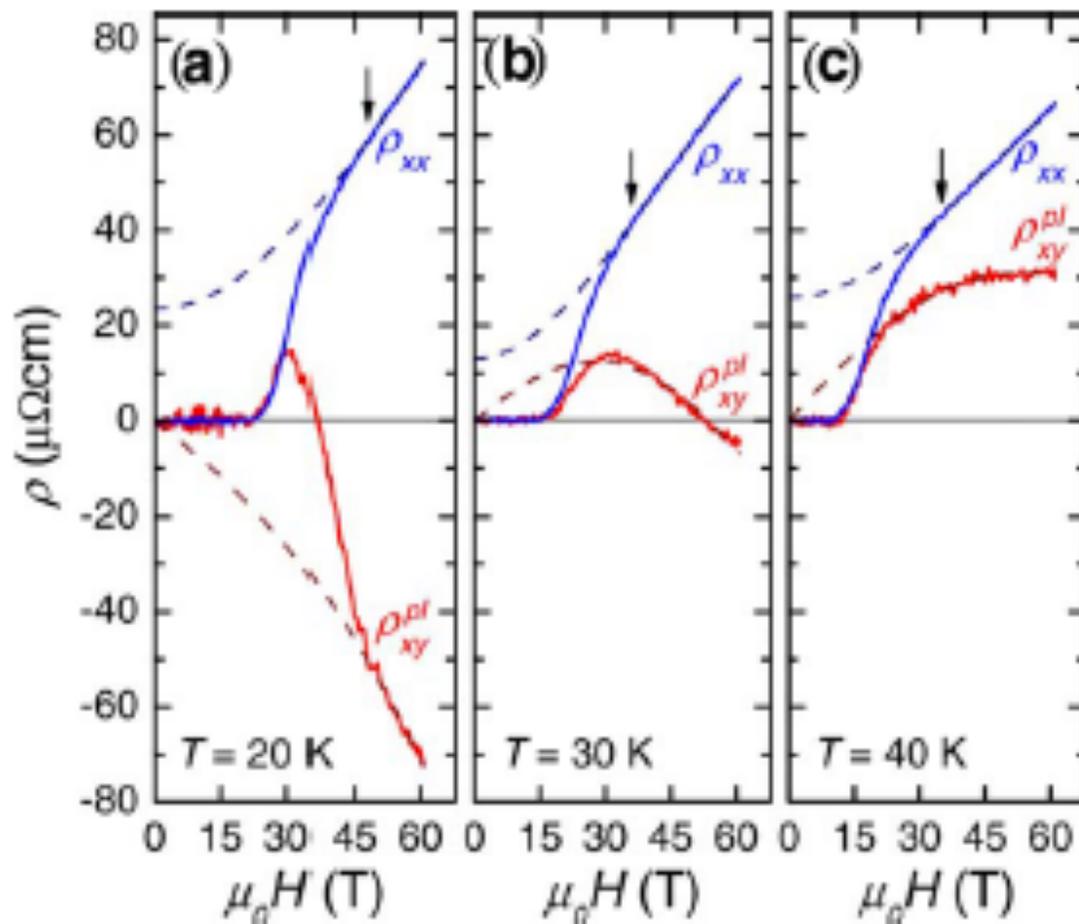
# Concluding quiz

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



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

# Magneto-resistance



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