

Tasks

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

20 & 25th April

2 & 4th May

9 & 16th May

18 & 23th May

30th May & 1st June

Chapter 6

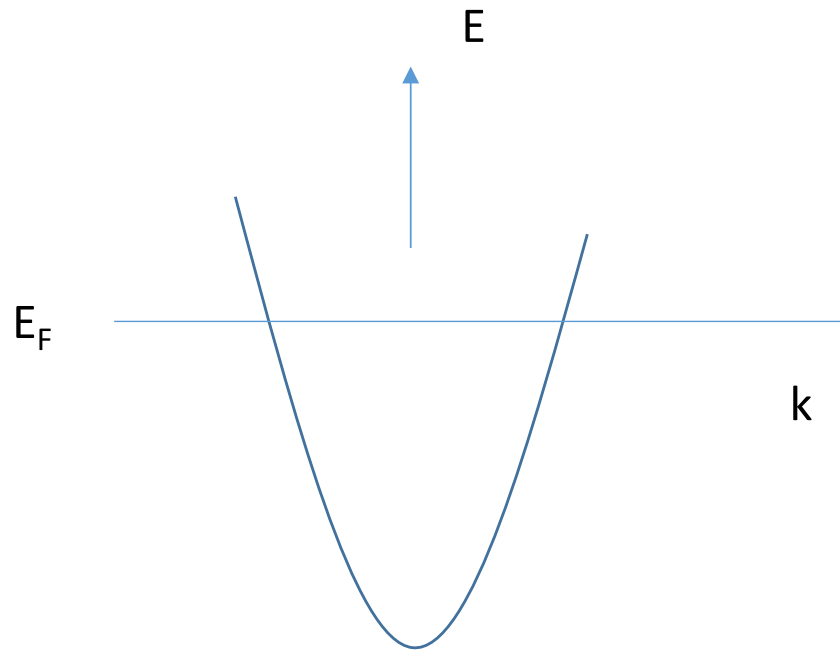
Chapter 7

Chapter 8

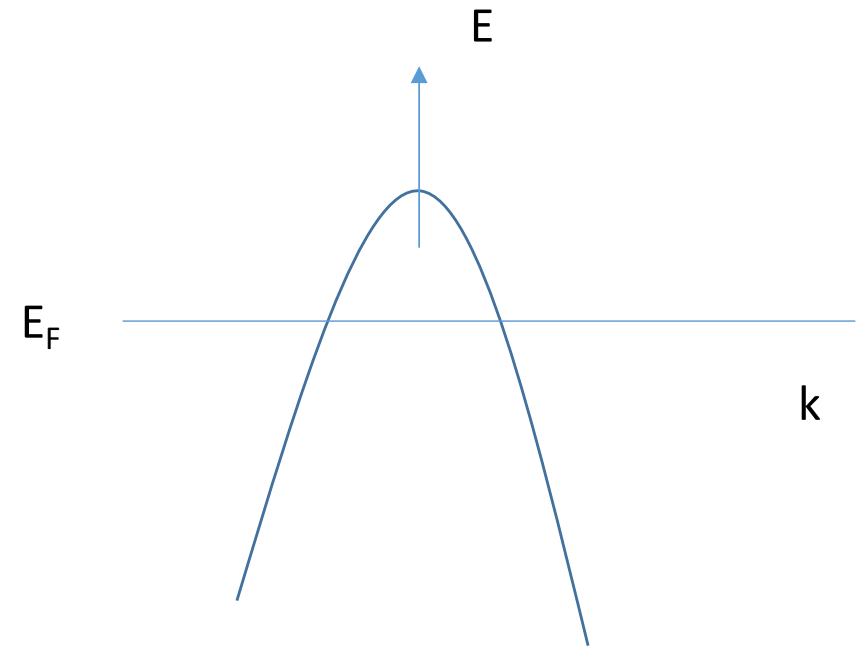
Chapter 9

Wrap-up

Electron versus Hole like bands

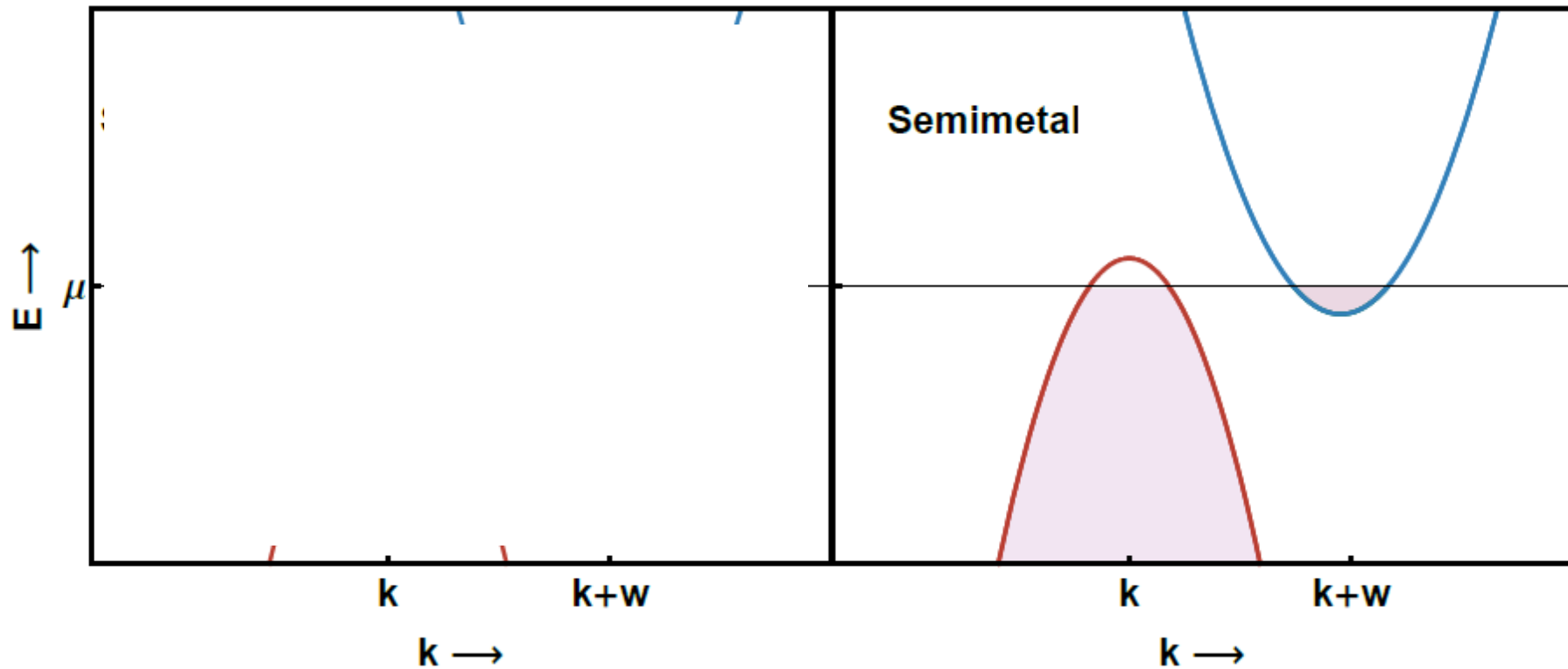


Electron-Like Band



Hole-Like Band

Consider two bands crossing the Fermi level



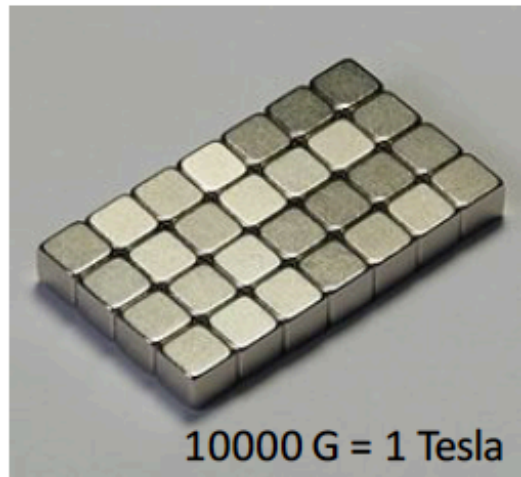
Magnetic field

Human Brain



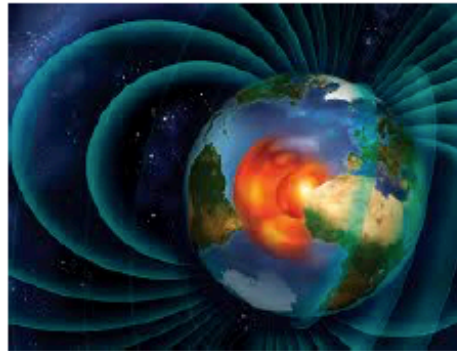
1 nG to 10 nG

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



10000 G = 1 Tesla

Earth



0.25 - 0.65 Gauss

Static 45 –Tesla
Hybrid magnet



Fridge Magnets



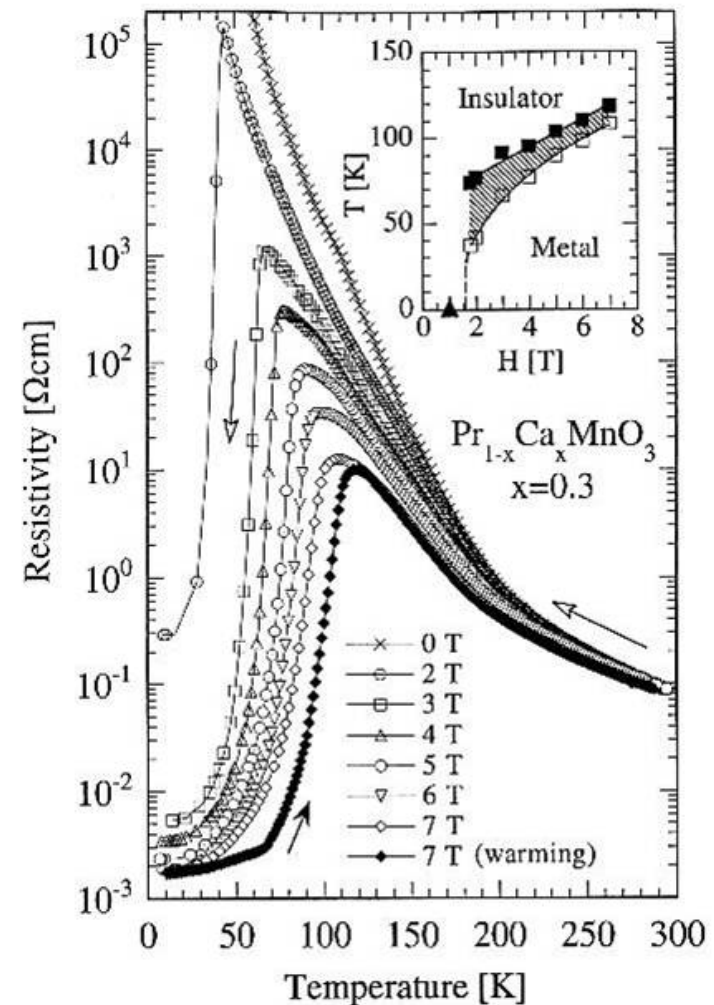
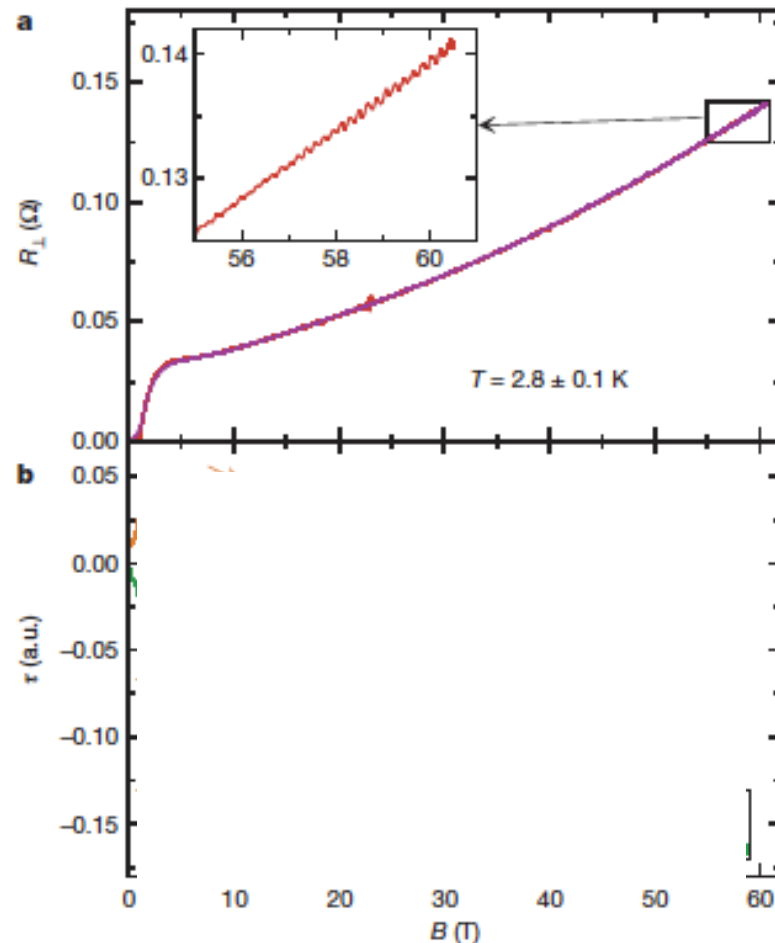
50 Gauss

100 Tesla
Pulsed magnet

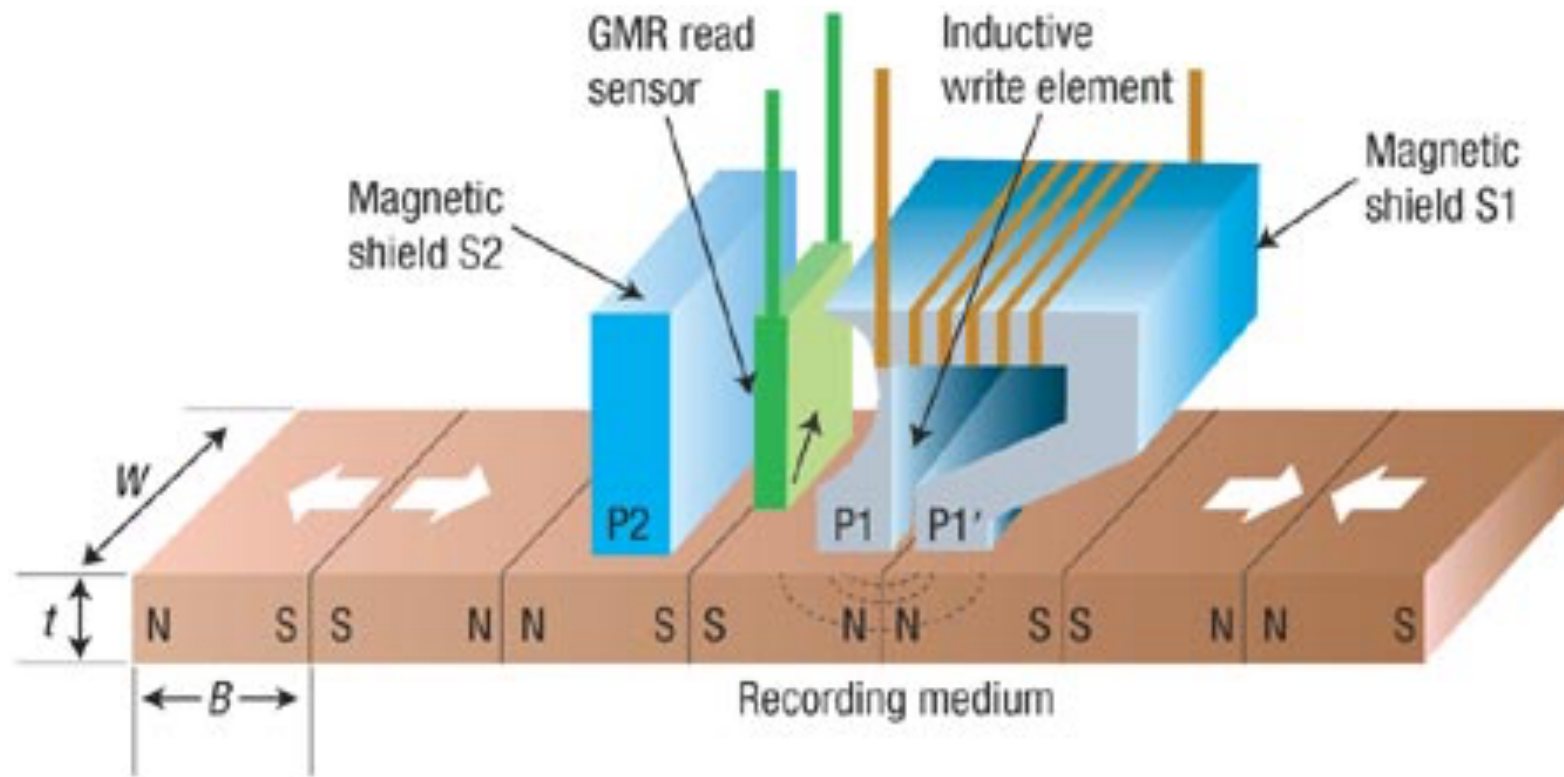


Magneto-resistance

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



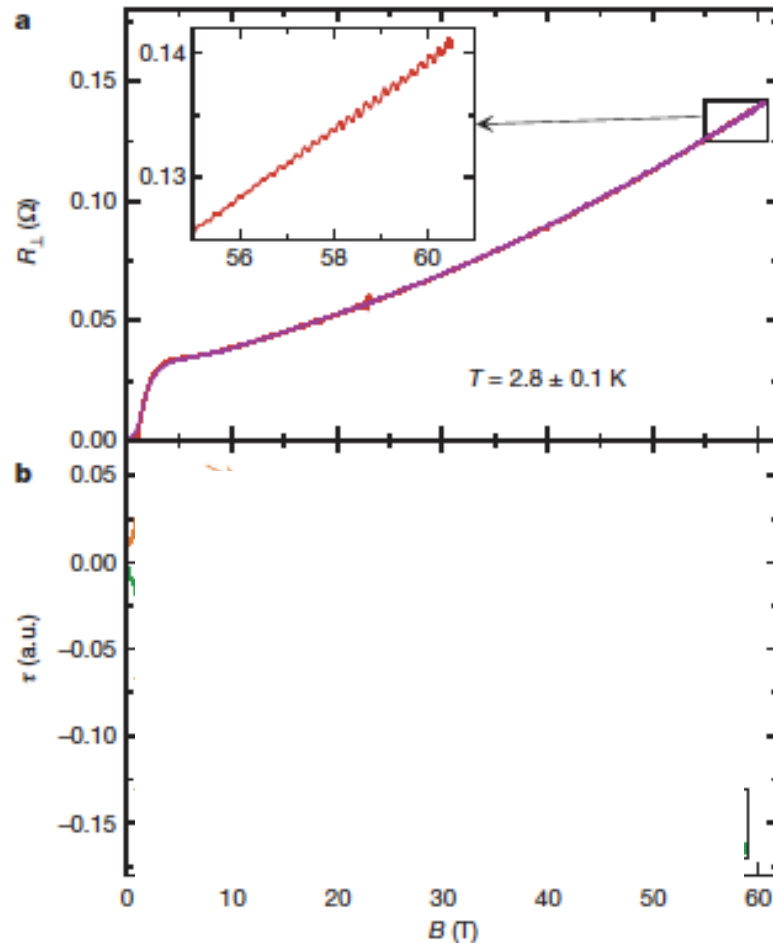
Nobel Prize 2007: Magneto-resistance

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:

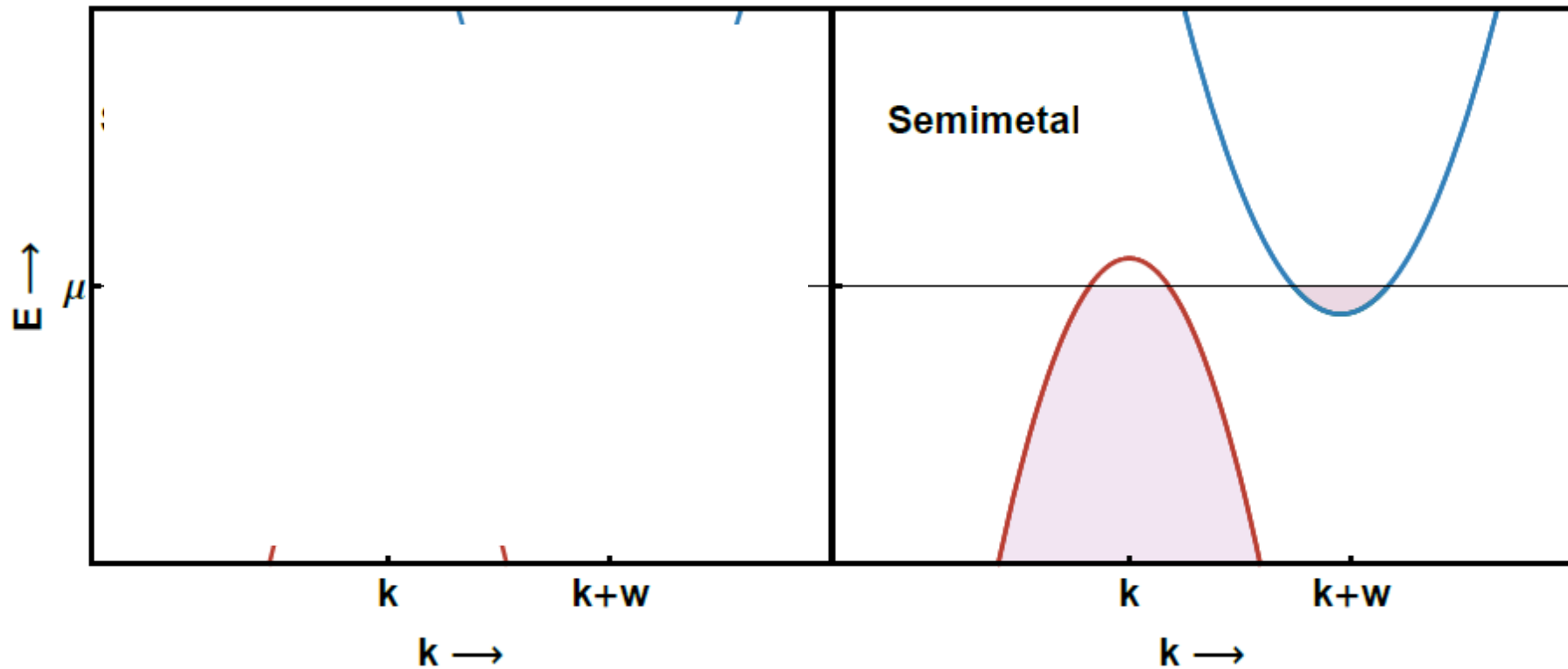
$$\boldsymbol{\rho} = \begin{pmatrix} \rho & -R_H B \\ R_H B & \rho \end{pmatrix} \quad (1)$$

(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^{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.

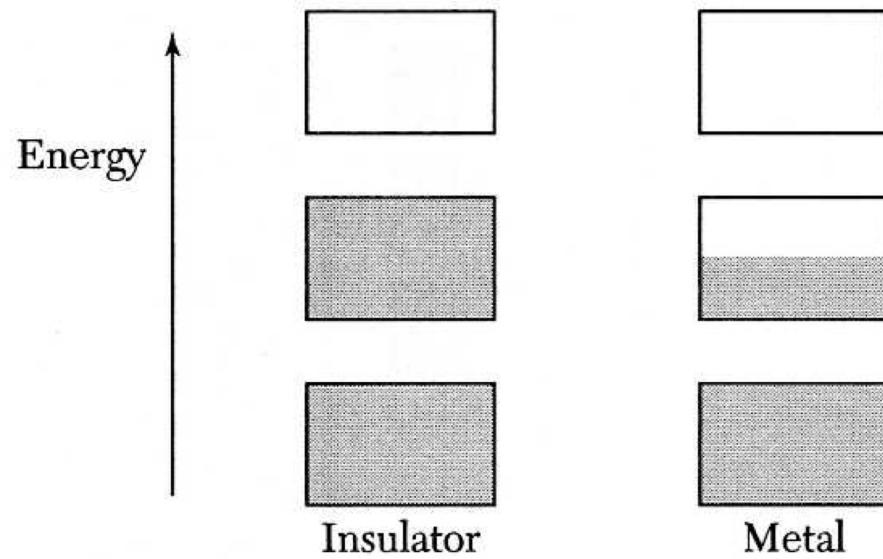
(c) Magnetic field dependence of resistivity is called magneto-resistance. If the two-band system has both electron-like and hole-like carriers so that $|R_{H,1}| \approx |R_{H,2}|$, what is the field dependence of ρ .

(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:

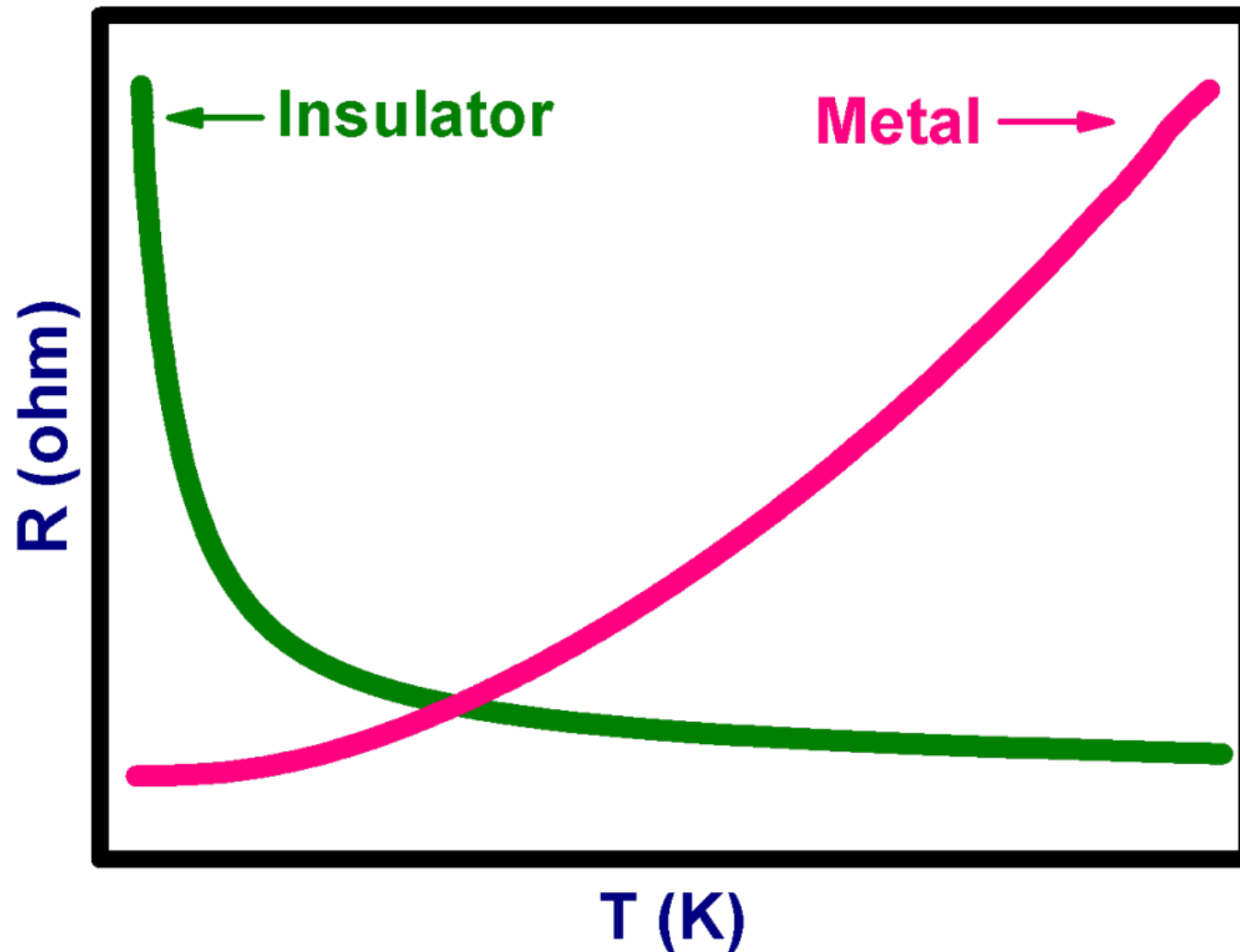
$$\sigma = ne\mu_e + pe\mu_h \quad (5)$$

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

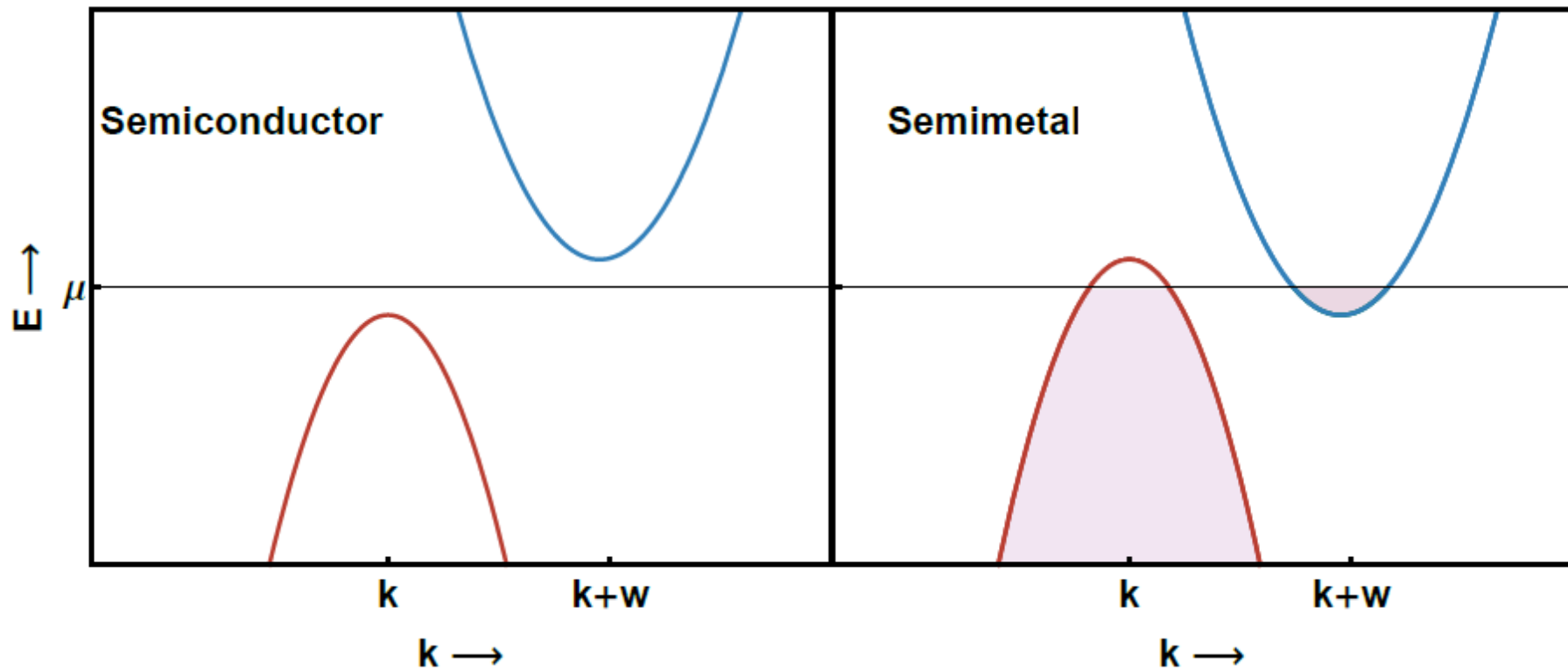
Metals & Insulators



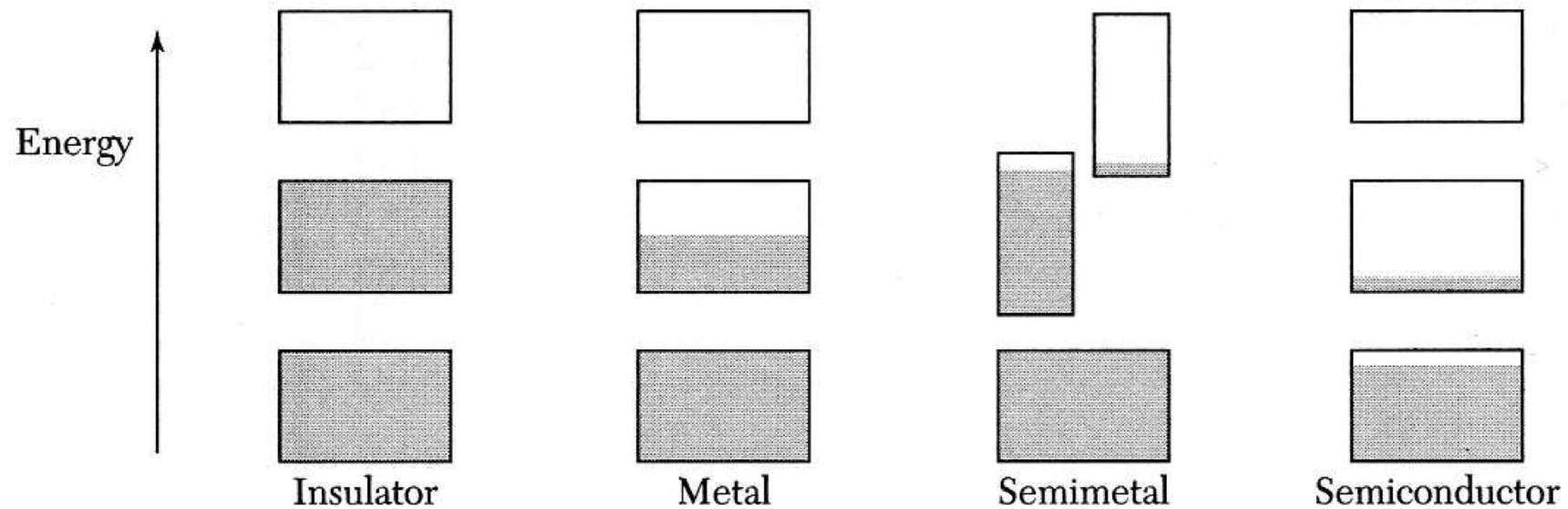
Metals and insulators: Resistivity



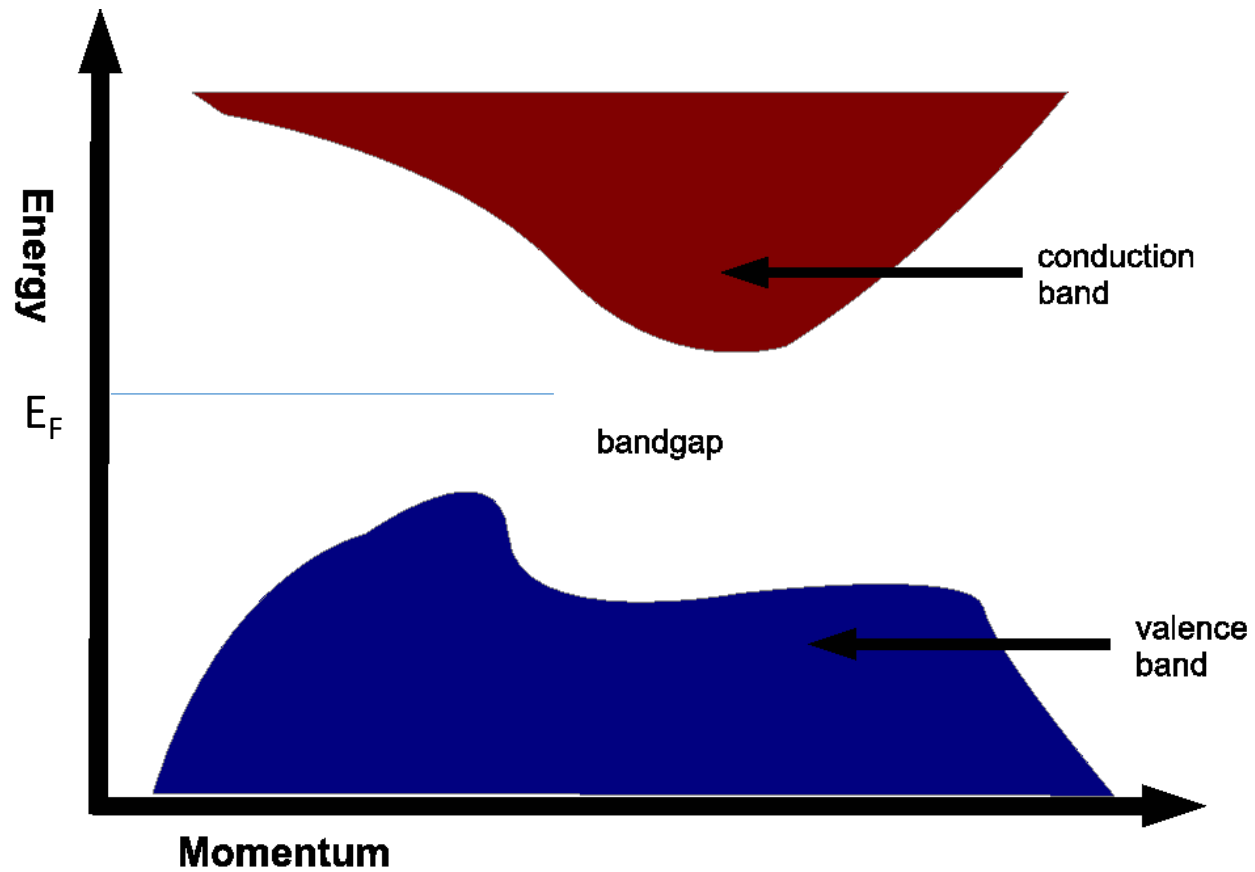
Semimetals & Semiconductors



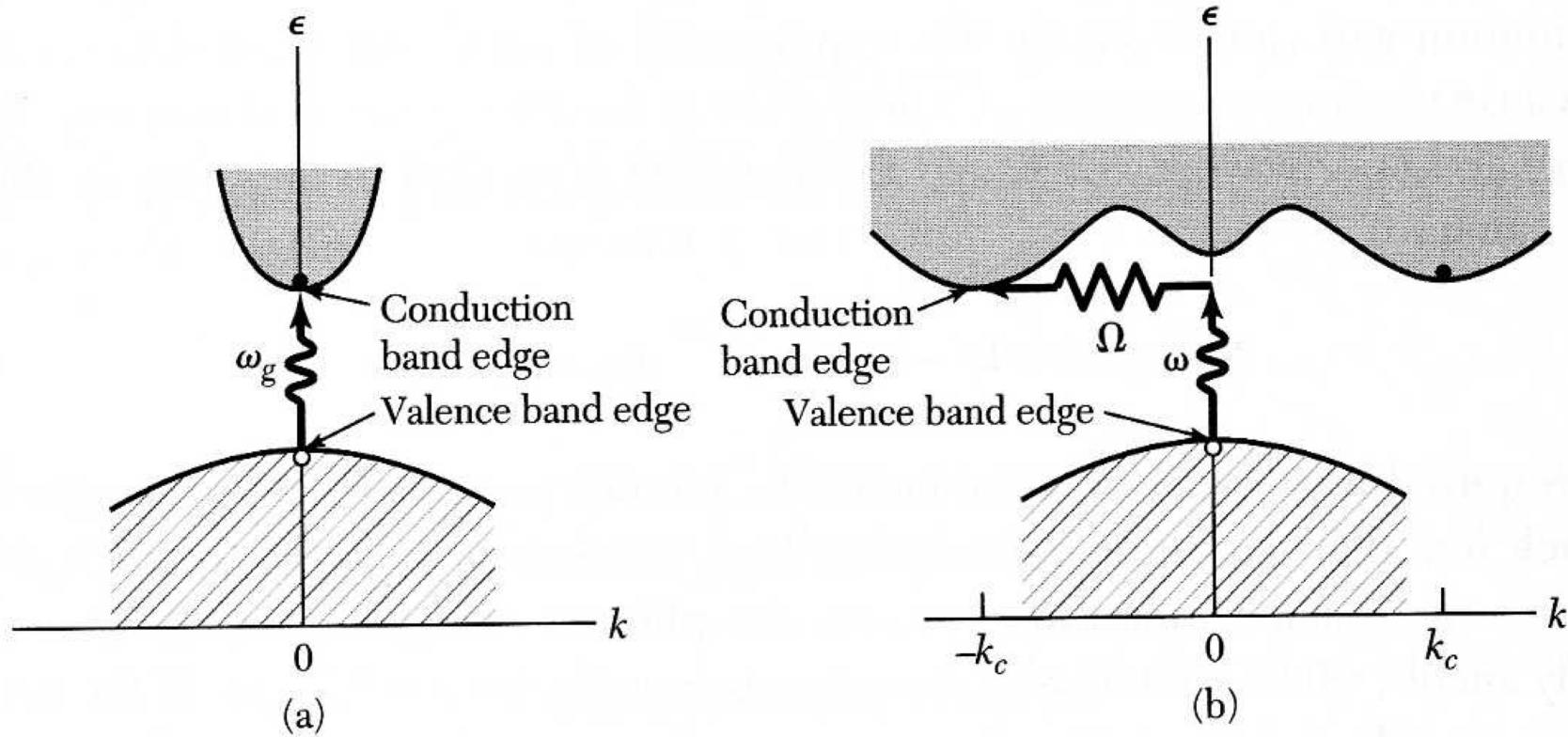
Semimetals & Semiconductors



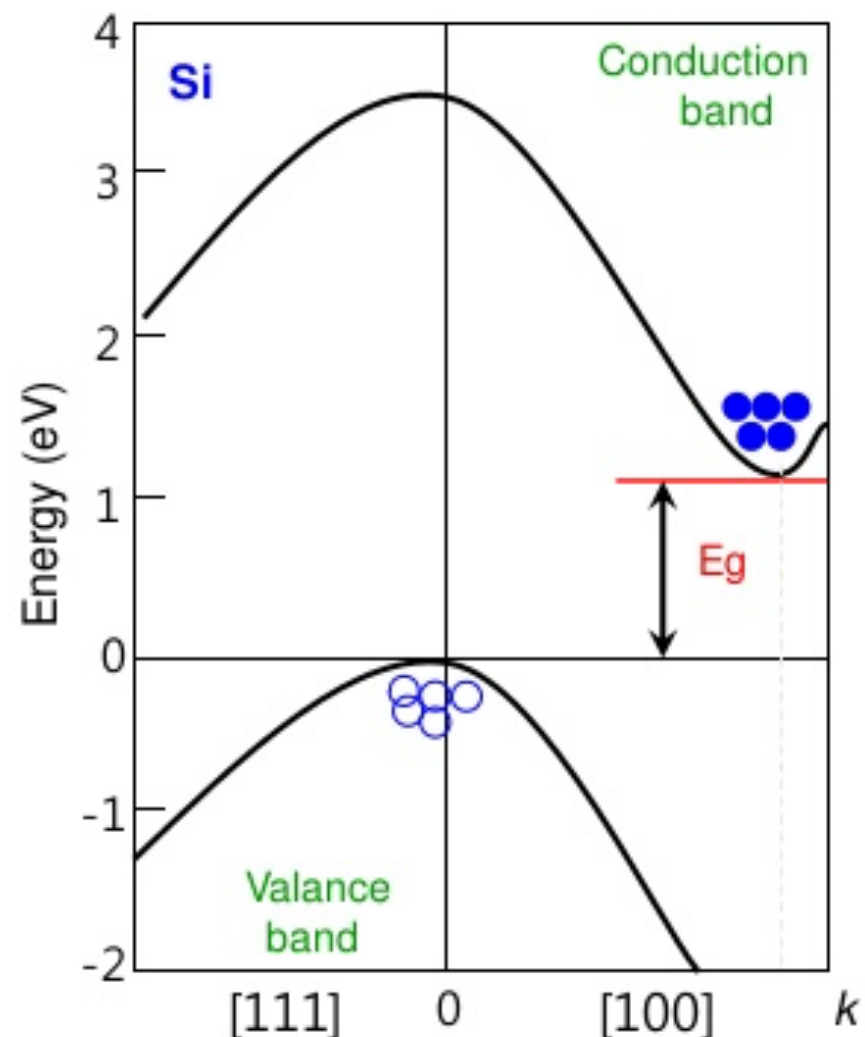
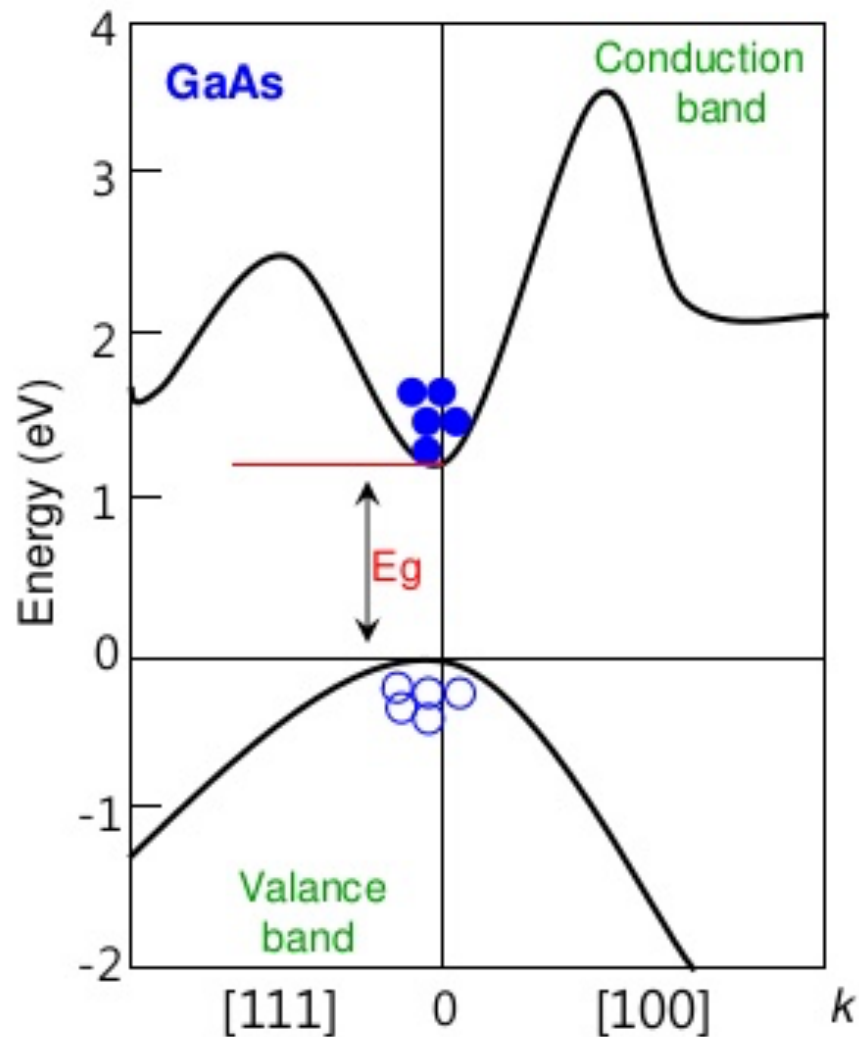
Valence and conduction band



Direct and indirect gap



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 ^a	<i>d</i>	-0.30	
α 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 ₂ O	<i>d</i>	2.172	—

^aHgTe 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 ₂ 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

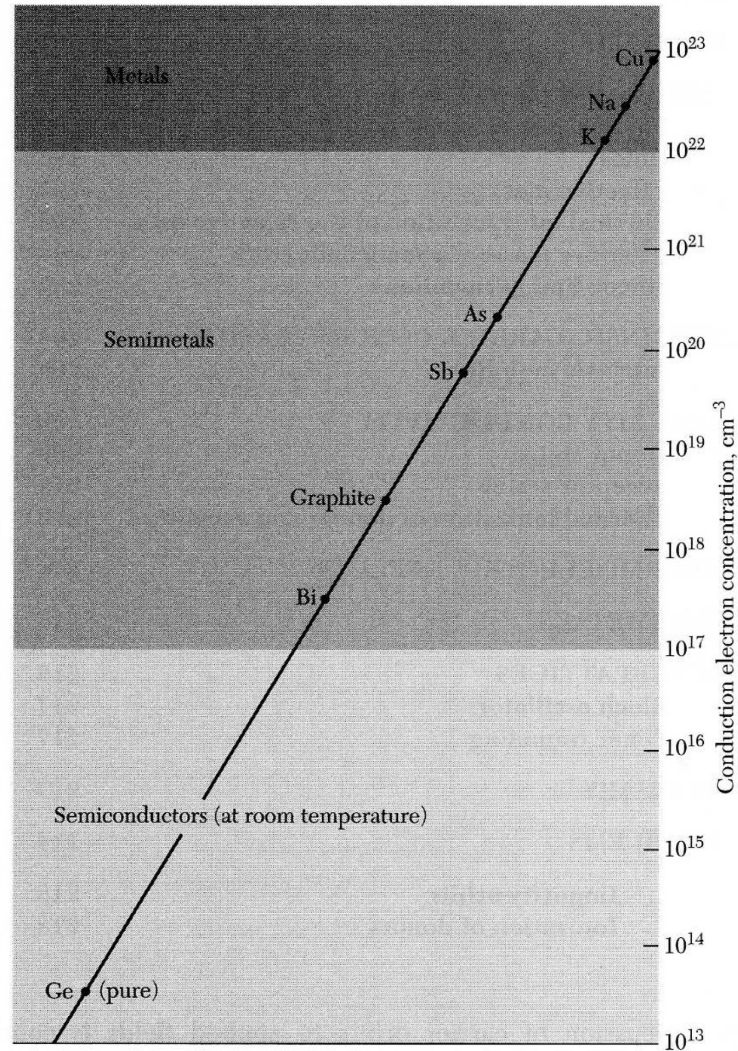


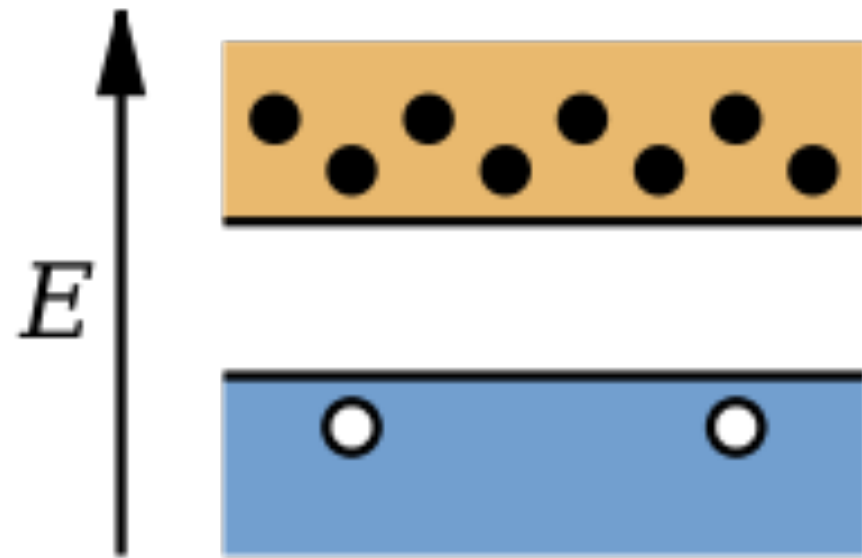
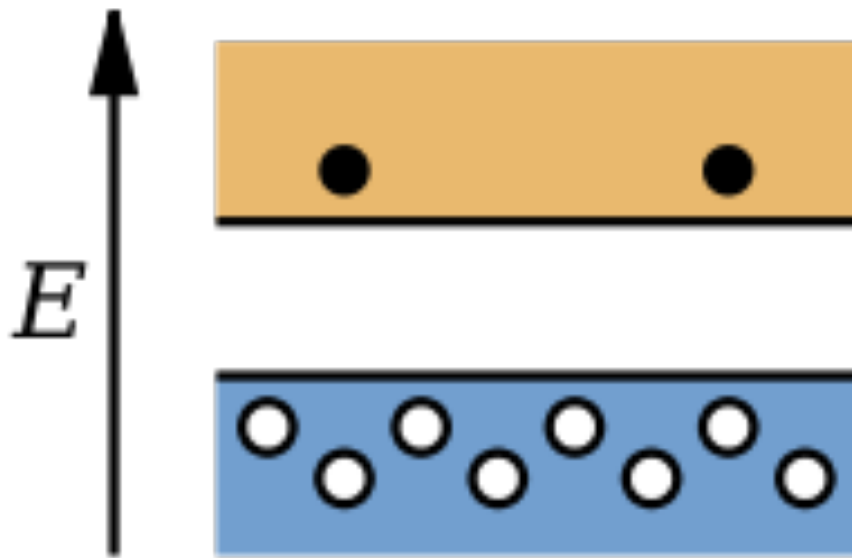
Figure 1 Carrier concentrations for metals, semimetals, and semiconductors. The semiconductor range may be extended upward by increasing the impurity concentration, and the range can be extended downward to merge eventually with the insulator range.

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

* Lanthanide series

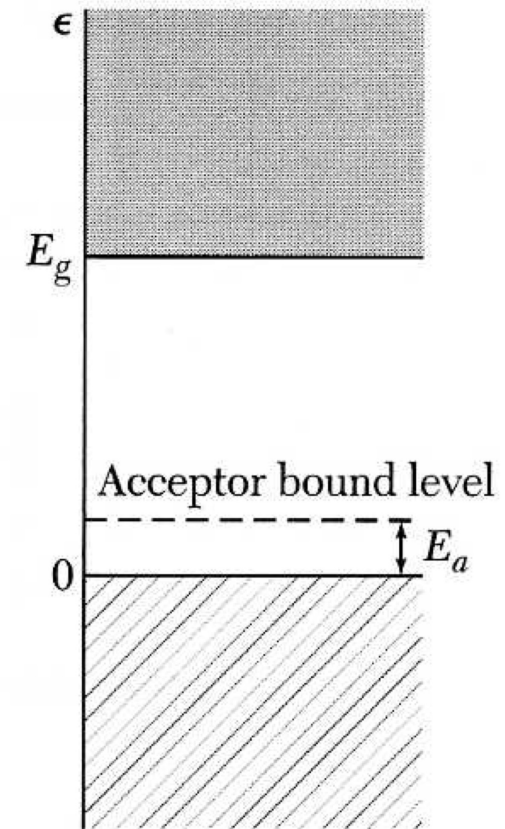
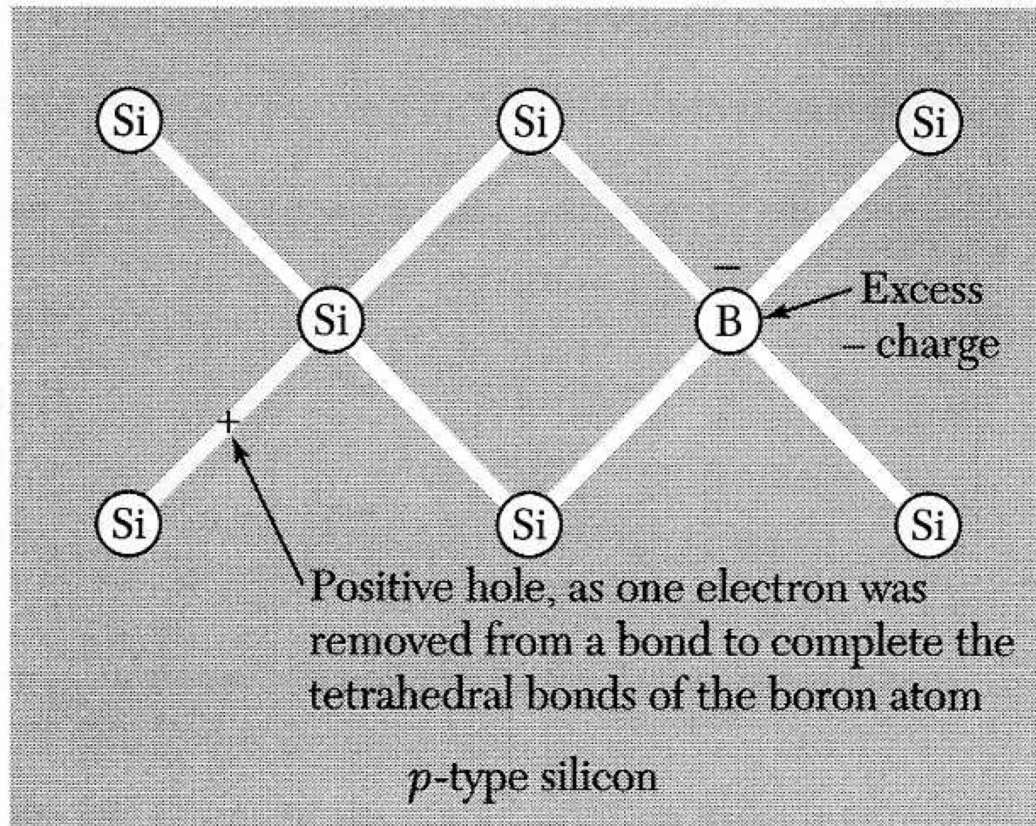
lanthanum 57 La 138.91	cerium 58 Ce 140.12	praseodymium 59 Pr 140.91	neodymium 60 Nd 144.24	promethium 61 Pm [145]	samarium 62 Sm 150.36	europium 63 Eu 151.96	gadolinium 64 Gd 157.25	terbium 65 Tb 158.93	dysprosium 66 Dy 162.50	holmium 67 Ho 164.93	erbium 68 Er 167.26	thulium 69 Tm 168.93	ytterbium 70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

** Actinide series

Diamond-type semiconductors

III – V compounds (GaAs, InSb)

Hole - doping

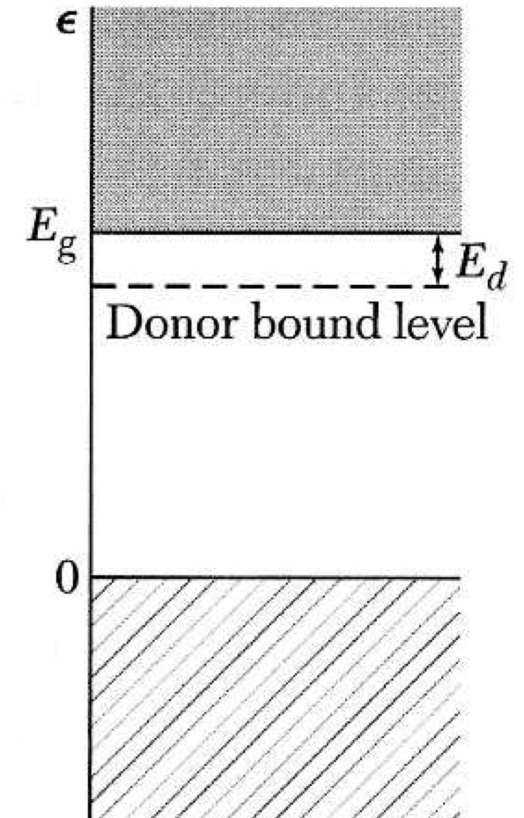
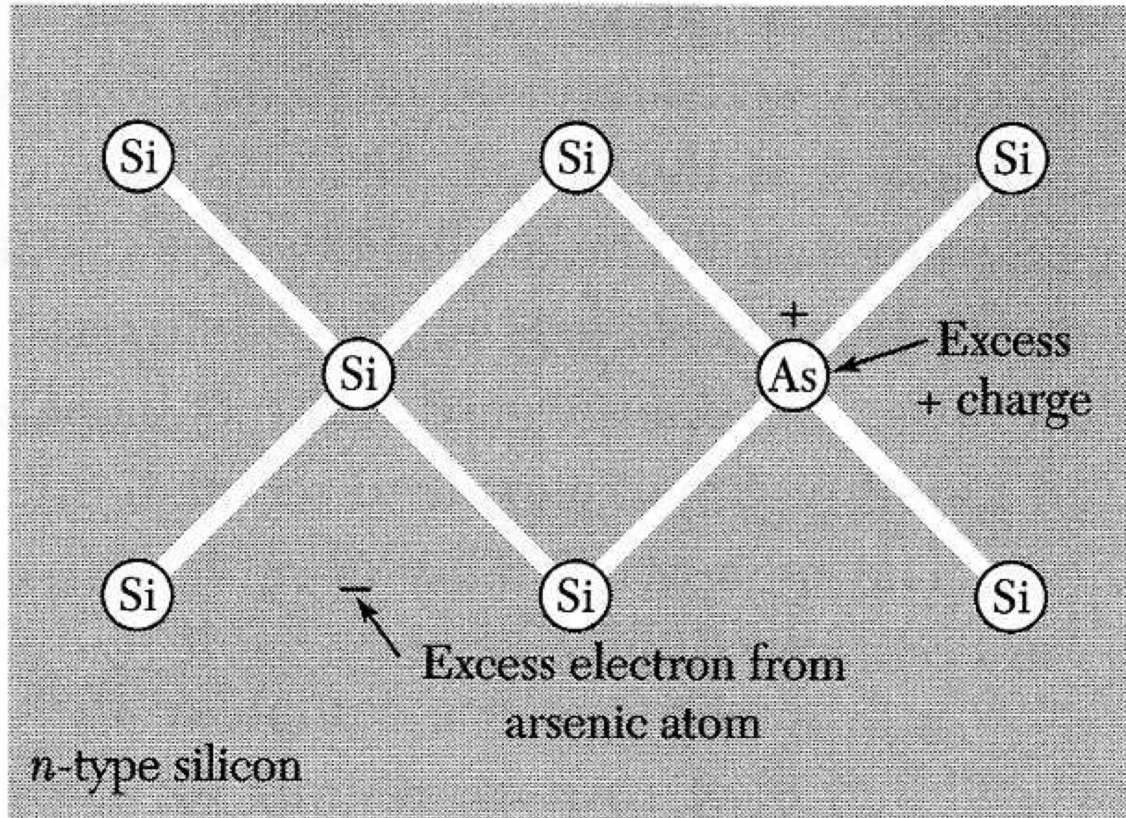


Si^{4+}

B^{3+}

From Kittel

Electron - doping

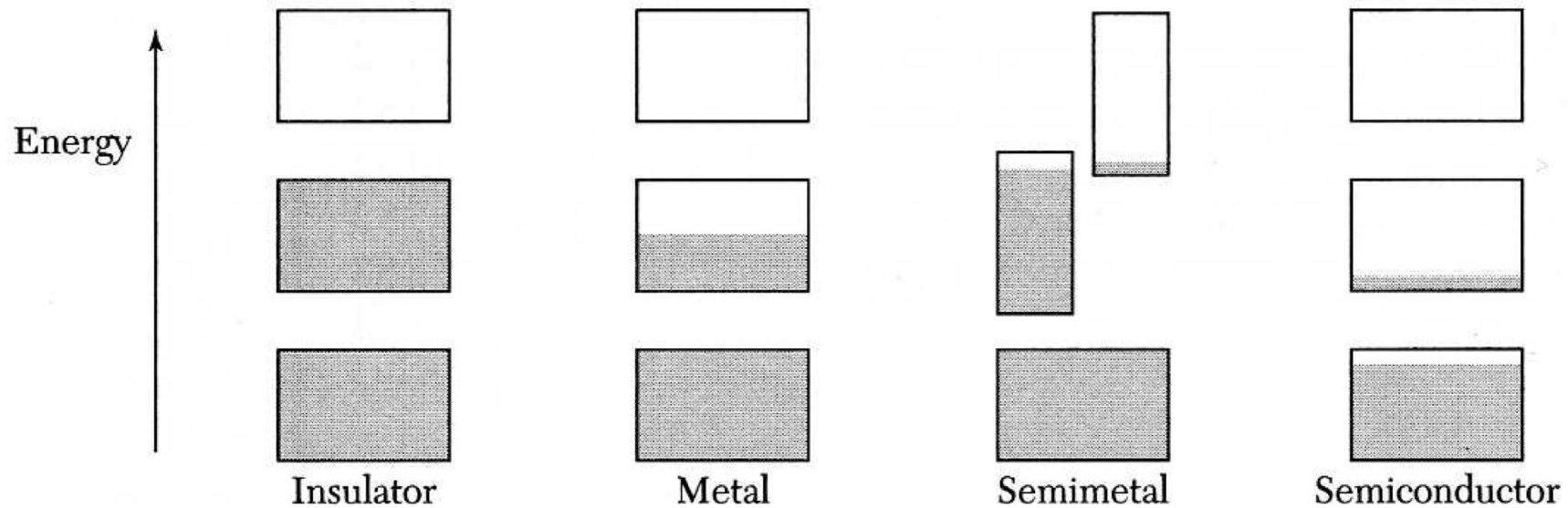


Si^{4+}

As^{5+}

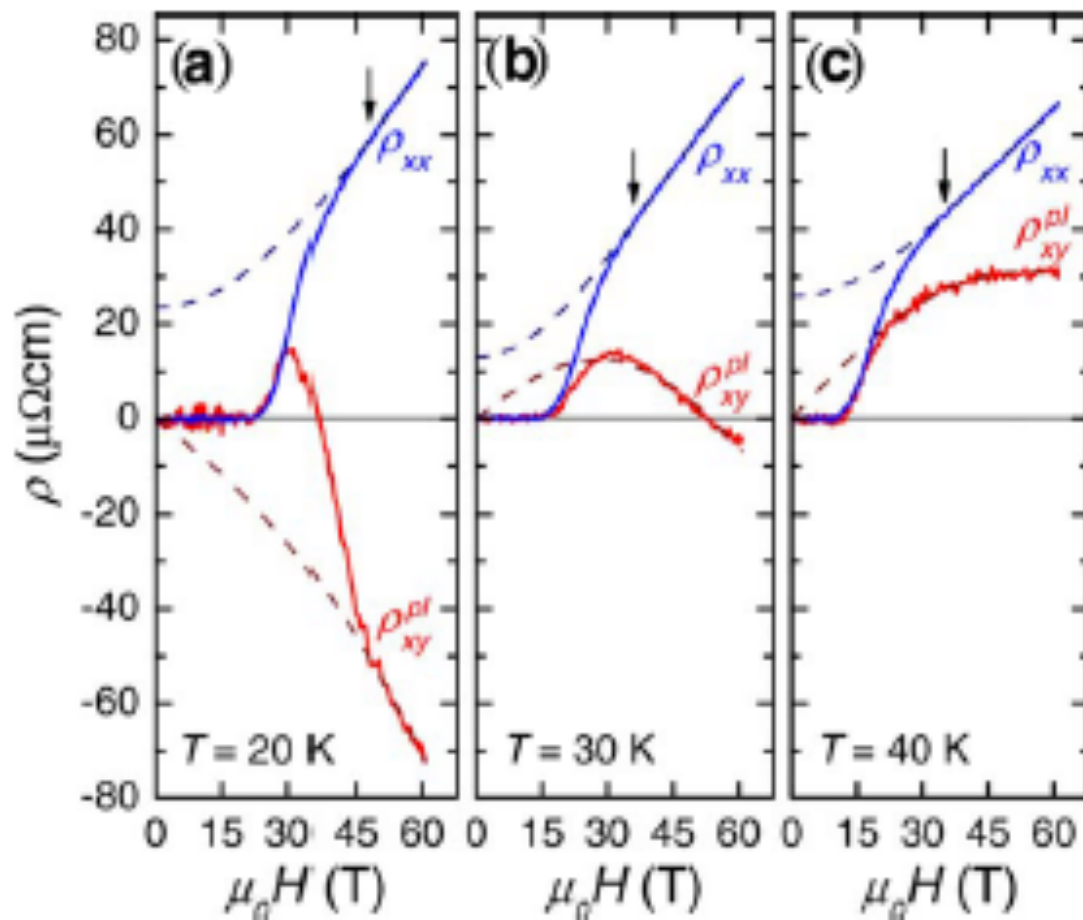
Concluding quiz

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



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

Magneto-resistance



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