

# **ECE 340 Lecture 4**

# **Semiconductor Electronics**

Spring 2022

10:00-10:50am

Professor Umberto Ravaioli

Department of Electrical and Computer Engineering

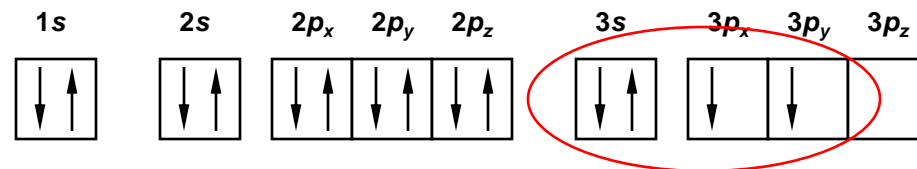
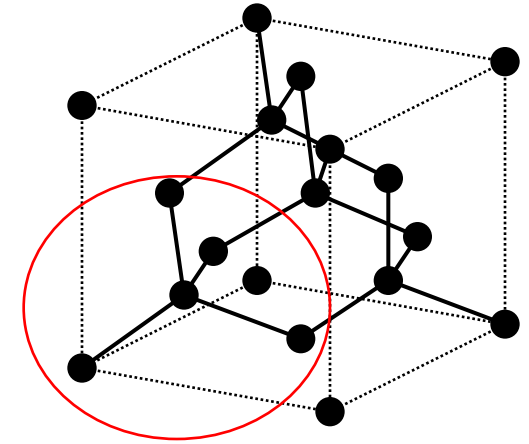
2062 ECE Building

# Today's Discussion

- Crystal States
- Types of Bonding
- Insulators, Metals, and Semiconductors
- Band structure
- Direct and Indirect Band Gap
- Electrons and Holes

# Crystal Bonding

- Each atom shares bonds with 4 other atoms.
- Silicon bonds are covalent, but compound semiconductors have a mix of ionic and covalent bonds.



When silicon atoms **COMBINE** to form a crystal the *s*- and *p*- orbitals **HYBRIDIZE** to form so-called  $sp^3$  ORBITALS that are mixtures of the *s*- and *p*-orbitals.



*s*-ORBITAL



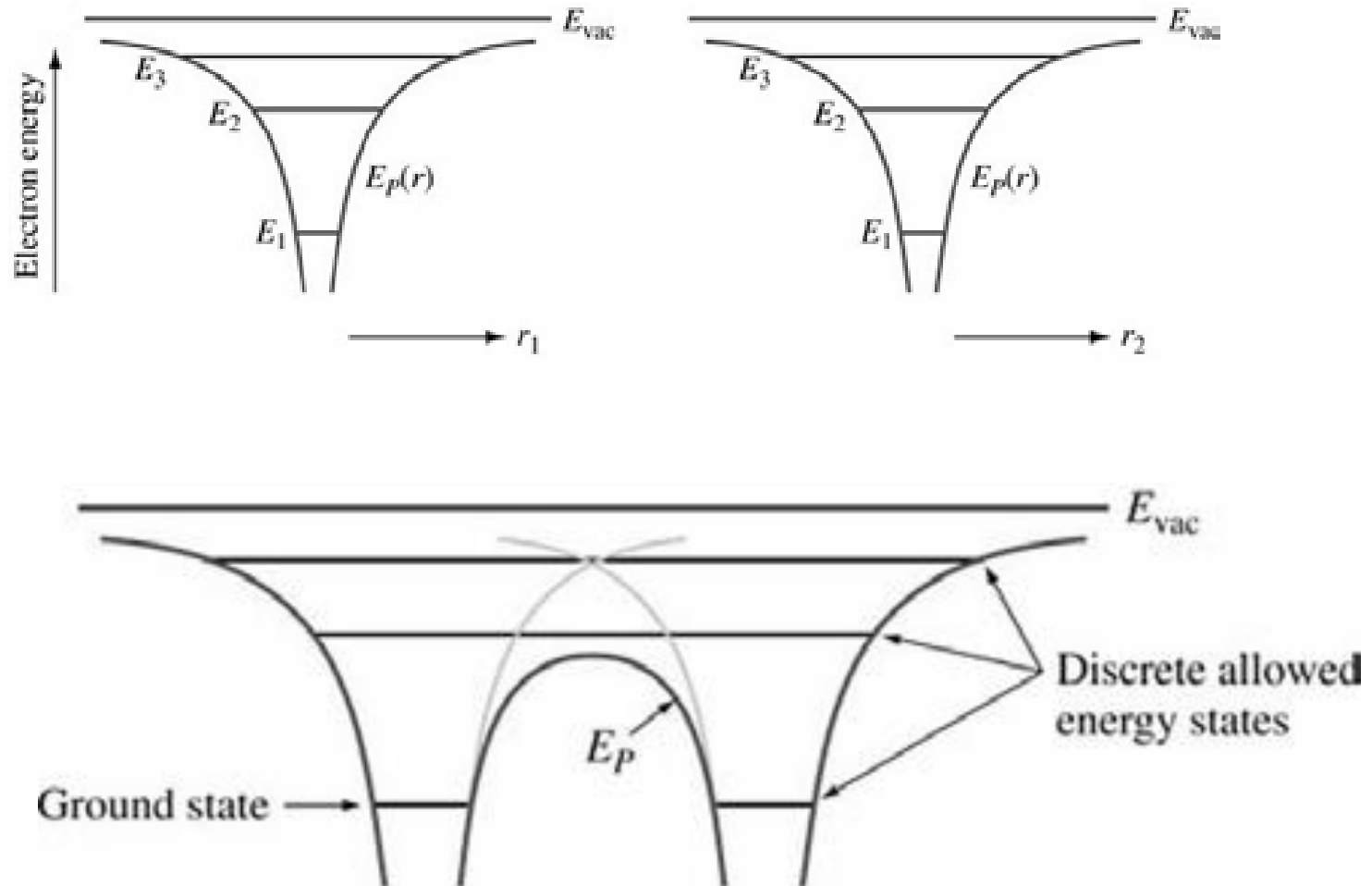
*p*-ORBITAL



$sp^3$ -ORBITAL

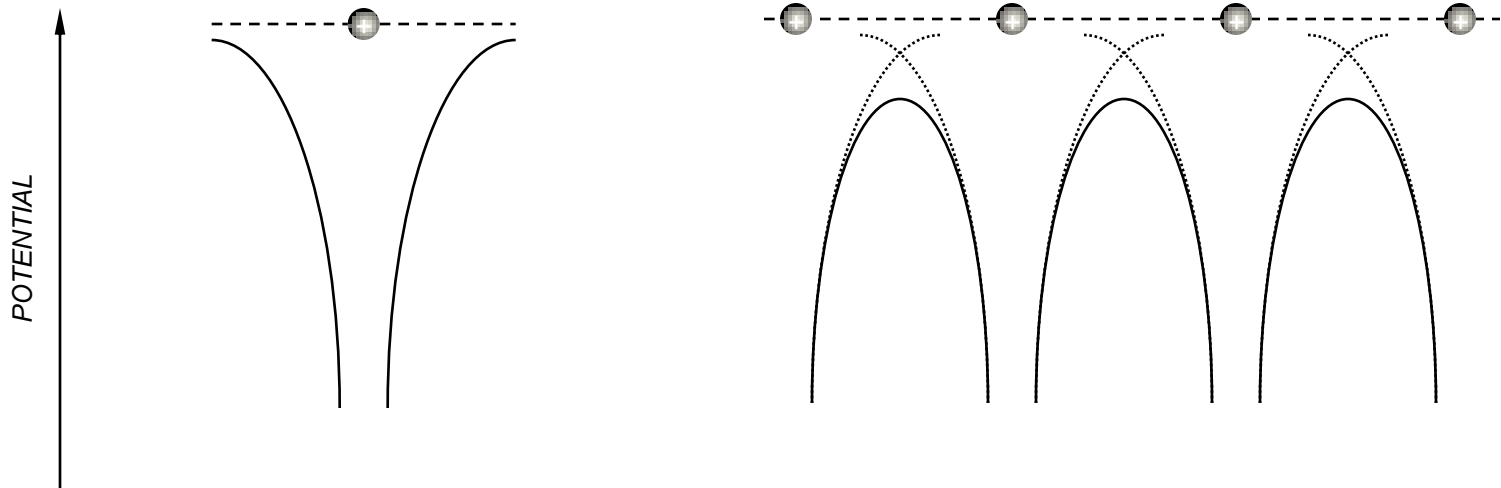
# Crystal Bonding

Bring atoms together, the wavefunctions begin to overlap.



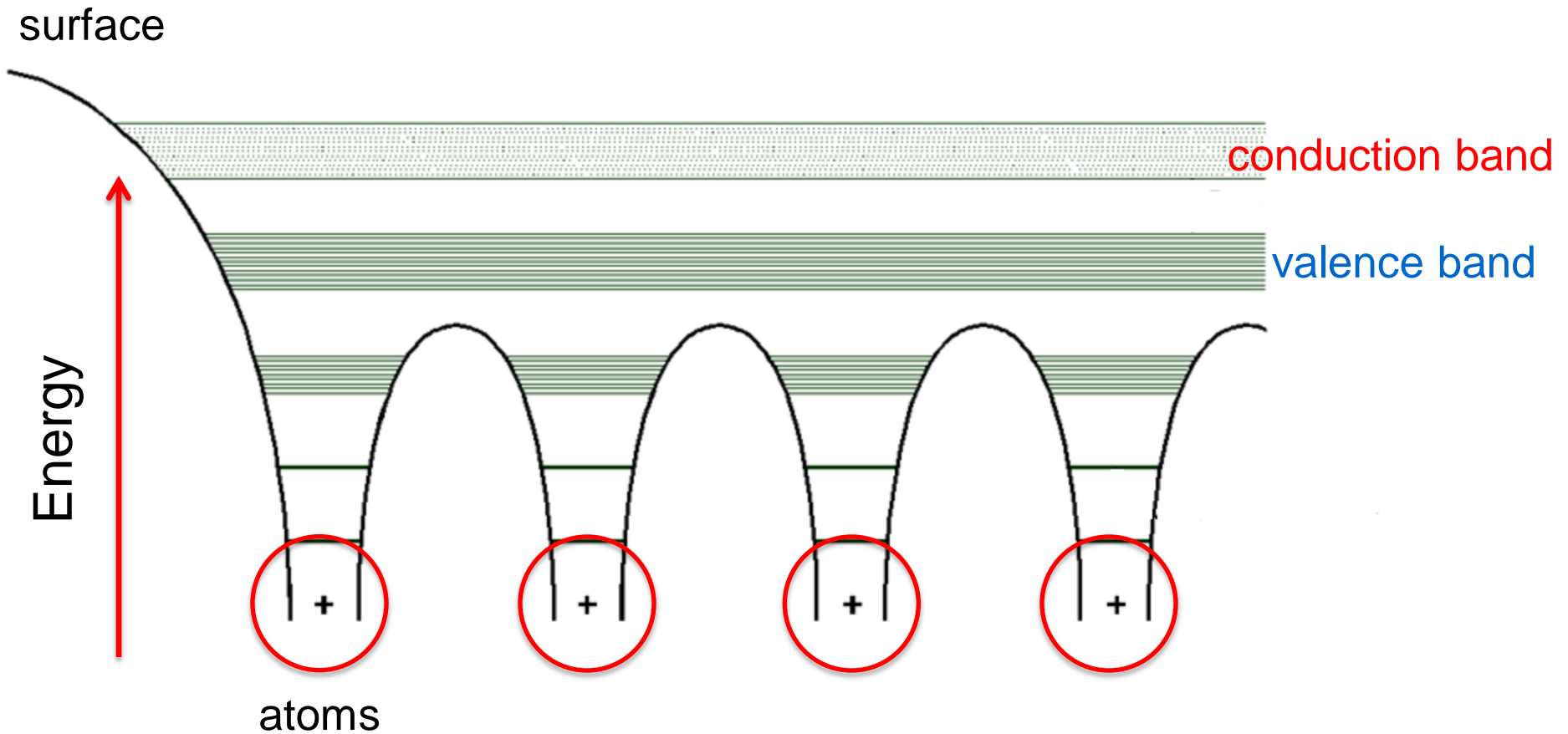
# Energy Band Formation

*IN A SINGLE ATOM ELECTRONS ARE TRAPPED IN A POTENTIAL WELL*

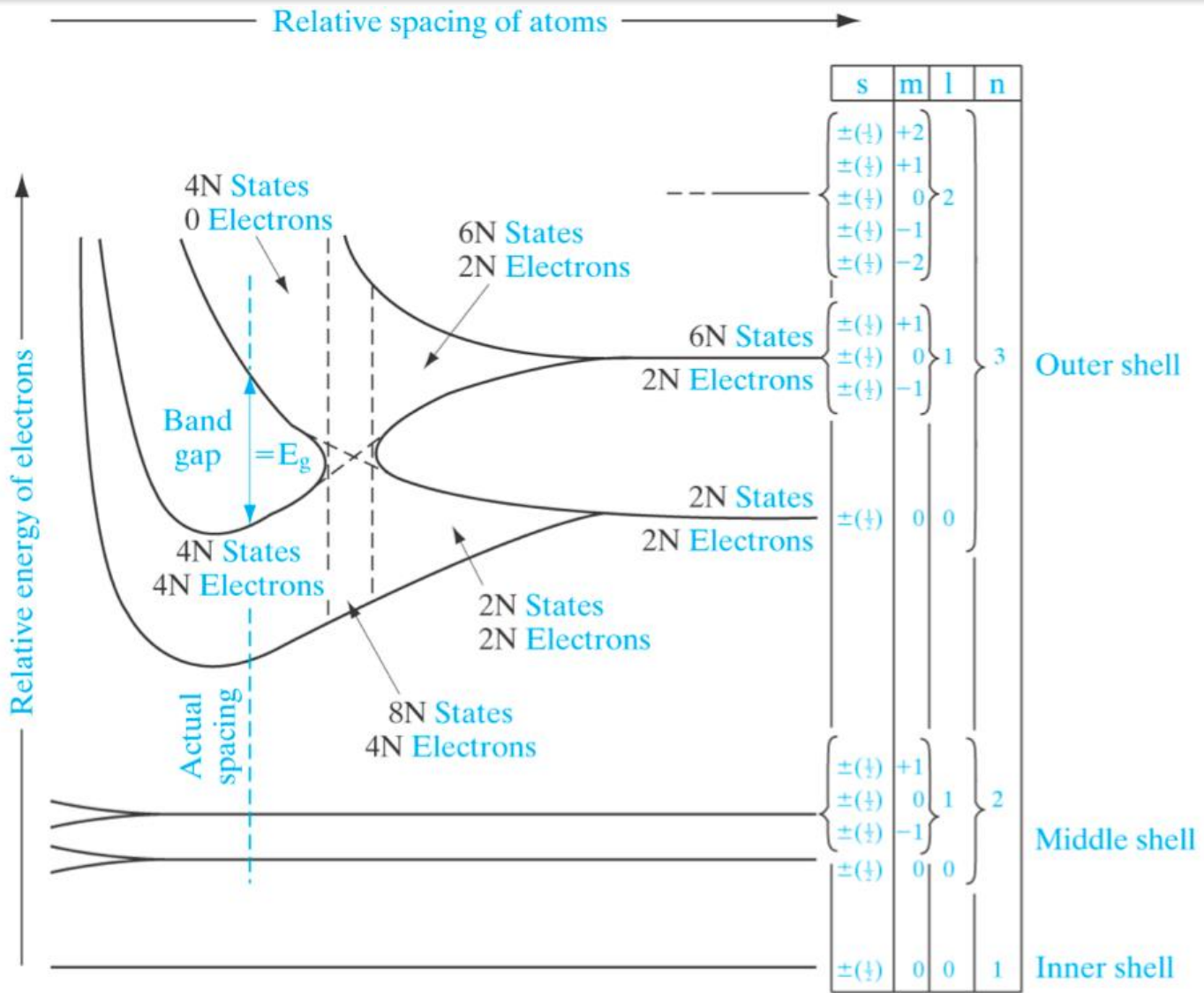


***WHEN MANY ATOMS COMBINE AND FORM A CRYSTAL THE ATOMIC POTENTIALS OVERLAP GIVING RISE TO A PERIODIC VARIATION***

# Energy Band Formation



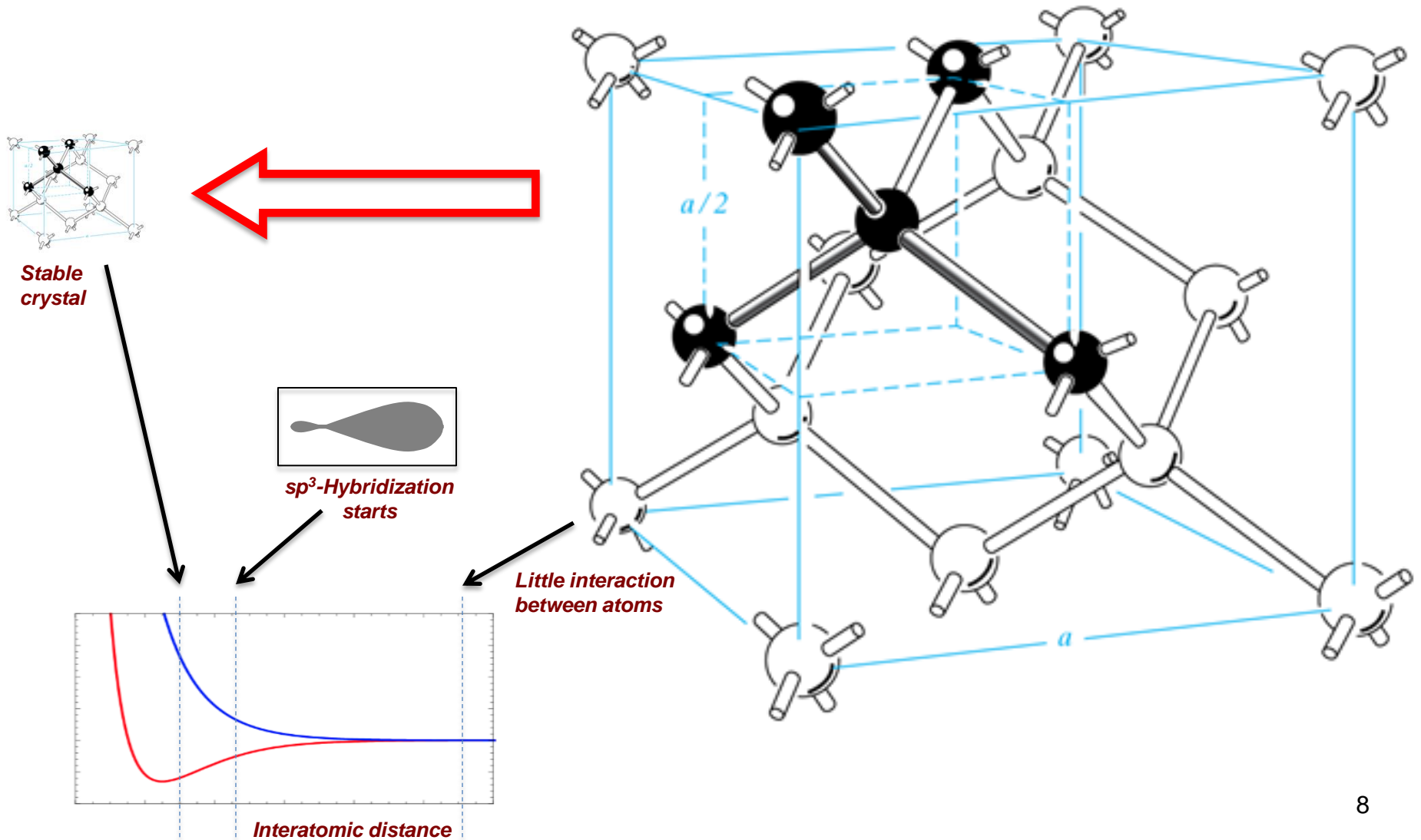
# Energy Band Formation



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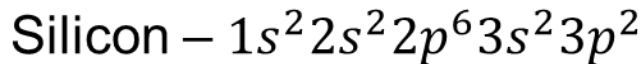
# Gedanken Experiment

Imagine you start with  $a \gg$  and then shrink down to exact size





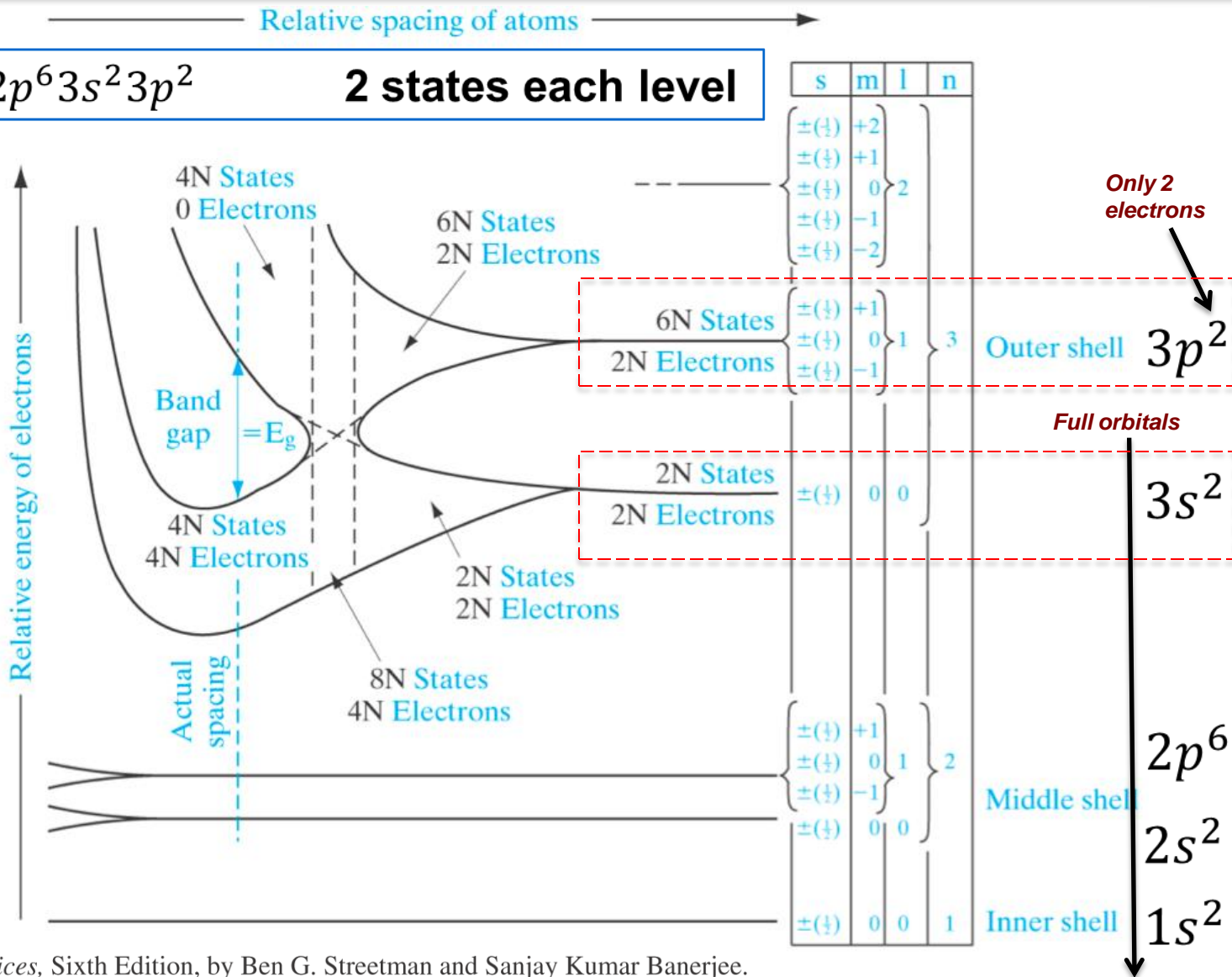
# Energy Bands Formation



2 states each level

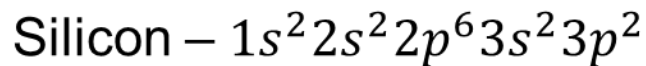
Atomic #  
 $Z = 14$

$N =$  atoms in crystal



# ATOMS ARE FAR AWAY FROM EACH OTHER AND DO NOT INTERACT

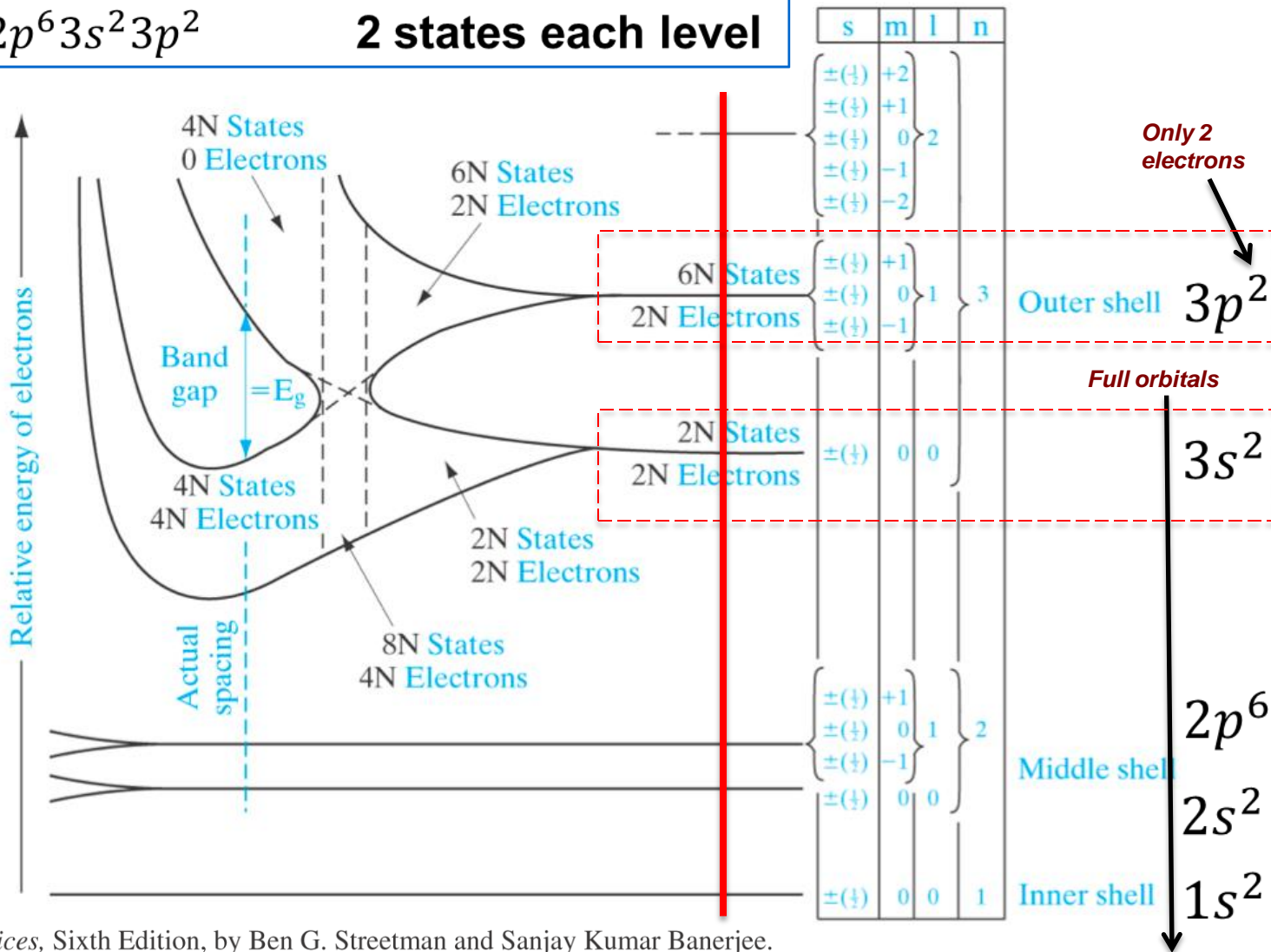
Relative spacing of atoms  $\rightarrow$



2 states each level

Atomic #  
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$N =$  atoms in crystal



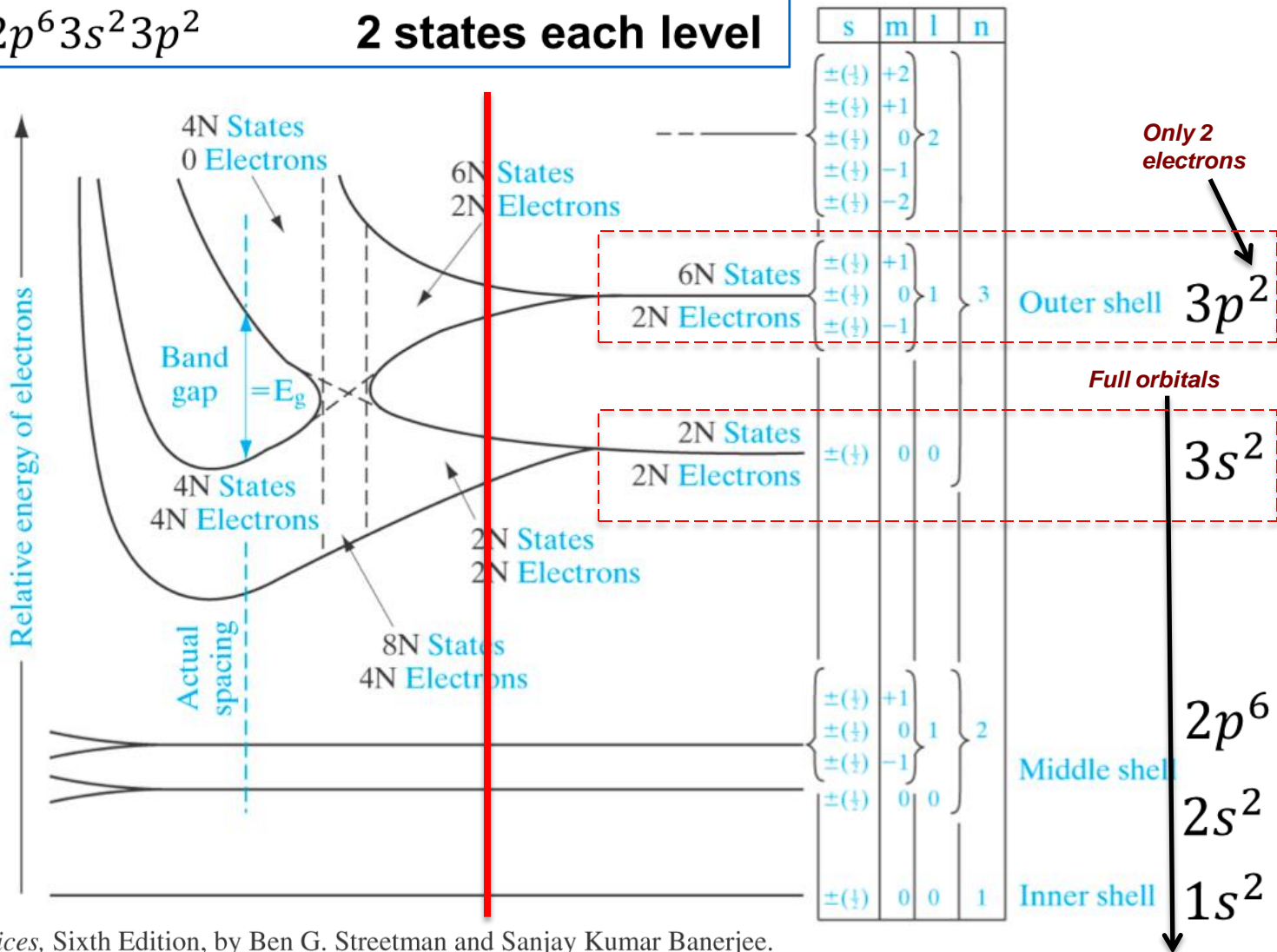
# ATOMS START INTERACTING – BONDING & ANTIBONDING STATES START FORMING

Relative spacing of atoms  $\rightarrow$

Silicon –  $1s^2 2s^2 2p^6 3s^2 3p^2$       2 states each level

Atomic #  
 $Z = 14$

$N =$  atoms in crystal



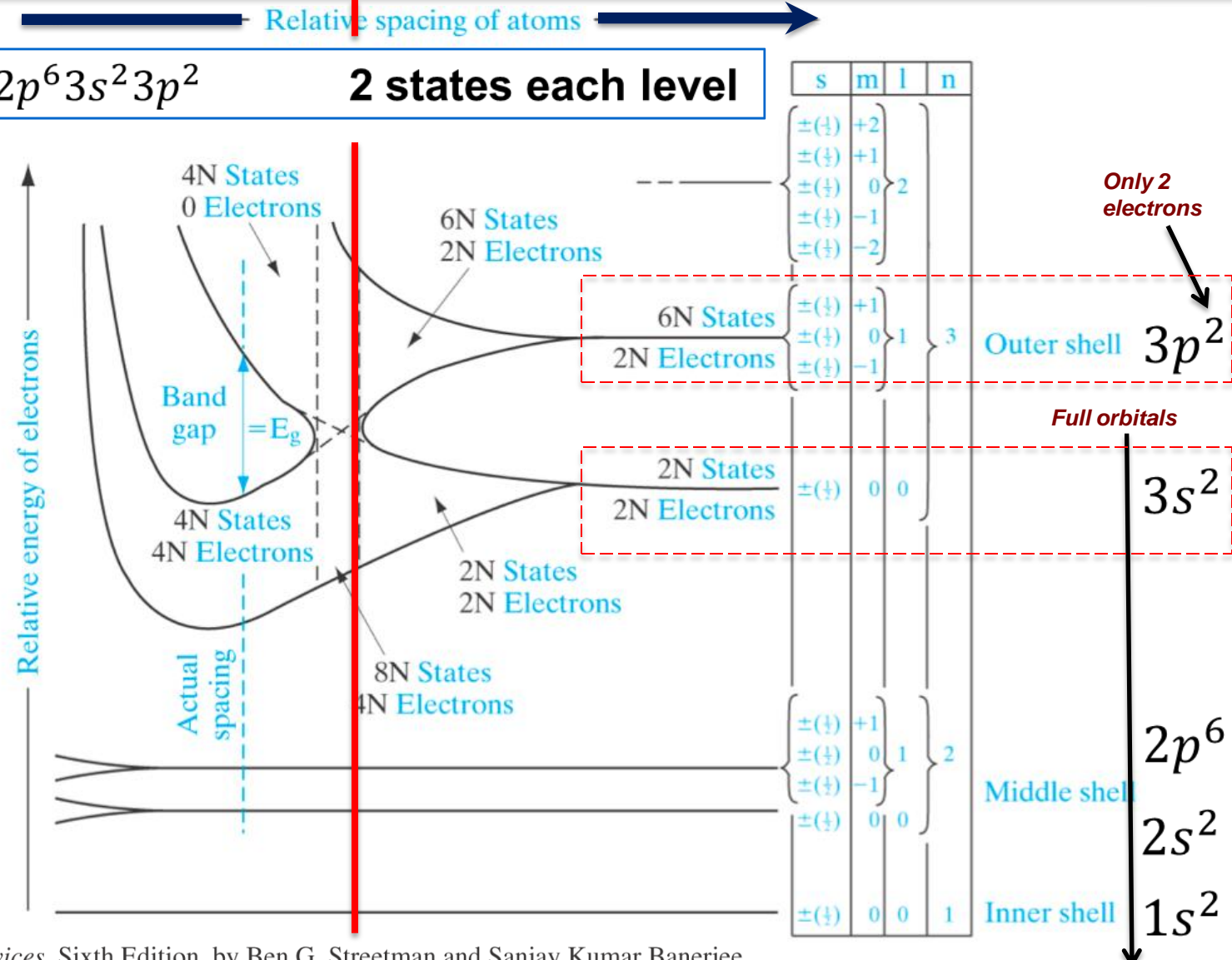
# STRONGER INTERACTION – $sp^3$ ORBITAL HYBRIDIZATION STARTS

Silicon –  $1s^2 2s^2 2p^6 3s^2 3p^2$

2 states each level

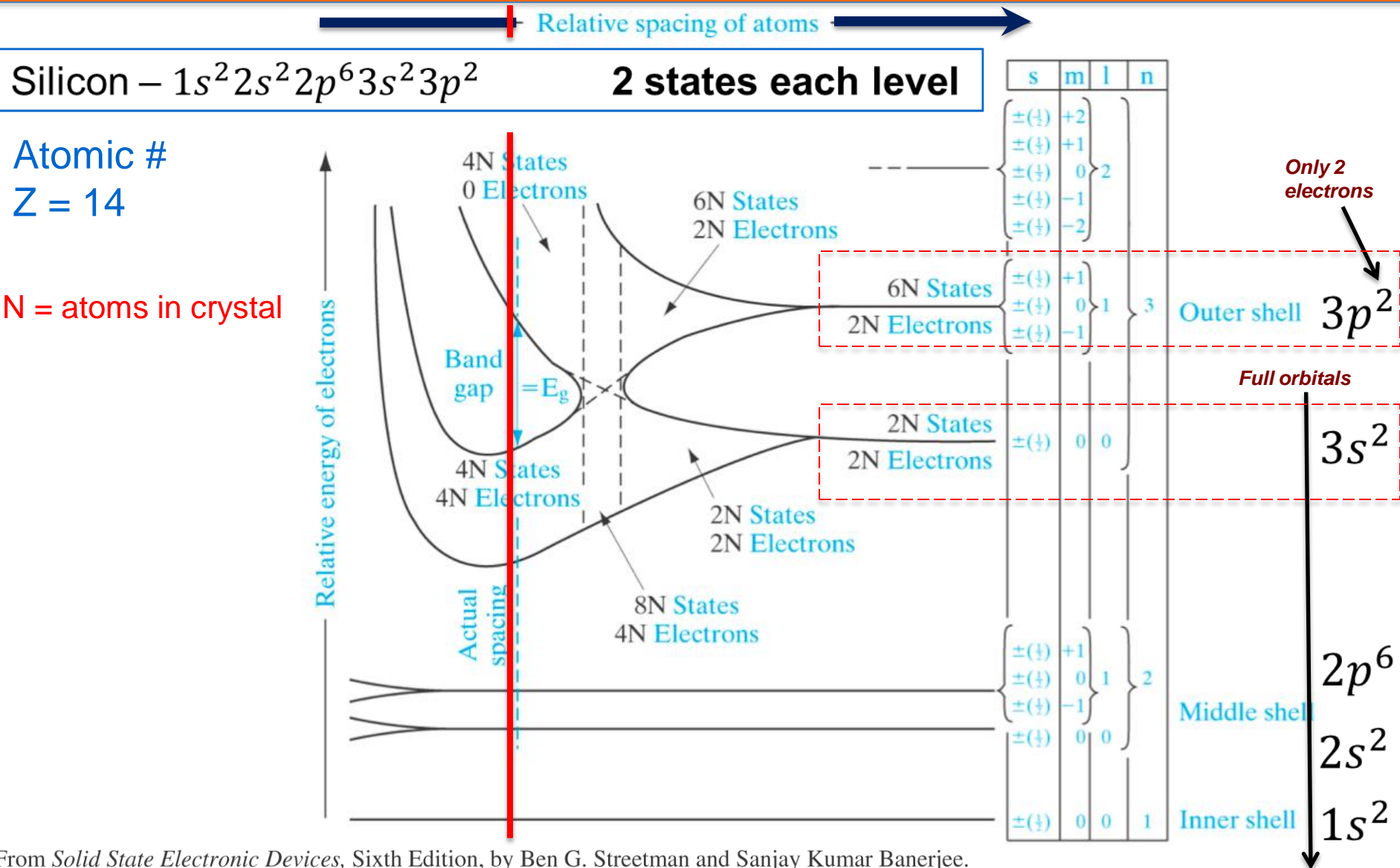
Atomic #  
 $Z = 14$

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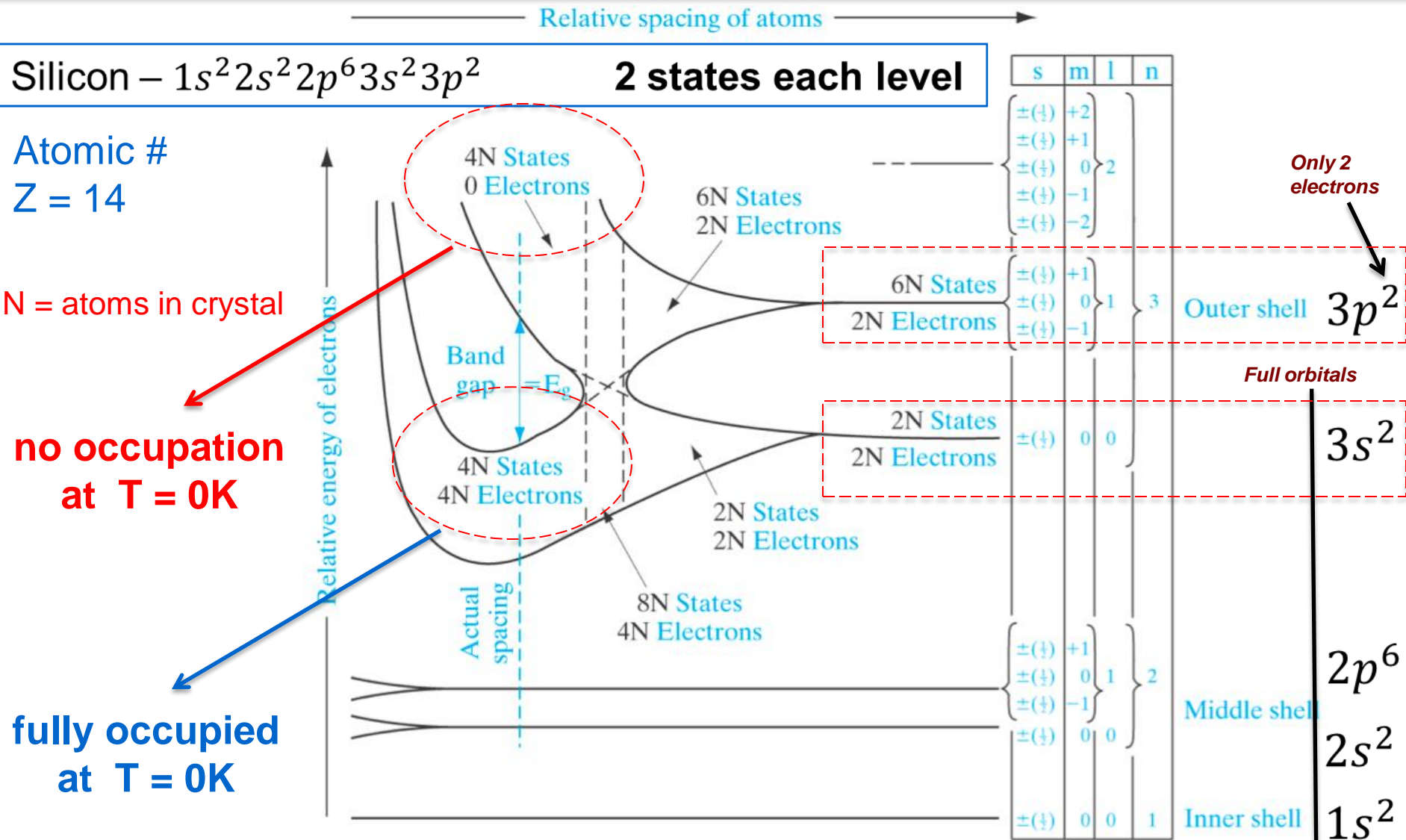
# STABLE CRYSTAL CONFIGURATION REACHED – COVALENT BONDING VALENCE AND CONDUCTION BANDS WITH BAND GAP ARE FORMED



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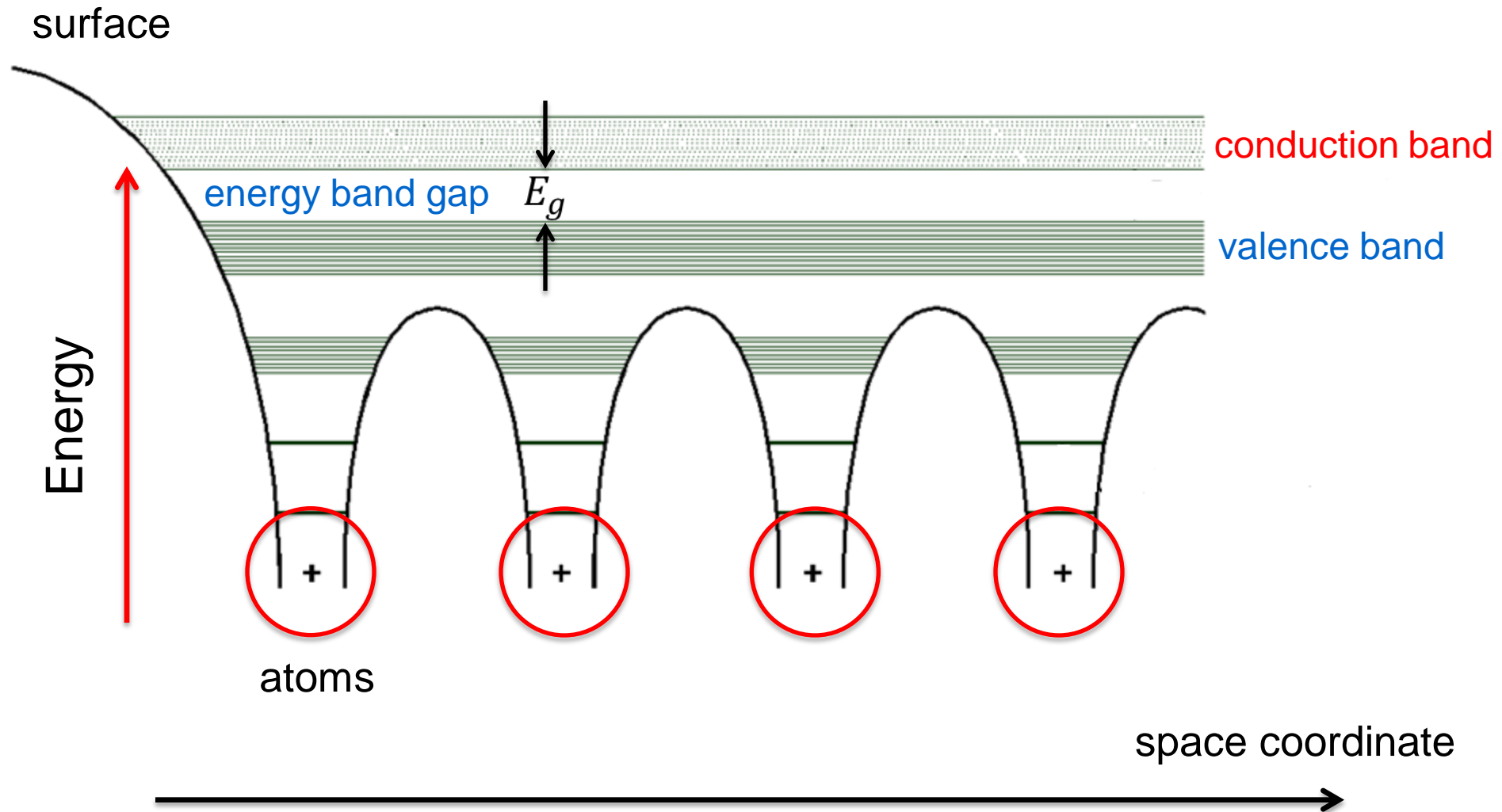


# Energy Bands Formation



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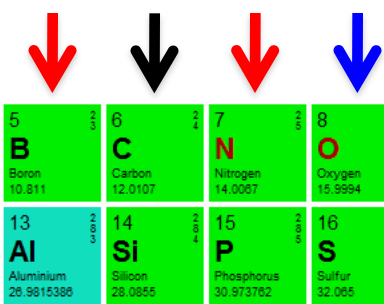
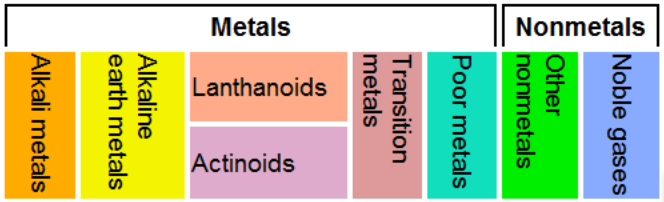
# Energy Band Formation



# Periodic Table of the Elements

1	2	3	4	5	6	7	8	9	10	11	12	III	IV	V	VI	17	18	
1 <b>H</b> Hydrogen 1.00794	2 <b>He</b> Helium 4.002602																	
3 <b>Li</b> Lithium 6.941	4 <b>Be</b> Beryllium 9.012182																	
11 <b>Na</b> Sodium 22.98976928	12 <b>Mg</b> Magnesium 24.3050																	
19 <b>K</b> Potassium 39.0983	20 <b>Ca</b> Calcium 40.078	21 <b>Sc</b> Scandium 44.955912	22 <b>Ti</b> Titanium 47.887	23 <b>V</b> Vanadium 50.9415	24 <b>Cr</b> Chromium 51.9961	25 <b>Mn</b> Manganese 54.938045	26 <b>Fe</b> Iron 55.845	27 <b>Co</b> Cobalt 58.933195	28 <b>Ni</b> Nickel 58.6934	29 <b>Cu</b> Copper 63.546	30 <b>Zn</b> Zinc 65.38	31 <b>Ga</b> Gallium 69.723	32 <b>Ge</b> Germanium 72.64	33 <b>As</b> Arsenic 74.92160	34 <b>Se</b> Selenium 78.96	35 <b>Br</b> Bromine 79.904	36 <b>Kr</b> Krypton 83.798	
37 <b>Rb</b> Rubidium 85.4678	38 <b>Sr</b> Strontium 87.62	39 <b>Y</b> Yttrium 88.90585	40 <b>Zr</b> Zirconium 91.224	41 <b>Nb</b> Niobium 92.90638	42 <b>Mo</b> Molybdenum 95.96	43 <b>Tc</b> Technetium (97.9072)	44 <b>Ru</b> Ruthenium 101.07	45 <b>Rh</b> Rhodium 102.90550	46 <b>Pd</b> Palladium 106.42	47 <b>Ag</b> Silver 107.8682	48 <b>Cd</b> Cadmium 112.411	49 <b>In</b> Indium 114.818	50 <b>Sn</b> Tin 118.710	51 <b>Sb</b> Antimony 121.760	52 <b>Te</b> Tellurium 127.60	53 <b>I</b> Iodine 126.90447	54 <b>Xe</b> Xenon 131.293	
55 <b>Cs</b> Caesium 132.9054519	56 <b>Ba</b> Barium 137.327	57-71		72 <b>Hf</b> Hafnium 178.49	73 <b>Ta</b> Tantalum 180.94788	74 <b>W</b> Tungsten 183.84	75 <b>Re</b> Rhenium 186.207	76 <b>Os</b> Osmium 190.23	77 <b>Ir</b> Iridium 192.217	78 <b>Pt</b> Platinum 195.084	79 <b>Au</b> Gold 196.966569	80 <b>Hg</b> Mercury 200.59	81 <b>Tl</b> Thallium 204.3833	82 <b>Pb</b> Lead 207.2	83 <b>Bi</b> Bismuth 208.98040	84 <b>Po</b> Polonium (209)	85 <b>At</b> Astatine (209)	86 <b>Rn</b> Radon (222)
87 <b>Fr</b> Francium (223)	88 <b>Ra</b> Radium (226)	89-103		104 <b>Rf</b> Rutherfordium (261)	105 <b>Db</b> Dubnium (262)	106 <b>Sg</b> Seaborgium (266)	107 <b>Bh</b> Bohrium (264)	108 <b>Hs</b> Hassium (277)	109 <b>Mt</b> Meitnerium (268)	110 <b>Ds</b> Darmstadtium (271)	111 <b>Rg</b> Roentgenium (272)	112 <b>Uub</b> Ununbium (285)	113 <b>Uut</b> Ununtrium (284)	114 <b>Uuq</b> Ununquadium (289)	115 <b>Uup</b> Ununpentium (288)	116 <b>Uuh</b> Ununhexium (292)	117 <b>Uus</b> Ununseptium	118 <b>Uuo</b> Ununoctium (294)

- C** Solid
- Hg** Liquid
- H** Gas
- Rf** Unknown



For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

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57 <b>La</b> Lanthanum 138.90547	58 <b>Ce</b> Cerium 140.116	59 <b>Pr</b> Praseodymium 140.90765	60 <b>Nd</b> Neodymium 144.242	61 <b>Pm</b> Promethium (145)	62 <b>Sm</b> Samarium 150.36	63 <b>Eu</b> Europium 151.964	64 <b>Gd</b> Gadolinium 157.25	65 <b>Tb</b> Terbium 158.92535	66 <b>Dy</b> Dysprosium 162.500	67 <b>Ho</b> Holmium 164.93032	68 <b>Er</b> Erbium 167.259	69 <b>Tm</b> Thulium 168.93421	70 <b>Yb</b> Ytterbium 173.054	71 <b>Lu</b> Lutetium 174.9668
89 <b>Ac</b> Actinium (227)	90 <b>Th</b> Thorium 232.03806	91 <b>Pa</b> Protactinium 231.03588	92 <b>U</b> Uranium 238.02891	93 <b>Np</b> Neptunium (237)	94 <b>Pu</b> Plutonium (244)	95 <b>Am</b> Americium (243)	96 <b>Cm</b> Curium (247)	97 <b>Bk</b> Berkelium (247)	98 <b>Cf</b> Californium (251)	99 <b>Es</b> Einsteinium (252)	100 <b>Fm</b> Fermium (257)	101 <b>Md</b> Mendelevium (258)	102 <b>No</b> Nobelium (259)	103 <b>Lr</b> Lawrencium (262)

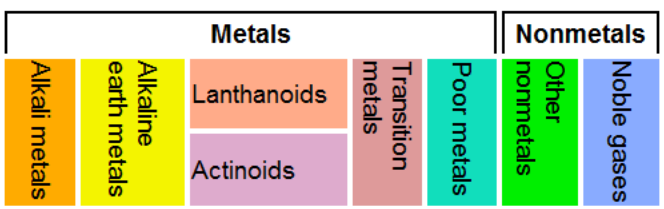




# Ionic Bonding

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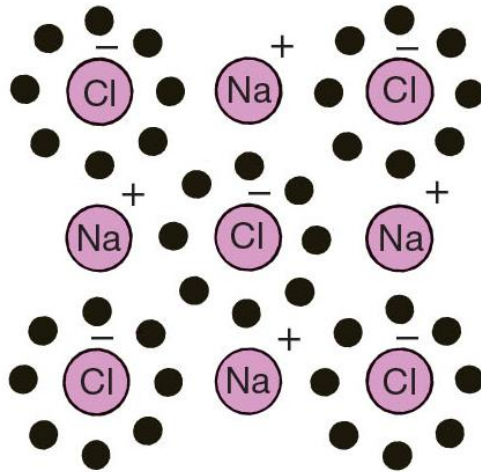
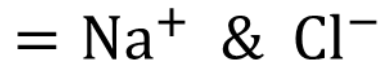
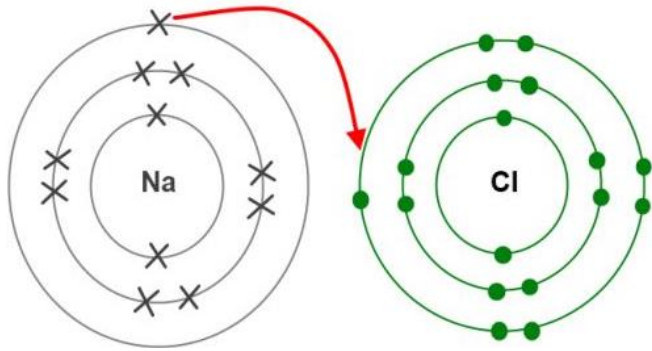
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# Ionic Bonding



ionic bonding  
electron transferred from Na to Cl

# Metallic Bonding

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<b>C</b> Solid	<b>Metals</b>					<b>Nonmetals</b>																																																																	
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87 <b>Fr</b> Francium (223)	88 <b>Ra</b> Radium (226)	89-103	104 <b>Rf</b> Rutherfordium (261)	105 <b>Db</b> Dubnium (262)	106 <b>Sg</b> Seaborgium (266)	107 <b>Bh</b> Bohrium (264)	108 <b>Hs</b> Hassium (277)	109 <b>Mt</b> Meitnerium (268)	110 <b>Ds</b> Darmstadtium (271)	111 <b>Rg</b> Roentgenium (272)	112 <b>Uub</b> Ununbium (285)	113 <b>Uut</b> Ununtrium (284)	114 <b>Uuq</b> Ununquadium (289)	115 <b>Uup</b> Ununpentium (288)	116 <b>Uuh</b> Ununhexium (292)	117 <b>Uus</b> Ununseptium	118 <b>Uuo</b> Ununoctium (294)																																																						

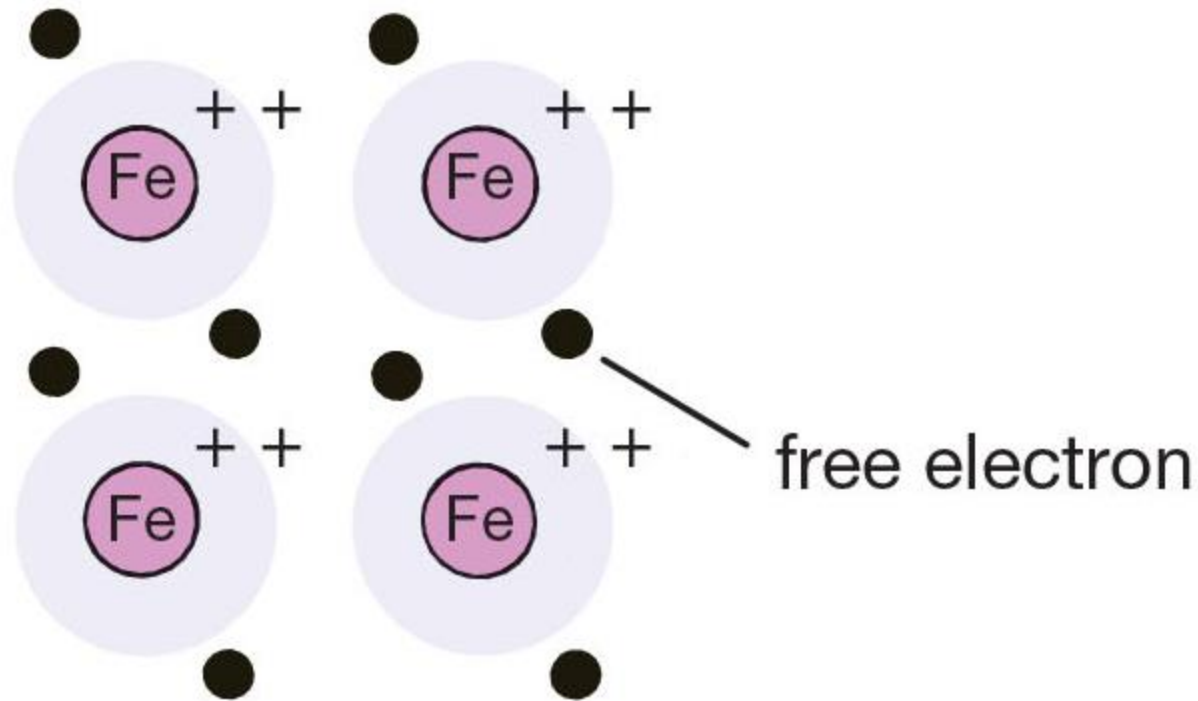
For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

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57 <b>La</b> Lanthanum 138.90547	58 <b>Ce</b> Cerium 140.116	59 <b>Pr</b> Praseodymium 140.90765	60 <b>Nd</b> Neodymium 144.242	61 <b>Pm</b> Promethium (145)	62 <b>Sm</b> Samarium 150.36	63 <b>Eu</b> Europium 151.964	64 <b>Gd</b> Gadolinium 157.25	65 <b>Tb</b> Terbium 158.92535	66 <b>Dy</b> Dysprosium 162.500	67 <b>Ho</b> Holmium 164.93032	68 <b>Er</b> Erbium 167.259	69 <b>Tm</b> Thulium 168.93421	70 <b>Yb</b> Ytterbium 173.054	71 <b>Lu</b> Lutetium 174.9668
89 <b>Ac</b> Actinium (227)	90 <b>Th</b> Thorium 232.03806	91 <b>Pa</b> Protactinium 231.03588	92 <b>U</b> Uranium 238.02891	93 <b>Np</b> Neptunium (237)	94 <b>Pu</b> Plutonium (244)	95 <b>Am</b> Americium (243)	96 <b>Cm</b> Curium (247)	97 <b>Bk</b> Berkelium (247)	98 <b>Cf</b> Californium (251)	99 <b>Es</b> Einsteinium (252)	100 <b>Fm</b> Fermium (257)	101 <b>Md</b> Mendelevium (258)	102 <b>No</b> Nobelium (259)	103 <b>Lr</b> Lawrencium (262)



# Metallic Bonding

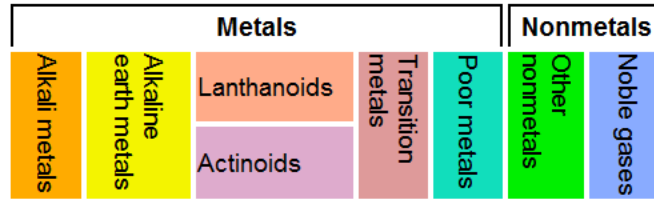


metallic bonding  
ions surrounded by free electrons

# Covalent Bonding

1	2	3	4	5	6	7	8	9	10	11	12	III	IV	V	VI	17	18		
1 <b>H</b> Hydrogen 1.00794	2 <b>He</b> Helium 4.002602													3 <b>B</b> Boron 10.811	4 <b>C</b> Carbon 12.0107	5 <b>N</b> Nitrogen 14.0067	6 <b>O</b> Oxygen 15.9994	7 <b>F</b> Fluorine 18.9984032	8 <b>Ne</b> Neon 20.1797
3 <b>Li</b> Lithium 6.941	4 <b>Be</b> Beryllium 9.012182													13 <b>Al</b> Aluminium 26.9815386	14 <b>Si</b> Silicon 28.0855	15 <b>P</b> Phosphorus 30.973762	16 <b>S</b> Sulfur 32.065	17 <b>Cl</b> Chlorine 35.453	18 <b>Ar</b> Argon 39.948
11 <b>Na</b> Sodium 22.98976928	12 <b>Mg</b> Magnesium 24.3050													31 <b>Ga</b> Gallium 69.723	32 <b>Ge</b> Germanium 72.64	33 <b>As</b> Arsenic 74.92160	34 <b>Se</b> Selenium 78.96	35 <b>Br</b> Bromine 79.904	36 <b>Kr</b> Krypton 83.798
19 <b>K</b> Potassium 39.0983	20 <b>Ca</b> Calcium 40.078	21 <b>Sc</b> Scandium 44.955912	22 <b>Ti</b> Titanium 47.887	23 <b>V</b> Vanadium 50.9415	24 <b>Cr</b> Chromium 51.9961	25 <b>Mn</b> Manganese 54.938045	26 <b>Fe</b> Iron 55.845	27 <b>Co</b> Cobalt 58.933195	28 <b>Ni</b> Nickel 58.6934	29 <b>Cu</b> Copper 63.546	30 <b>Zn</b> Zinc 65.38	31 <b>Ga</b> Gallium 69.723	32 <b>Ge</b> Germanium 72.64	33 <b>As</b> Arsenic 74.92160	34 <b>Se</b> Selenium 78.96	35 <b>Br</b> Bromine 79.904	36 <b>Kr</b> Krypton 83.798		
37 <b>Rb</b> Rubidium 85.4678	38 <b>Sr</b> Strontium 87.62	39 <b>Y</b> Yttrium 88.90585	40 <b>Zr</b> Zirconium 91.224	41 <b>Nb</b> Niobium 92.90638	42 <b>Mo</b> Molybdenum 95.96	43 <b>Tc</b> Technetium (97.9072)	44 <b>Ru</b> Ruthenium 101.07	45 <b>Rh</b> Rhodium 102.90550	46 <b>Pd</b> Palladium 106.42	47 <b>Ag</b> Silver 107.8682	48 <b>Cd</b> Cadmium 112.411	49 <b>In</b> Indium 114.818	50 <b>Sn</b> Tin 118.710	51 <b>Sb</b> Antimony 121.760	52 <b>Te</b> Tellurium 127.60	53 <b>I</b> Iodine 126.90447	54 <b>Xe</b> Xenon 131.293		
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87 <b>Fr</b> Francium (223)	88 <b>Ra</b> Radium (226)	89-103	104 <b>Rf</b> Rutherfordium (261)	105 <b>Db</b> Dubnium (262)	106 <b>Sg</b> Seaborgium (266)	107 <b>Bh</b> Bohrium (264)	108 <b>Hs</b> Hassium (277)	109 <b>Mt</b> Meitnerium (268)	110 <b>Ds</b> Darmstadtium (271)	111 <b>Rg</b> Roentgenium (272)	112 <b>Uub</b> Ununbium (285)	113 <b>Uut</b> Ununtrium (284)	114 <b>Uuq</b> Ununquadium (289)	115 <b>Uup</b> Ununpentium (288)	116 <b>Uuh</b> Ununhexium (292)	117 <b>Uus</b> Ununseptium	118 <b>Uuo</b> Ununoctium (294)		

- C** Solid
- Hg** Liquid
- H** Gas
- Rf** Unknown

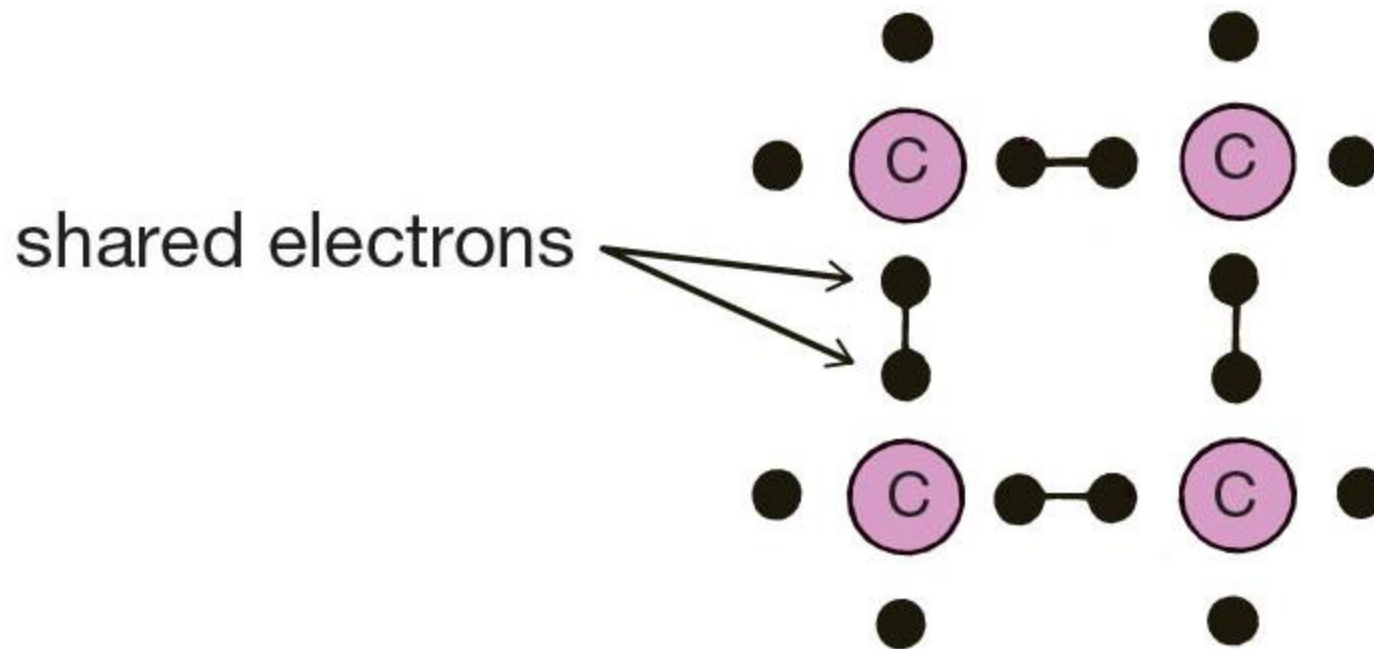


For elements with no stable isotopes, the mass number of the isotope with the longest half-life is in parentheses.

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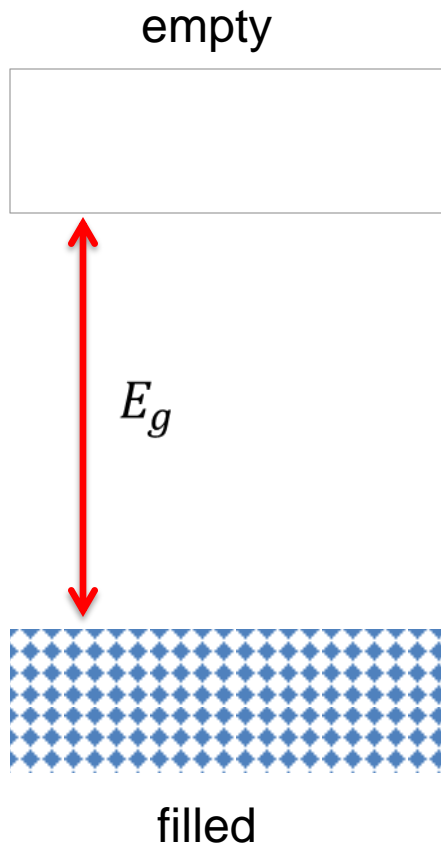
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# Covalent Bonding

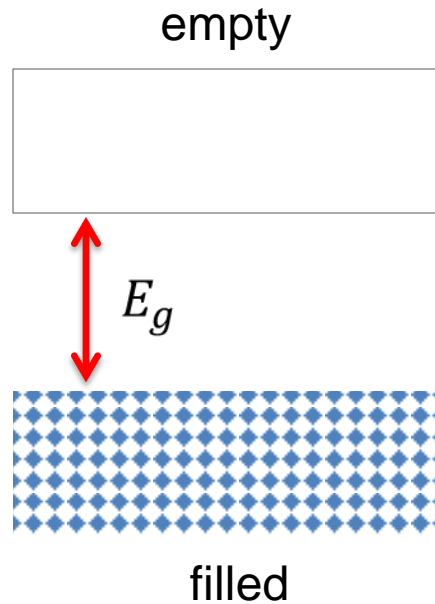


# Behavioral Classification

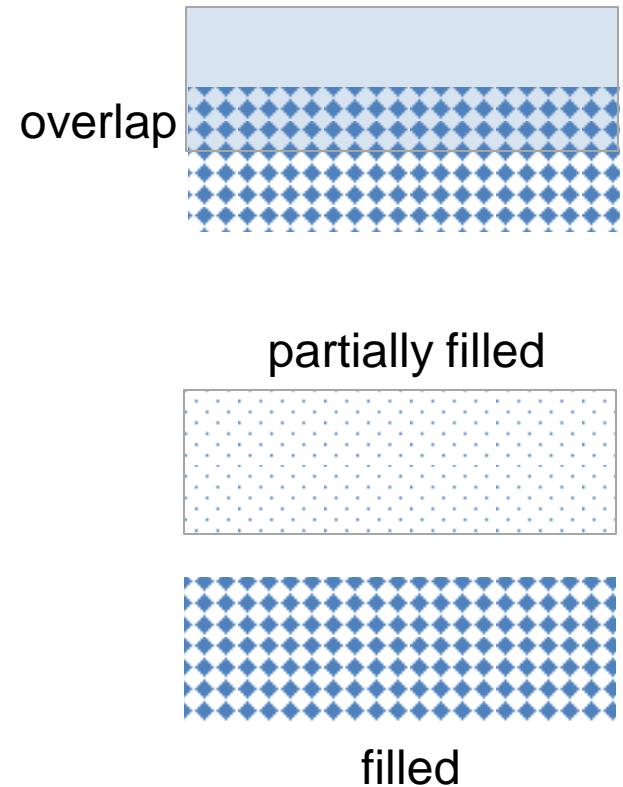
insulator



semiconductor



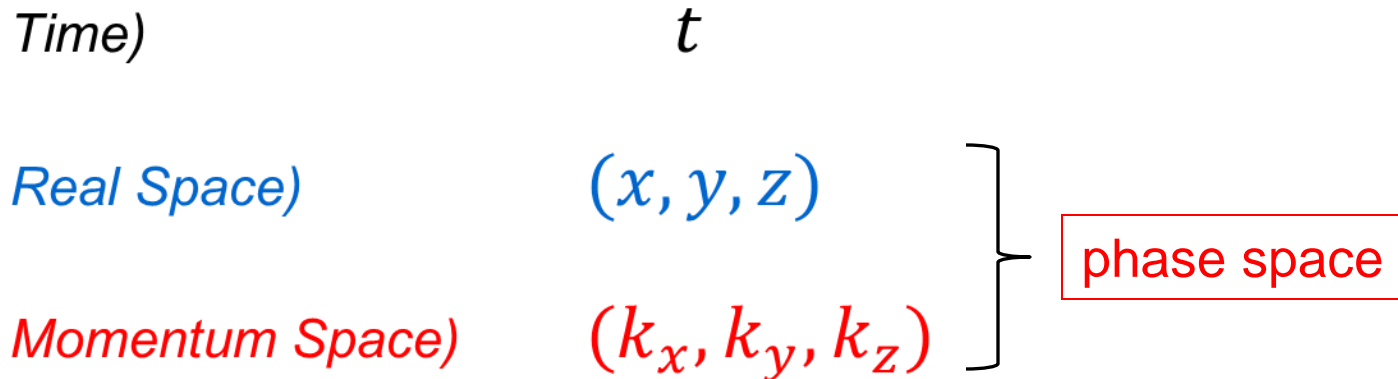
metal



$T = 0\text{ K}$

# Phase Space

Dynamics of electrons is studied in a generalized system of coordinates:



The kinetic energy state of the particle is given by a function

$$E = f(k_x, k_y, k_z)$$

This is usually known as “band structure”.

As we have seen, energy in a crystal is a multi-valued function, so the band structure has many branches.



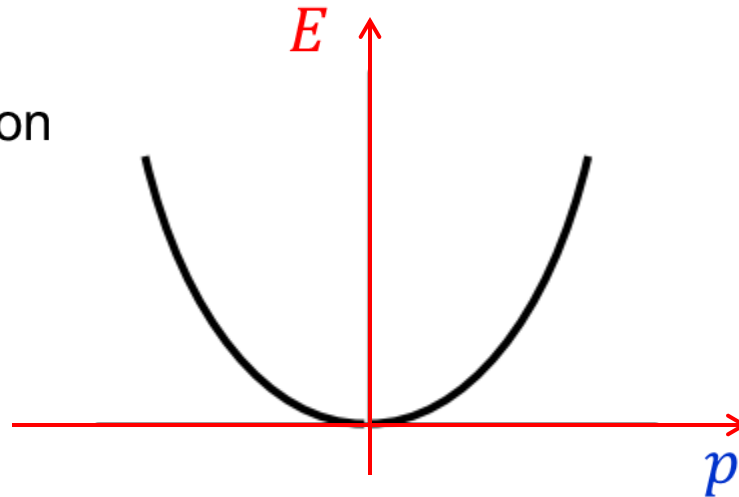
# Classical particle

For a classical particle in **free space** there is only a single value of energy for each set of momentum coordinates.

$$E = \frac{1}{2}mv^2$$

Momentum is defined as  $p = mv \rightarrow E = \frac{p^2}{2m}$

This is a simple parabolic relation



# Quantum mechanical particle

For a quantum mechanical particle described by the Schrödinger equation inside a crystal, we define a new “crystal” momentum

$$\langle p \rangle = \hbar k$$

Here  $k$  is the wave number of the wave describing the particle quantum-mechanically and for convenience it is used most often as momentum coordinate.

# Quantum mechanical particle

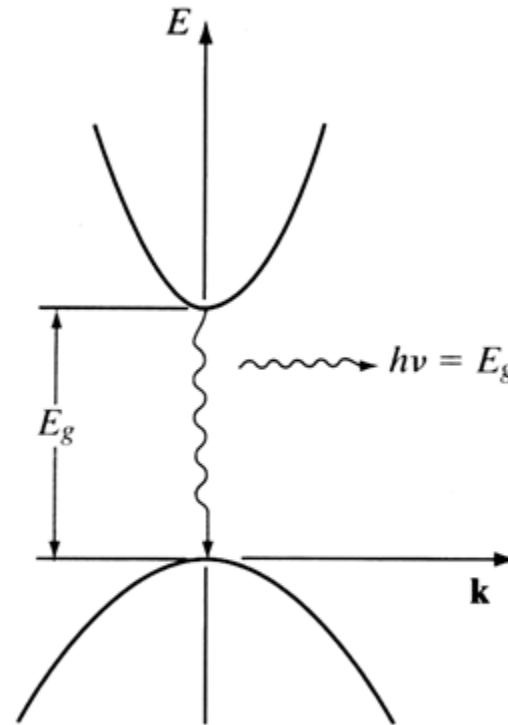
We model the crystal as a new kind of “free space” where the particles obey a new energy-momentum relationship given by the band structure, containing the effects of the periodic atomic potentials.

Therefore, what we study is not an electron “particle” as in an isolated atom or in vacuum, but an electron “quasi-particle” which obeys special dynamic laws as dictated by the specific crystal in which it moves.

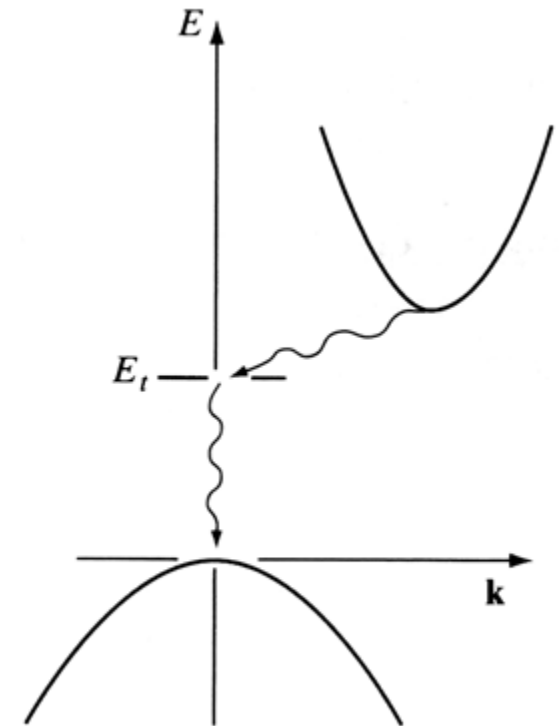
# Simple examples of band structure

Lowest energy solution in the conduction band

Highest energy solution in the valence band



(a) Direct

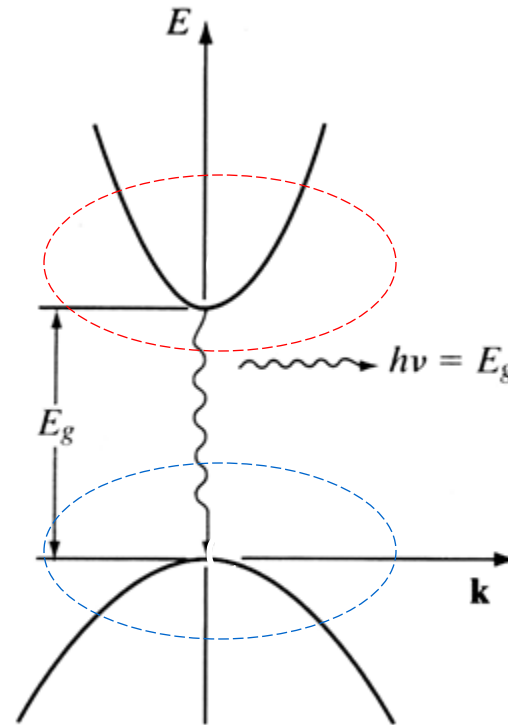


(b) Indirect

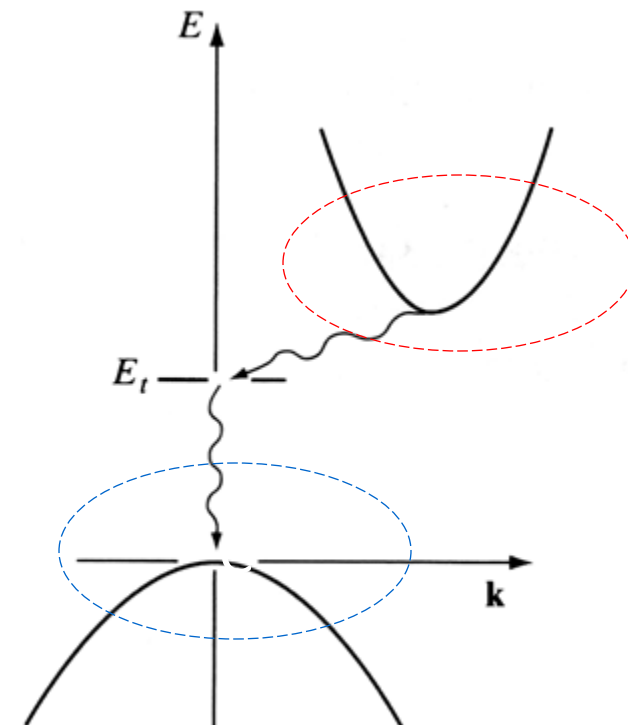
# Simple examples of band structure

Often it is sufficient to analyze conduction band behavior only in the region close to the minimum of the lowest energy branch, called a “valley”.

In many cases the  $E(k)$  relations in the valleys are with good approximation parabolic



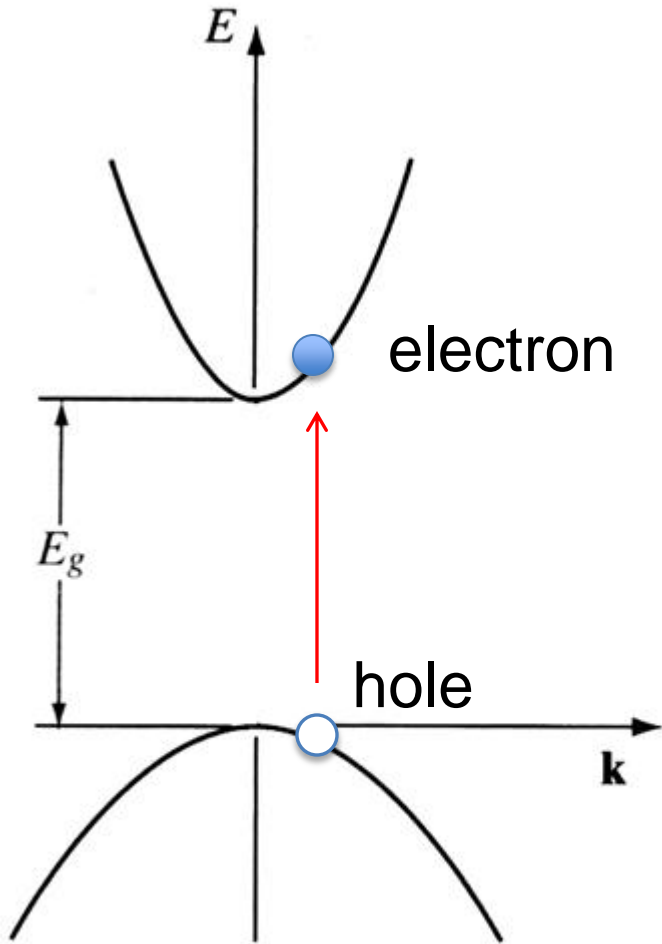
(a) Direct



(b) Indirect

Often it is sufficient to analyze valence band behavior only in the region close to the maximum of the highest energy branch, also called a “valley”.

# Simple examples of band structure

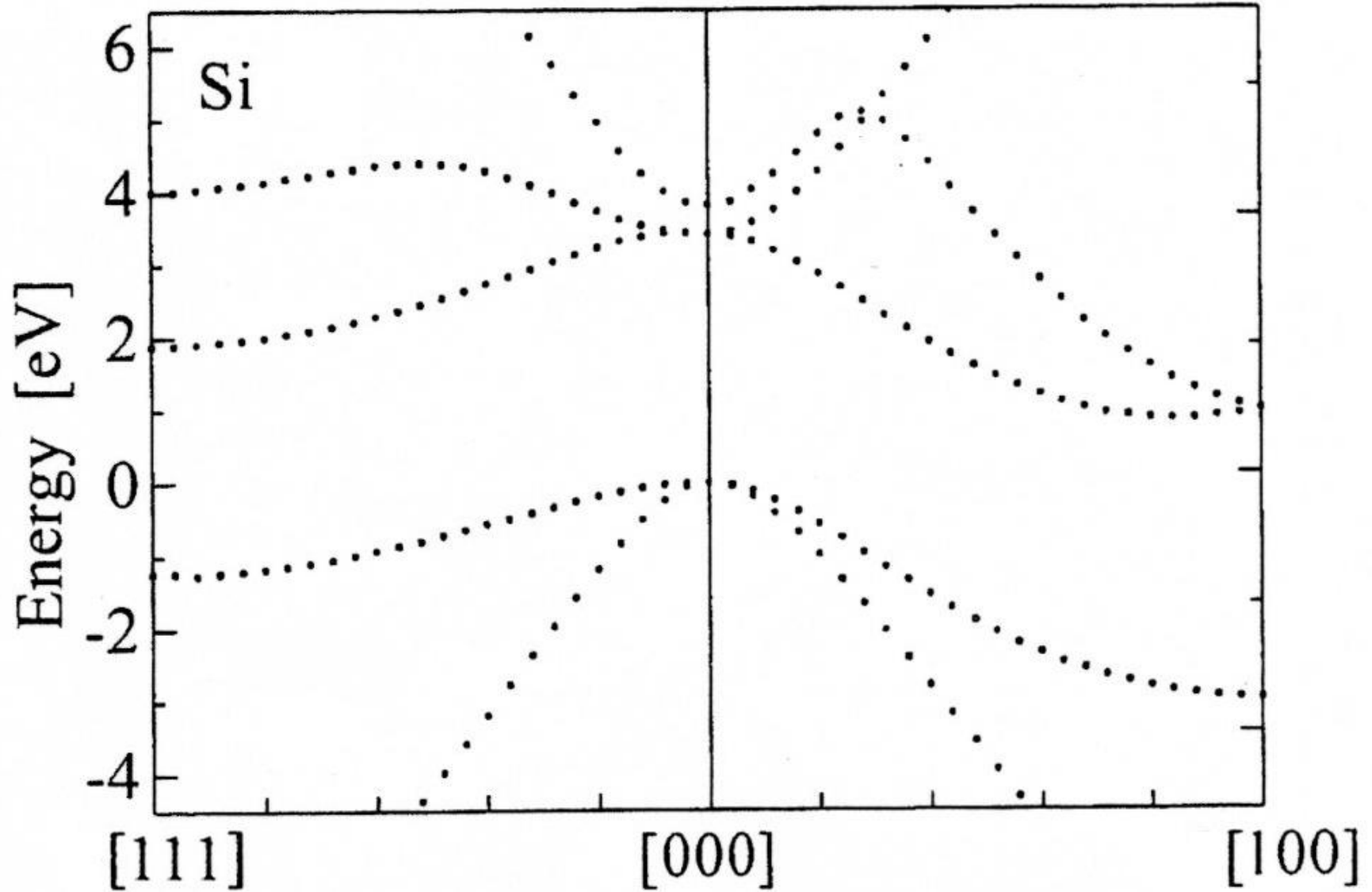


(a) Direct

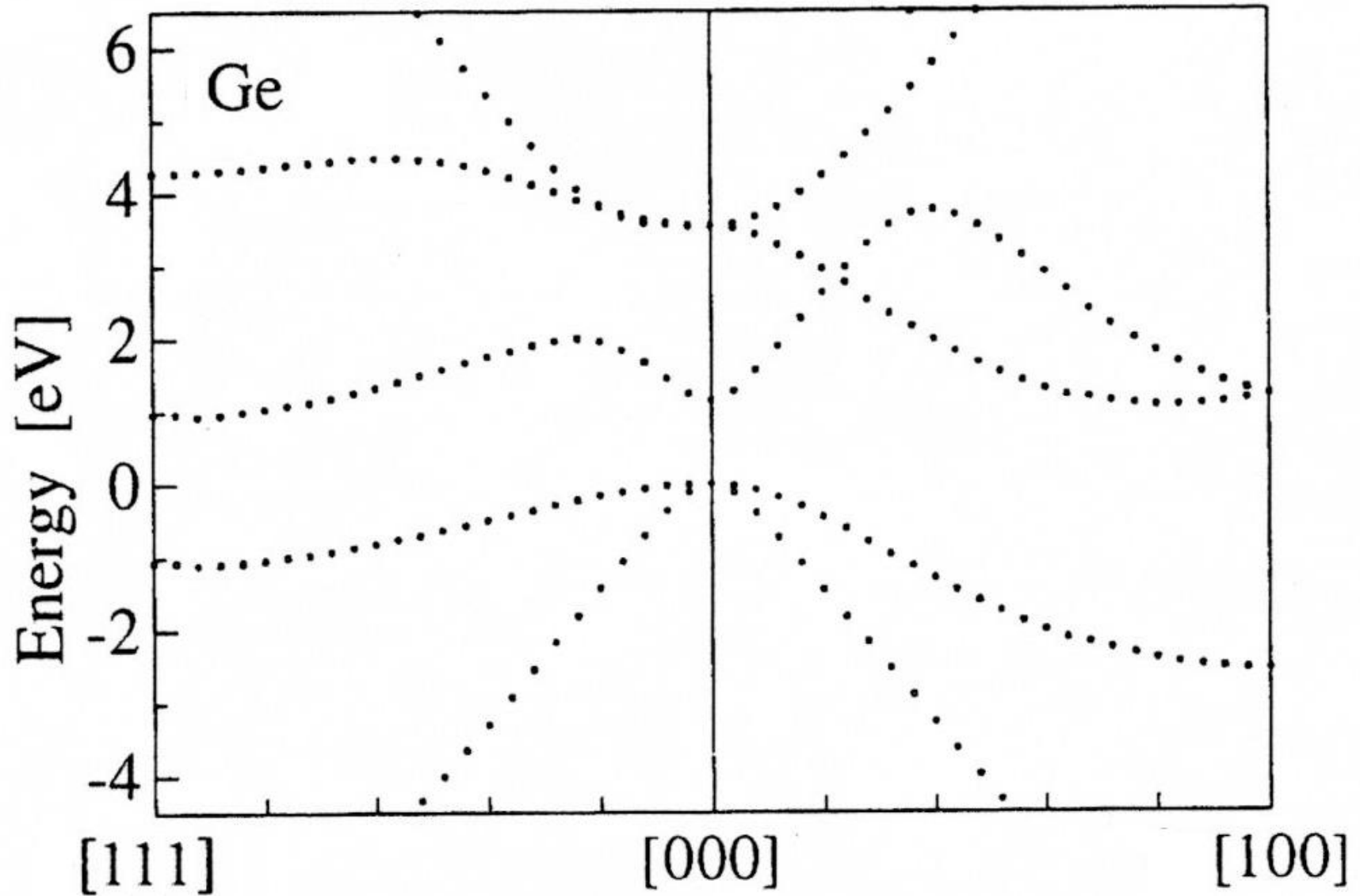
At finite temperature, electrons have the probability to acquire sufficient thermal energy to be excited to the conduction band.

An empty state is left behind, which essentially behaves like a positive “quasi-particle” (hole) moving when neighboring valence electron jump into that empty space leaving another one behind

# Direct or indirect?

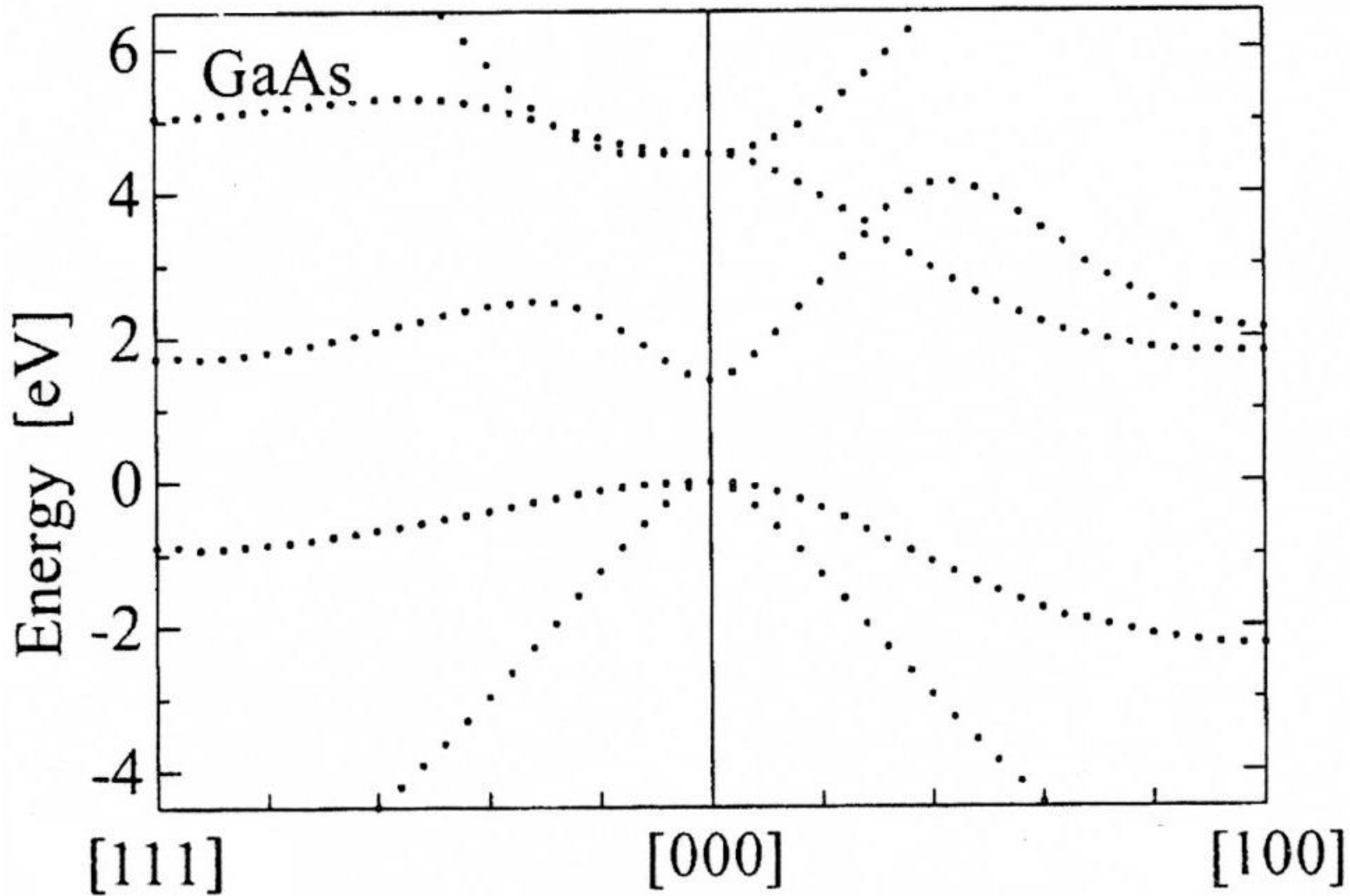


# Direct or indirect?





# Direct or indirect?



# Semiconductor Material Properties

		$E_g$ (eV)	$\mu_n$ ( $\text{cm}^2/\text{V-s}$ )	$\mu_p$ ( $\text{cm}^2/\text{V-s}$ )	$m_n^*/m_0$ ( $m_l, m_t$ )	$m_p^*/m_0$ ( $m_{lh}, m_{hh}$ )	$a$ (Å)	$\epsilon_r$	Density ( $\text{g}/\text{cm}^3$ )	Melting point (°C)
Si	(i/D)	1.11	1350	480	0.98, 0.19	0.16, 0.49	5.43	11.8	2.33	1415
Ge	(i/D)	0.67	3900	1900	1.64, 0.082	0.04, 0.28	5.65	16	5.32	936
SiC ( $\alpha$ )	(i/W)	2.86	500	—	0.6	1.0	3.08	10.2	3.21	2830
AlP	(i/Z)	2.45	80	—	—	0.2, 0.63	5.46	9.8	2.40	2000
AlAs	(i/Z)	2.16	1200	420	2.0	0.15, 0.76	5.66	10.9	3.60	1740
AlSb	(i/Z)	1.6	200	300	0.12	0.98	6.14	11	4.26	1080
GaP	(i/Z)	2.26	300	150	1.12, 0.22	0.14, 0.79	5.45	11.1	4.13	1467
GaAs	(d/Z)	1.43	8500	400	0.067	0.074, 0.50	5.65	13.2	5.31	1238
GaN	(d/Z, W)	3.4	380	—	0.19	0.60	4.5	12.2	6.1	2530
GaSb	(d/Z)	0.7	5000	1000	0.042	0.06, 0.23	6.09	15.7	5.61	712
InP	(d/Z)	1.35	4000	100	0.077	0.089, 0.85	5.87	12.4	4.79	1070
InAs	(d/Z)	0.36	22600	200	0.023	0.025, 0.41	6.06	14.6	5.67	943
InSb	(d/Z)	0.18	$10^5$	1700	0.014	0.015, 0.40	6.48	17.7	5.78	525
ZnS	(d/Z, W)	3.6	180	10	0.28	—	5.409	8.9	4.09	1650*
ZnSe	(d/Z)	2.7	600	28	0.14	0.60	5.671	9.2	5.65	1100*
ZnTe	(d/Z)	2.25	530	100	0.18	0.65	6.101	10.4	5.51	1238*
CdS	(d/W, Z)	2.42	250	15	0.21	0.80	4.137	8.9	4.82	1475
CdSe	(d/W)	1.73	800	—	0.13	0.45	4.30	10.2	5.81	1258
CdTe	(d/Z)	1.58	1050	100	0.10	0.37	6.482	10.2	6.20	1098
PbS	(i/H)	0.37	575	200	0.22	0.29	5.936	17.0	7.6	1119
PbSe	(i/H)	0.27	1500	1500	—	—	6.147	23.6	8.73	1081
PbTe	(i/H)	0.29	6000	4000	0.17	0.20	6.452	30	8.16	925

C (diamond)  
 $E_g = 5.5\text{eV}$

SiO<sub>2</sub>  
 $E_g = 9.0\text{eV}$

All values at 300 K.

\*Vaporizes