

Digital Integrated Circuit Design  
CMPE 530/630

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# Semiconductor Basics

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# What Should We Build Our Chips Out Of?

1  
IA  
1A  
H  
Hydrogen  
1.008  
-252.762

2  
IIA  
2A  
Be  
Beryllium  
9.012  
2471

3  
Li  
Lithium  
6.941  
1342

4  
B  
Boron  
10.811  
4000

5  
Al  
Aluminum  
26.982  
2519

6  
C  
Carbon  
12.011  
graphite 3825 SP  
diamond 4097

7  
N  
Nitrogen  
14.007  
-195.798

8  
O  
Oxygen  
15.999  
-182.953

9  
F  
Fluorine  
18.998  
-188.12

10  
Ne  
Neon  
20.180  
-246.053

11  
Na  
Sodium  
22.990  
882.940

12  
Mg  
Magnesium  
24.305  
1090

13  
III A  
3A  
Al  
Aluminum  
26.982  
2519

14  
IV A  
4A  
Si  
Silicon  
28.086  
3265

15  
V A  
5A  
P  
Phosphorus  
30.974  
white 280.5  
red 280.5

16  
VI A  
6A  
S  
Sulfur  
32.066  
444.61

17  
VII A  
7A  
Cl  
Chlorine  
35.453  
-101.5

18  
VIII A  
8A  
Ar  
Argon  
39.948  
-185.847

19  
K  
Potassium  
39.098  
759

20  
Ca  
Calcium  
40.078  
1484

21  
Sc  
Scandium  
44.956  
2836

22  
Ti  
Titanium  
47.88  
3287

23  
V  
Vanadium  
50.942  
3407

24  
Cr  
Chromium  
51.996  
2671

25  
Mn  
Manganese  
54.938  
2061

26  
Fe  
Iron  
55.933  
2861

27  
Co  
Cobalt  
58.933  
2927

28  
Ni  
Nickel  
58.693  
2913

29  
Cu  
Copper  
63.546  
2562

30  
Zn  
Zinc  
65.39  
907

31  
Ga  
Gallium  
69.723  
2204

32  
Ge  
Germanium  
72.61  
2833

33  
As  
Arsenic  
74.922  
616 SP

34  
Se  
Selenium  
78.972  
685

35  
Br  
Bromine  
79.904  
58.8

36  
Kr  
Krypton  
84.80  
-153.34

37  
Rb  
Rubidium  
84.468  
688

38  
Sr  
Strontium  
87.62  
1382

39  
Y  
Yttrium  
88.906  
3345

40  
Zr  
Zirconium  
91.224  
4409

41  
Nb  
Niobium  
92.906  
4744

42  
Mo  
Molybdenum  
95.95  
4639

43  
Tc  
Technetium  
98.907  
4265

44  
Ru  
Ruthenium  
101.07  
4150

45  
Rh  
Rhodium  
102.906  
3695

46  
Pd  
Palladium  
106.42  
2963

47  
Ag  
Silver  
107.868  
2162

48  
Cd  
Cadmium  
112.411  
767

49  
In  
Indium  
114.818  
2072

50  
Sn  
Tin  
118.71  
2602

51  
Sb  
Antimony  
121.760  
1587

52  
Te  
Tellurium  
127.6  
988

53  
I  
Iodine  
126.904  
184.4

54  
Xe  
Xenon  
131.29  
-108.09

55  
Cs  
Cesium  
132.905  
671

56  
Ba  
Barium  
137.327  
1897

57-71  
Lanthanide Series

72  
Hf  
Hafnium  
178.49  
4603

73  
Ta  
Tantalum  
180.948  
5458

74  
W  
Tungsten  
183.85  
5555

75  
Re  
Rhenium  
186.207  
5596

76  
Os  
Osmium  
190.23  
5012

77  
Ir  
Iridium  
192.22  
4428

78  
Pt  
Platinum  
195.08  
3825

79  
Au  
Gold  
196.967  
2856

80  
Hg  
Mercury  
200.59  
356.62

81  
Tl  
Thallium  
204.383  
1473

82  
Pb  
Lead  
207.2  
1749

83  
Bi  
Bismuth  
208.980  
1564

84  
Po  
Polonium  
[209]  
962

85  
At  
Astatine  
209.987  
337

86  
Rn  
Radon  
222.018  
-61.7

87  
Fr  
Francium  
223.020  
677

88  
Ra  
Radium  
226.025  
1737

89-103  
Actinide Series

104  
Rf  
Rutherfordium  
[261]  
unknown

105  
Db  
Dubnium  
[262]  
unknown

106  
Sg  
Seaborgium  
[266]  
unknown

107  
Bh  
Bohrium  
[264]  
unknown

108  
Hs  
Hassium  
[269]  
unknown

109  
Mt  
Meitnerium  
[268]  
unknown

110  
Ds  
Darmstadtium  
[271]  
unknown

111  
Rg  
Roentgenium  
[272]  
unknown

112  
Cn  
Copernicium  
[277]  
unknown

113  
Uut  
Ununtrium  
[278]  
unknown

114  
Fl  
Flerovium  
[279]  
unknown

115  
Uup  
Ununpentium  
[285]  
unknown

116  
Lv  
Livermorium  
[289]  
unknown

117  
Uus  
Ununseptium  
[294]  
unknown

118  
Uuo  
Ununoctium  
[294]  
unknown

57  
La  
Lanthanum  
138.905  
3464

58  
Ce  
Cerium  
140.115  
3443

59  
Pr  
Praseodymium  
140.908  
3520

60  
Nd  
Neodymium  
144.24  
3074

61  
Pm  
Promethium  
144.913  
3000

62  
Sm  
Samarium  
150.36  
1794

63  
Eu  
Europium  
151.966  
1529

64  
Gd  
Gadolinium  
157.25  
3273

65  
Tb  
Terbium  
158.925  
3230

66  
Dy  
Dysprosium  
162.50  
2567

67  
Ho  
Holmium  
164.930  
2700

68  
Er  
Erbium  
167.26  
2868

69  
Tm  
Thulium  
168.934  
1950

70  
Yb  
Ytterbium  
173.04  
1196

71  
Lu  
Lutetium  
174.967  
3402

89  
Ac  
Actinium  
227.028  
3198

90  
Th  
Thorium  
232.038  
4783

91  
Pa  
Protactinium  
231.036  
4027

92  
U  
Uranium  
238.029  
4131

93  
Np  
Neptunium  
237.048  
4174

94  
Pu  
Plutonium  
244.064  
3228

95  
Am  
Americium  
243.061  
2011

96  
Cm  
Curium  
247.070  
3100

97  
Bk  
Berkelium  
247.070  
2627

98  
Cf  
Californium  
251.080  
unknown

99  
Es  
Einsteinium  
[254]  
unknown

100  
Fm  
Fermium  
257.095  
unknown

101  
Md  
Mendelevium  
258.1  
unknown

102  
No  
Nobelium  
259.101  
unknown

103  
Lr  
Lawrencium  
[262]  
unknown

Atomic Number

Boiling Point

Symbol

Name

Atomic Mass

Normal boiling points are in °C.  
SP = Triple Point  
Pressure is listed if not 1 atm.  
Allotrope is listed if more than one allotrope.

Alkali Metal

Alkaline Earth

Transition Metal

Basic Metal

Semimetal

Nonmetal

Halogen

Noble Gas

Lanthanide

Actinide

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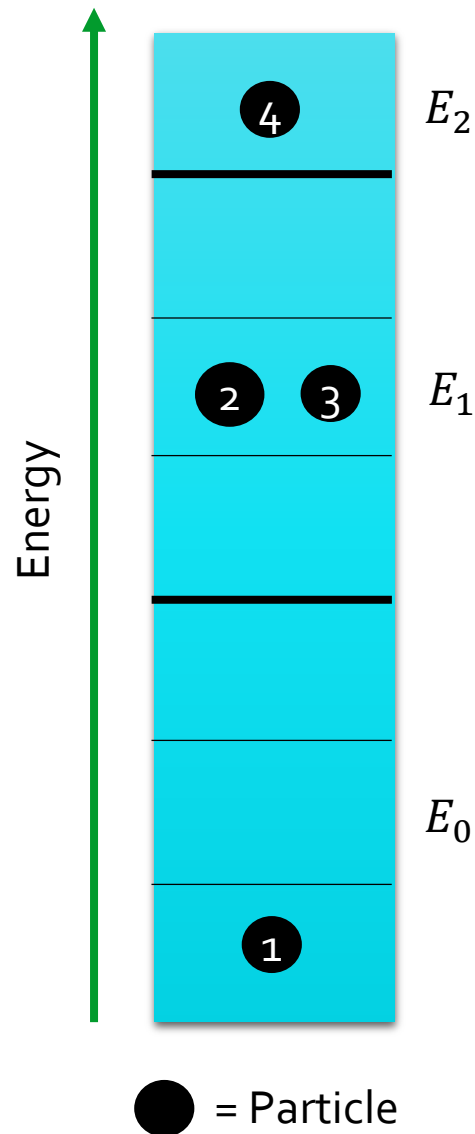
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# What is a Semiconductor?

- » You've probably heard:
  - "It's a material that conducts better than an insulator, but not as well as a metal."
- » This is true, but the full answer is much deeper
- » Wasn't until the development of **quantum mechanics** in early 20<sup>th</sup> century that people understood why some materials conduct better than others

# Quantum Statistics



» What is the distribution of particles among the different energy states in a material?

» Boltzmann statistics

- Particles are distinguishable
- Multiple particles per state allowed

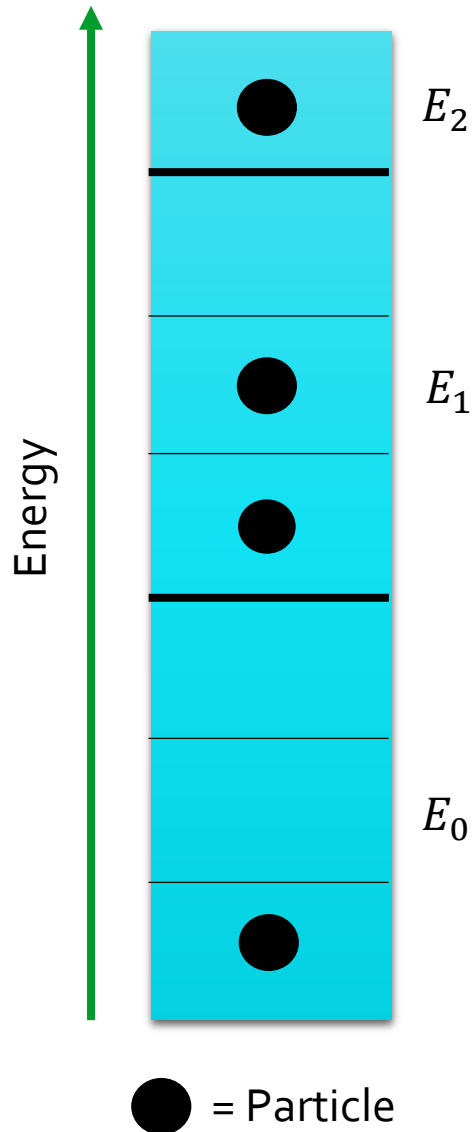
» Fermi-Dirac statistics

- Particles are indistinguishable
- Only one particle per state

» Bose-Einstein statistics

- Particles are indistinguishable
- Multiple particles per state allowed

# Quantum Statistics



» Electrons and holes follow Fermi-Dirac statistics

» Number of ways to arrange the particles is

$$W = \frac{7!}{4! (7 - 4)!} = 35$$

» In general

$$W = \prod_{i=0}^{\infty} \frac{g_i!}{N_i! (g_i - N_i)!}$$

# of states at level  $i$       # of particles at level  $i$

# Quantum Statistics

» What is the most probable distribution of particles?

$$\max \ln W \text{ subject to } \sum_{i=0}^{\infty} N_i = N, \sum_{s=0}^{\infty} N_i E_s = E$$

» Solve using the method of Lagrange multipliers:

$$\max f(\mathbf{x}) \text{ subject to } c_1(\mathbf{x}), = 0 \ c_2(\mathbf{x}), = 0 \ \dots, c_m(\mathbf{x}) = 0$$

↓  
Vector of  $n$   
unknowns

$$\mathcal{L}(\mathbf{x}, \boldsymbol{\lambda}) = f(\mathbf{x}) + \sum_{k=1}^m \lambda_k c_k(\mathbf{x})$$

# Quantum Statistics

$$\nabla \mathcal{L} = \mathbf{0} \quad \rightarrow \quad \frac{\partial f}{\partial x_i} - \sum_{k=1}^m \lambda_k \frac{\partial c_k}{\partial x_i} = 0, \forall i = 1, 2, \dots, n$$
$$c_k(\mathbf{x}) = 0, \forall k = 1, 2, \dots, m$$

»  $n + m$  equations in  $n + m$  unknowns

» For our problem:

$$f = \ln(W)$$

$$c_1 = \sum_{s=1}^{\infty} N_s - N \quad c_2 = \sum_{s=1}^{\infty} N_s E_s - U$$

# Quantum Statistics

» Our gradients become

$$\frac{\partial \ln W}{\partial N_j} \approx -\ln N_j + \ln(g_j - N_j)$$

$$\frac{\partial c_1}{\partial N_j} = 1, \quad \frac{\partial c_2}{\partial N_j} = E_j$$

» Putting it all together:

$$\ln\left(\frac{g_j}{N_j} - 1\right) = -\alpha - \beta E_j \quad \Rightarrow \quad \frac{N_j}{g_j} = f(E_j) = \frac{1}{1 + e^{-\alpha - \beta E_j}}$$

$\downarrow$                        $\downarrow$   
 $\alpha$  and  $\beta$  are our  $\lambda_1$   
and  $\lambda_2$



## Quantum Statistics

- » Using the ideal gas law and the Maxwell-Boltzmann distribution, the multipliers  $\alpha$  and  $\beta$  can be shown to be

Fermi energy  
↓

$$\alpha = \frac{E_f}{kT} \qquad \beta = -\frac{1}{kT}$$

So,

$$f(E) = \frac{1}{1 + e^{(E-E_f)/kT}}$$

Fermi-Dirac Distribution Function

## Fermi Energy

- » Note that  $E_f$ , by definition, is the energy level of the highest occupied energy level of the system at  $T = 0$
- » Equivalently,  $E_f$  is the energy level at which there is a 50/50 chance that a state is occupied

# Band Theory of Solids

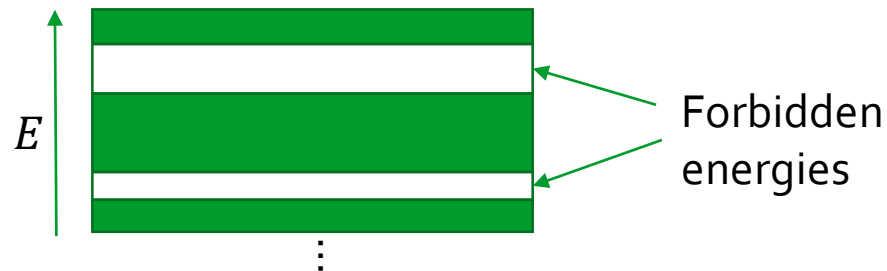
- » Quantum mechanics is governed by the Schrodinger Equation, which describes the probability of particles being in particular energy states
- » The 1-dimensional time-independent Schrodinger Equation:

$$\frac{d^2\psi(x)}{dx^2} + \frac{2m}{\hbar^2} [E - V(x)]\psi(x) = 0$$

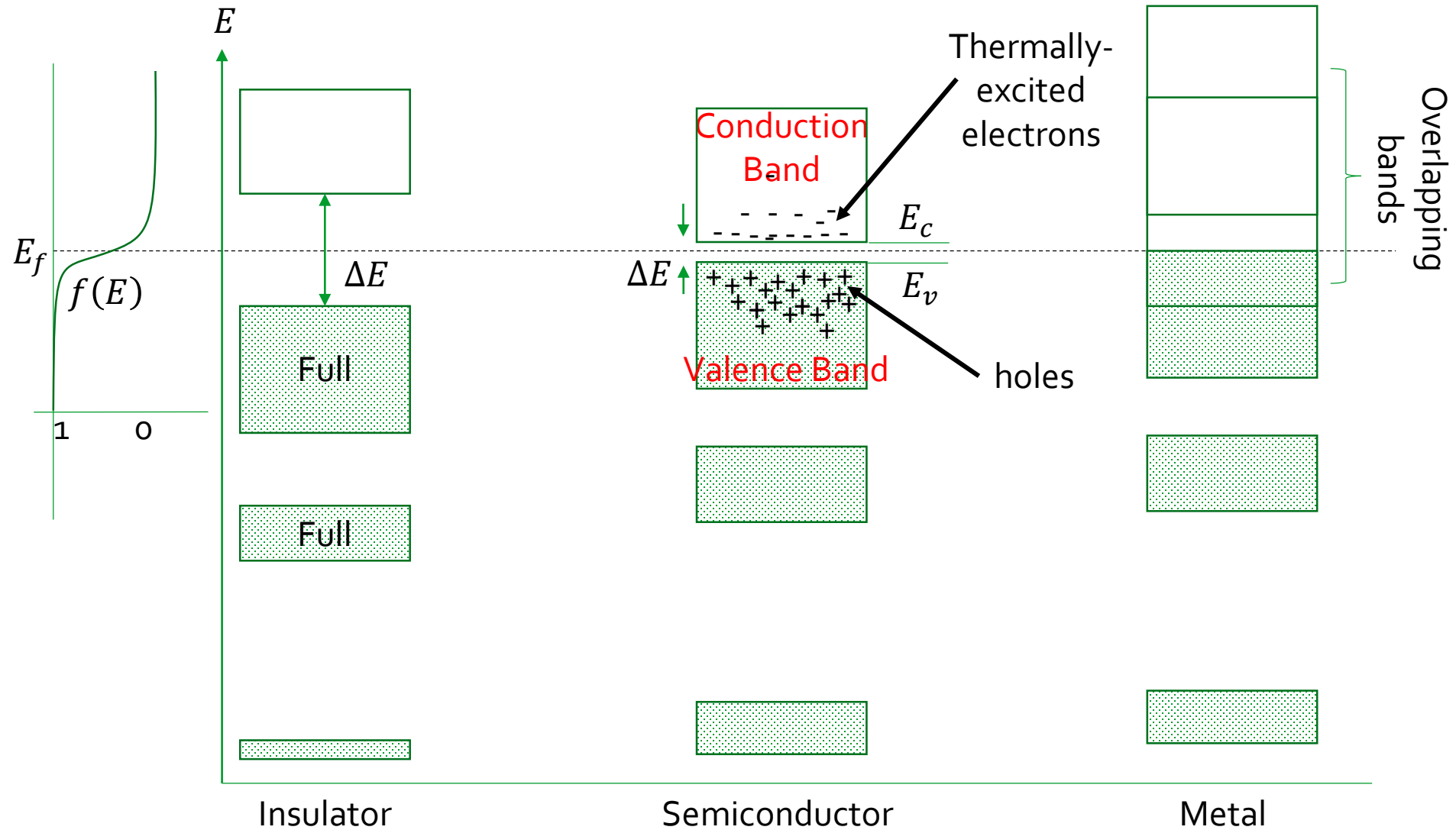
- $\psi$  – Wave function
- $m$  – Particle mass
- $E$  – Total energy
- $V$  – Potential energy

# Band Theory of Solids in 1 Slide

- » Suppose  $V(x)$  is a periodic function  $u(x) = u(x + a)$ 
  - $a$  is the period of  $u$
- » By the Bloch Theorem, the solution of the Schrodinger equation is:
$$\psi(x) = e^{ikx}u(x)$$
- » In a crystalline solid,  $u$  is a square wave with peaks occurring at atomic nuclei
- » Solving the Schrodinger equation using the Bloch Theorem with  $u$  equal to a square wave reveals bands of energy where no quantum states exist:



# Insulators, Metals, Semiconductors



# Carrier Statistics of Semiconductors

» Two types of carriers:

- Electrons (n) – Excited into conductance band by thermal energy or applied electric field
- Holes (p) – Available electron state in valence band – “left behind” by excited electron

» Concentration of electrons in conduction band is

$$n_0 = \int_{E_c}^{\infty} f(E)g(E)dE = c_n e^{-(E_c - E_f)/kT}$$

where  $c_n$  is a messy temperature-dependent term

» Similarly:  $p_0 = c_p e^{-(E_f - E_v)/kT}$

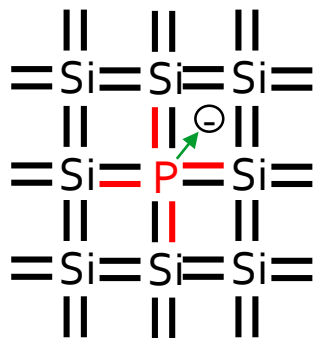
» For *intrinsic* (pure) semiconductors:  $n_0 = p_0 \equiv n_i$

# Extrinsic Semiconductors

- » Carrier concentrations of intrinsic semiconductors is too small to make good electronics
- » Idea: Add dopants that can produce more carriers

## n-type silicon:

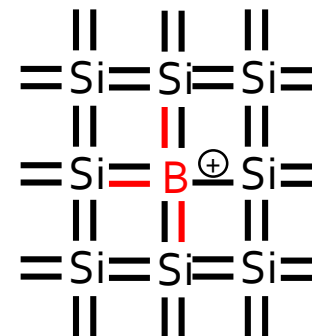
- Doped with donor atoms
- “Donate free electrons”
- $n_0 \approx N_D$
- $n_0 p_0 = n_i^2 \rightarrow p_0 \approx \frac{n_i^2}{N_D}$



Periodic table showing elements grouped by columns (I to VIII) and rows (1 to 6). A red circle highlights the elements Phosphorus (P), Arsenic (As), and Antimony (Sb), which are donor atoms for n-type semiconductors.

## p-type silicon:

- Doped with acceptor atoms
- “Accept free electrons”
- Creates holes
- $p_0 \approx N_A$
- $n_0 p_0 = n_i^2 \rightarrow n_0 \approx \frac{n_i^2}{N_A}$



Periodic table showing elements grouped by columns (I to VIII) and rows (1 to 6). A red circle highlights the elements Boron (B), Carbon (C), Nitrogen (N), Phosphorus (P), Sulfur (S), Chlorine (Cl), and Argon (Ar), which are acceptor atoms for p-type semiconductors.

- » Sometimes superscripts are used to denote relative dopant concentration (e.g.  $n^+$  for highly-doped n-type,  $p^-$  for lightly-doped p-type, etc.)

## So, Why Use Semiconductors?

- » Easy to manipulate properties through doping
- » Easy to control conductivity using electric fields
- » Why Si?
  - Forms good oxide ( $\text{SiO}_2$ ), which is critical to insulate/isolate devices and useful during fabrication process



# Debye Length