

ECE 3030

Physical Foundations of Computer Engineering

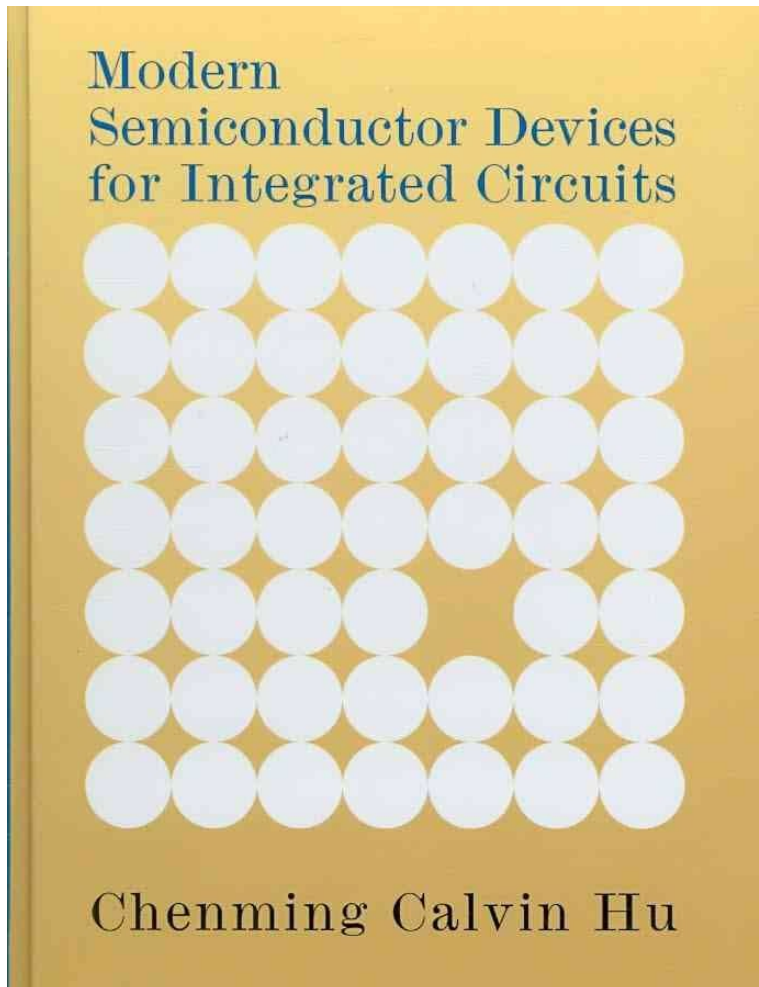
Physics of Semiconductors (Bond Model)

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Reference



Modern Semiconductor Devices for Integrated Circuits

Chapter 1: Section 1.2

Resources

Recorded lecture available at: <https://youtu.be/NKPeZBMX6Dw>

Physics of Semiconductors

Intel Broadwell 14 nm node, 2014

Metal

Oxide

Semiconductor

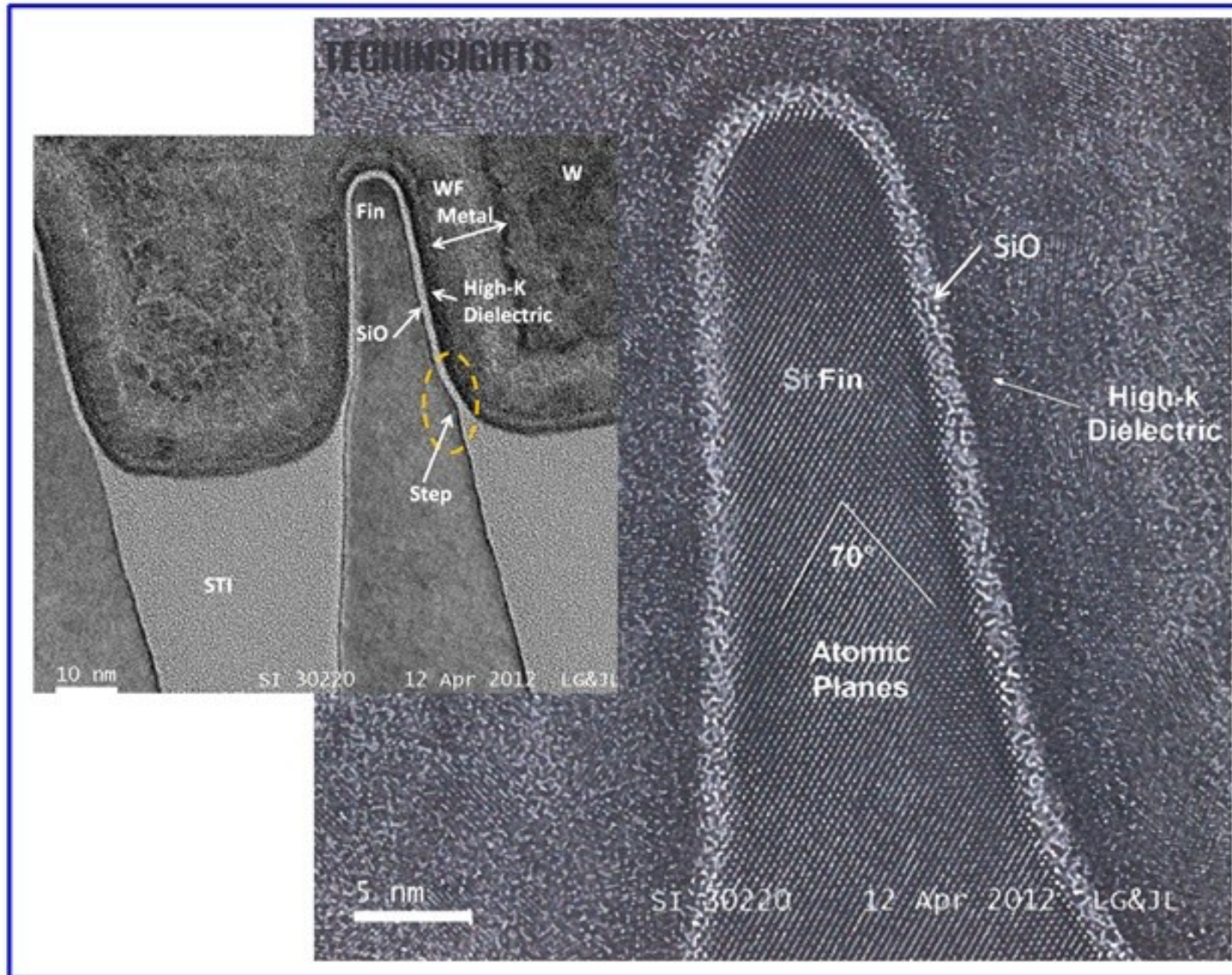
chipworks

MOSFET

http://electroi.com/chipworks_real_chips_blog/2014/

<http://www.extremetech.com/computing/193200-intels-14nm-broadwell-chip-reverse-engineered-reveals-impressive-finfets-13-layer-design>

Physics of Semiconductors



Physics of Semiconductors

Periodic Table of the Elements

1 H Hydrogen 1.01																	2 He Helium 4.00
3 Li Lithium 6.94	4 Be Beryllium 9.01											5 B Boron 10.81	6 C Carbon 12.01	7 N Nitrogen 14.01	8 O Oxygen 16.00	9 F Fluorine 19.00	10 Ne Neon 20.18
11 Na Sodium 22.99	12 Mg Magnesium 24.31											13 Al Aluminum 26.98	14 Si Silicon 28.09	15 P Phosphorus 30.97	16 S Sulfur 32.06	17 Cl Chlorine 35.45	18 Ar Argon 39.95
19 K Potassium 39.10	20 Ca Calcium 40.08	21 Sc Scandium 44.96	22 Ti Titanium 47.88	23 V Vanadium 50.94	24 Cr Chromium 51.99	25 Mn Manganese 54.94	26 Fe Iron 55.93	27 Co Cobalt 58.93	28 Ni Nickel 58.69	29 Cu Copper 63.55	30 Zn Zinc 65.39	31 Ga Gallium 69.73	32 Ge Germanium 72.61	33 As Arsenic 74.92	34 Se Selenium 78.09	35 Br Bromine 79.90	36 Kr Krypton 84.80
37 Rb Rubidium 84.49	38 Sr Strontium 87.62	39 Y Yttrium 88.91	40 Zr Zirconium 91.22	41 Nb Niobium 92.91	42 Mo Molybdenum 95.94	43 Tc Technetium 98.91	44 Ru Ruthenium 101.07	45 Rh Rhodium 102.91	46 Pd Palladium 106.42	47 Ag Silver 107.87	48 Cd Cadmium 112.41	49 In Indium 114.82	50 Sn Tin 118.71	51 Sb Antimony 121.76	52 Te Tellurium 127.6	53 I Iodine 126.90	54 Xe Xenon 131.29
55 Cs Cesium 132.91	56 Ba Barium 137.33	57-71 Lanthanides	72 Hf Hafnium 178.49	73 Ta Tantalum 180.95	74 W Tungsten 183.85	75 Re Rhenium 186.21	76 Os Osmium 190.23	77 Ir Iridium 192.22	78 Pt Platinum 195.08	79 Au Gold 196.97	80 Hg Mercury 200.59	81 Tl Thallium 204.38	82 Pb Lead 207.20	83 Bi Bismuth 208.98	84 Po Polonium [209]	85 At Astatine 209.98	86 Rn Radon 222.02
87 Fr Francium 223.02	88 Ra Radium 226.03	89-103 Actinides	104 Rf Rutherfordium [261]	105 Db Dubnium [262]	106 Sg Seaborgium [266]	107 Bh Bohrium [264]	108 Hs Hassium [269]	109 Mt Meitnerium [268]	110 Ds Darmstadtium [269]	111 Rg Roentgenium [272]	112 Cn Copernicium [277]	113 Uut Ununtrium unknown	114 Fl Flerovium [289]	115 Uup Ununpentium unknown	116 Lv Livermorium [293]	117 Uus Ununseptium unknown	118 Uuo Ununoctium unknown
57 La Lanthanum 138.91	58 Ce Cerium 140.12	59 Pr Praseodymium 140.91	60 Nd Neodymium 144.24	61 Pm Promethium 144.91	62 Sm Samarium 150.36	63 Eu Europium 151.97	64 Gd Gadolinium 157.25	65 Tb Terbium 158.93	66 Dy Dysprosium 162.50	67 Ho Holmium 164.93	68 Er Erbium 167.26	69 Tm Thulium 168.93	70 Yb Ytterbium 173.04	71 Lu Lutetium 174.97			
89 Ac Actinium 227.03	90 Th Thorium 232.04	91 Pa Protactinium 231.04	92 U Uranium 238.03	93 Np Neptunium 237.05	94 Pu Plutonium 244.06	95 Am Americium 243.06	96 Cm Curium 247.07	97 Bk Berkelium 247.07	98 Cf Californium 251.08	99 Es Einsteinium [254]	100 Fm Fermium 257.10	101 Md Mendelevium 258.10	102 No Nobelium 259.10	103 Lr Lawrencium [262]			

Alkali Metal

Alkaline Earth

Transition Metal

Basic Metal

Semimetal

Nonmetal

Halogen

Noble Gas

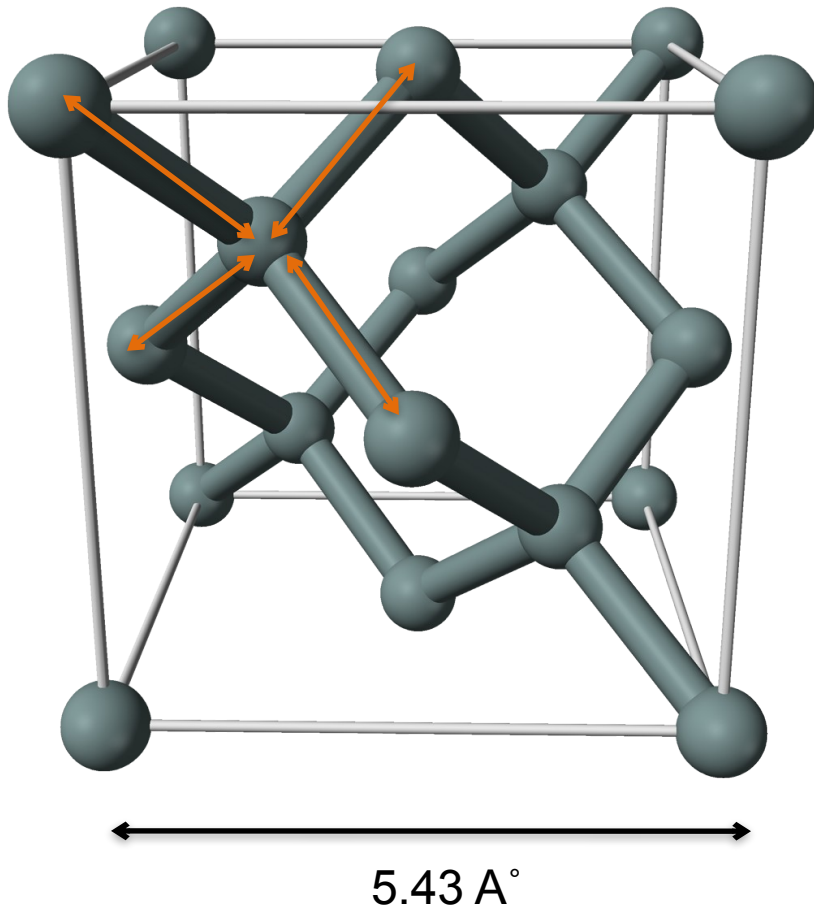
Lanthanide

Actinide

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Physics of Semiconductors

Si crystal structure



Each atom has 4 nearest neighbors

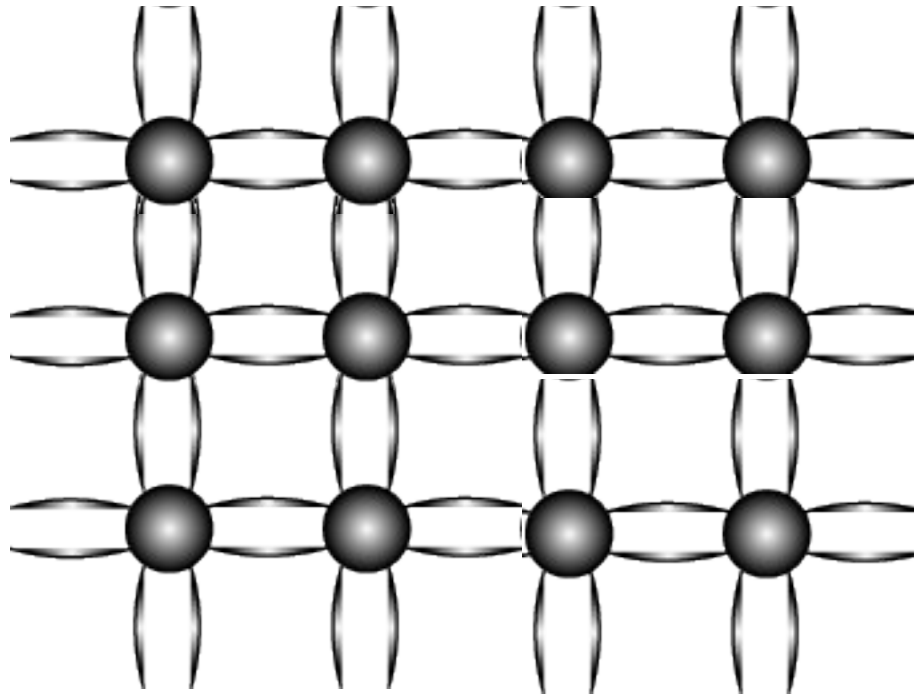


4 valence electrons

Each atom shares 2 electrons
with 4 nearest neighbors to form
a covalent bond

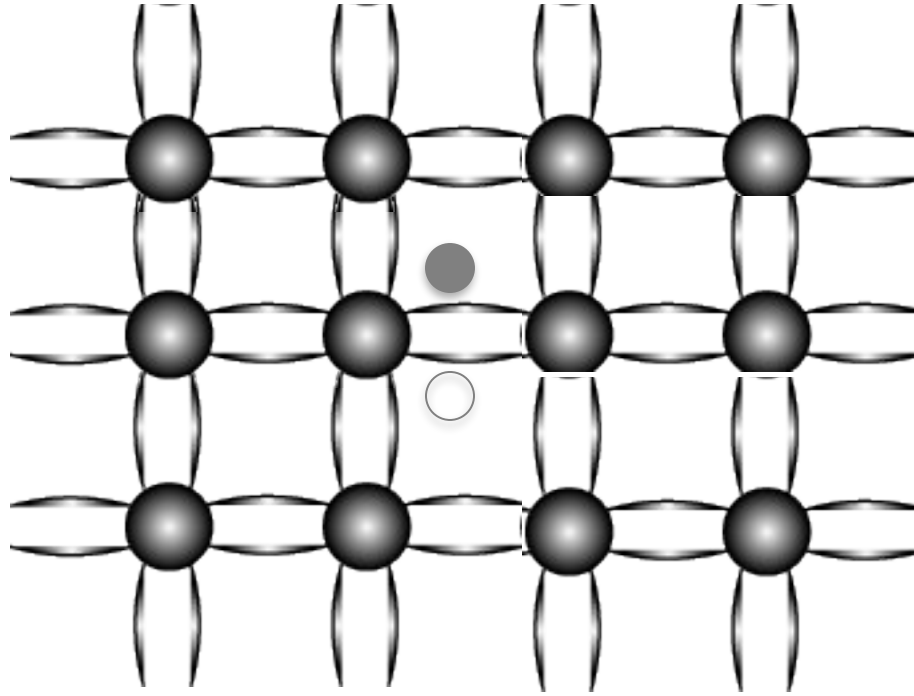
Intrinsic Si: The Bond Model

Each atom shares 2 electrons with 4 nearest neighbors to form a covalent bond



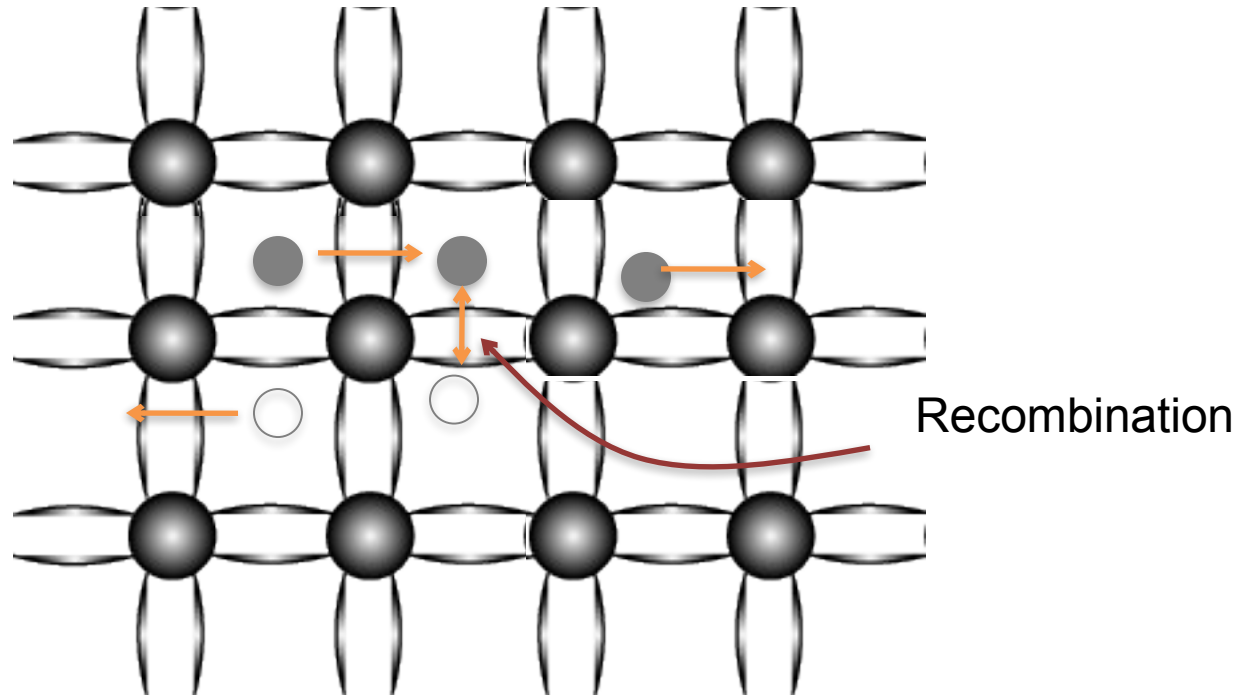
At $T=0\text{K}$, all bonds are satisfied, there are no free carriers, no current flows, looks like an insulator

Intrinsic Si: The Bond Model: Electrons



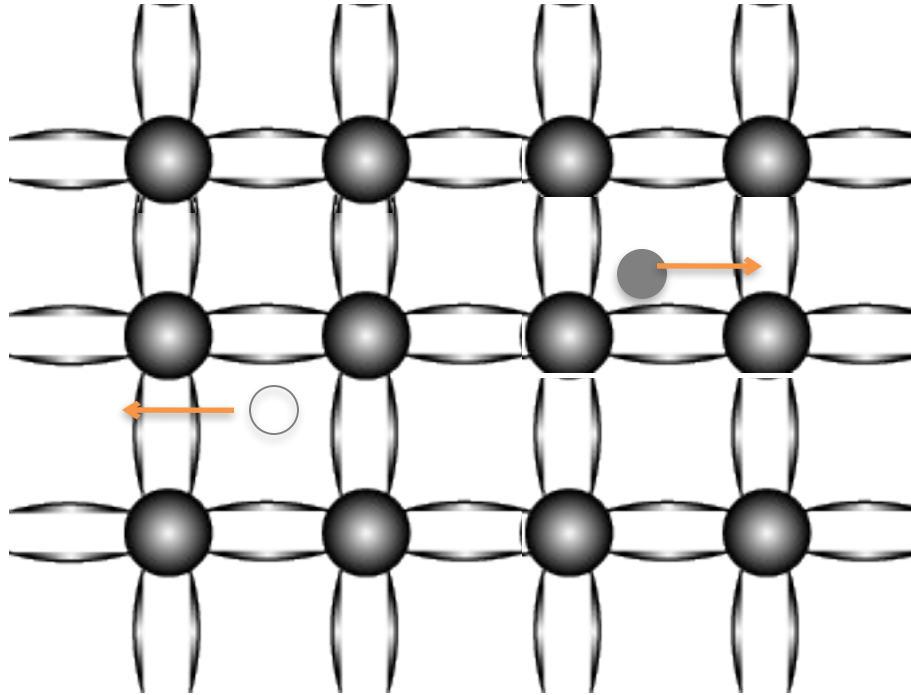
At finite temperature, an electron may gain enough energy to break the covalent bond, become free and move around. As a result, current will flow if a voltage is applied to Si. As the electrons move, they leave behind a hole, which itself can move.

Intrinsic Si: The Bond Model: Holes



Movement of electrons is equivalent to opposite movement of holes. How? If the electron moves towards right and there is enough thermal energy in the system to dislodge electrons, after some time another electron from left will come and recombine with the hole. The net result is that the hole moves from right to left. For all practical purposes, it is easy to consider holes as equivalent to electrons with positive charge.

Si: The Bond Model: Holes

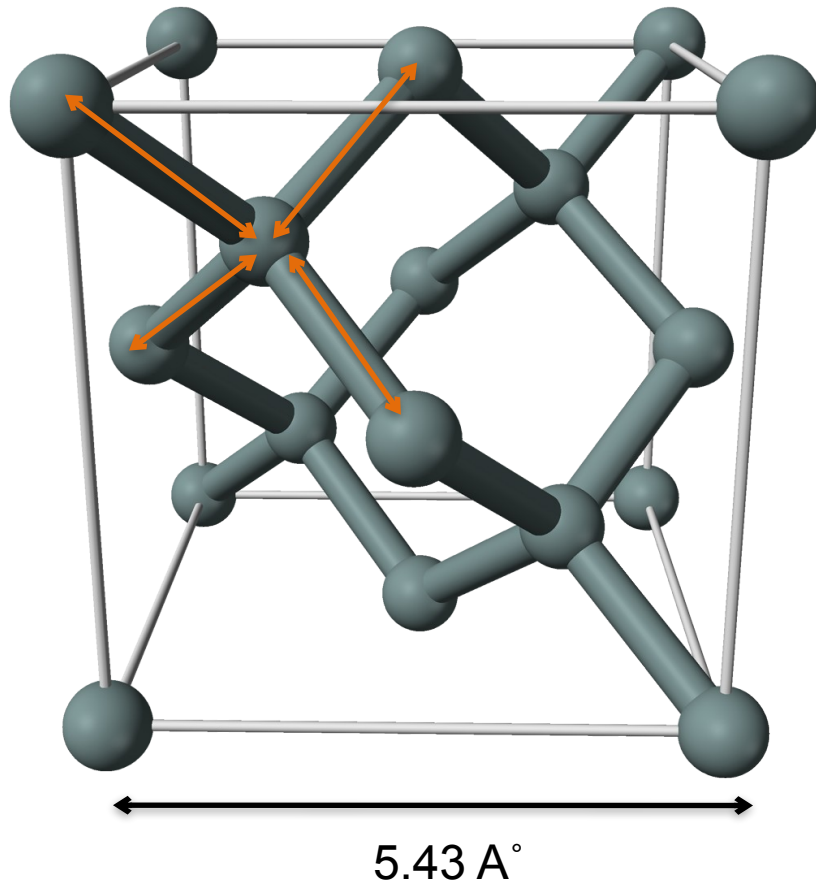


Note that each electron is associated with a complementary hole. So the material is charge neutral.

However, electrons and holes are not exactly the same quantity with opposite charges. We shall see why when we discuss band model.

Physics of Semiconductors

What is the atomic density of pure Si?

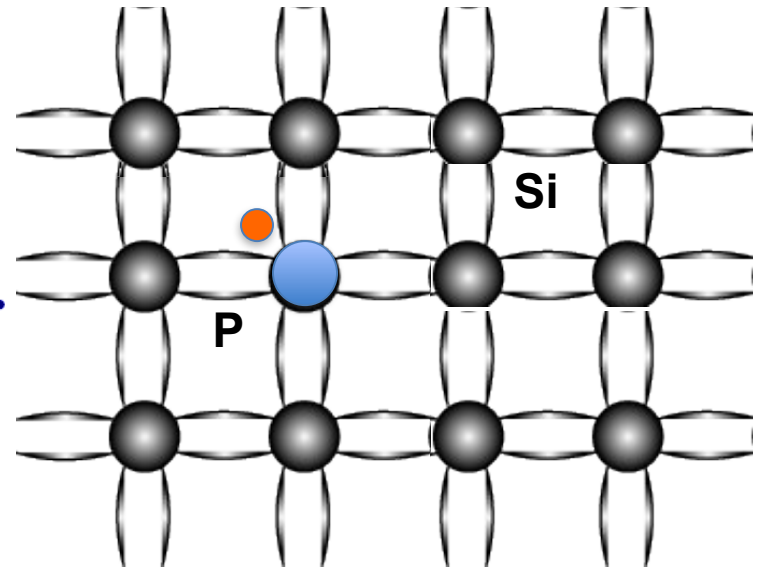


- Atomic Density: $8/(0.543 \times 10^{-9})^3 = 5 \times 10^{28} \text{ /m}^3$
- Bond Density: $2 \times 10^{29} \text{ /m}^3$
- Free Carrier: $1.5 \times 10^{16} \text{ /m}^3$

Only 1 in $\sim 10^{13}$ bonds is broken at room temperature in Si!

Adding Dopants: Donors (non-intrinsic Si)

	III	IV	V	
	Boron (B)	Carbon (C)		
...	Aluminum (Al)	Silicon (Si)	Phosphorous (P)	...
	Galium (Al)	Germanium (Ge)	Arsenic (As)	
		⋮		



Si(14)= [Ne(10)] $3s^2 3p^2$
 P(15): [Ne(10)] $3s^2 3p^3$

Electron density $n = N_D$ (donor
doping density)

Group V elements have 5 valence electrons. Therefore, if one Si atom is replaced by one group V atom (e.g. P or As), then 4 electrons are shared among the 4 nearest neighbors which complete the shell, leaving one electron to freely wonder around. Thus each dopant 'donates' an extra electron to the material. Thus the name 'Donors'.

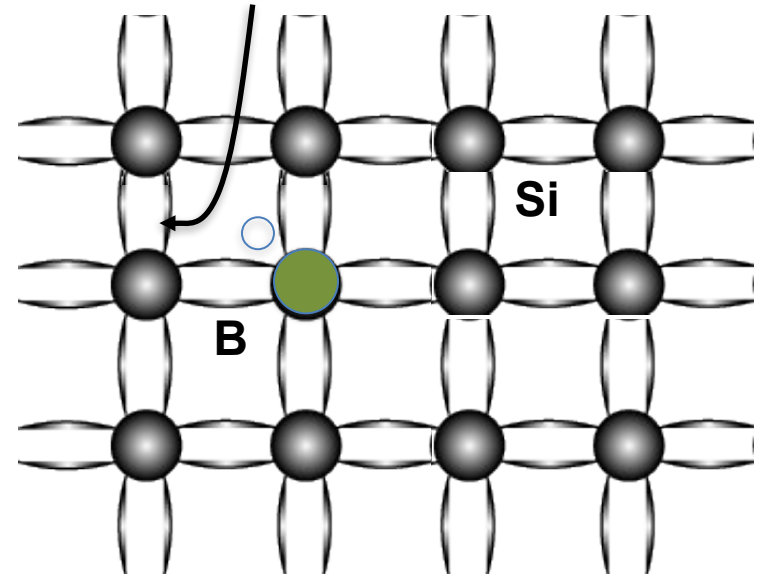
Dopants: Acceptors

III	IV	V
Boron (B)	Carbon (C)	
Aluminum (Al)	Silicon (Si)	Phosphorous (P)
Galium (Al)	Germanium (Ge)	Arsenic (As)
	⋮	

Si(14)= [Ne(10)] $3s^2 3p^2$

B(5): [He(2)] $2s^2 2p^1$

A bond breaks to produce the necessary electron



Hole density $p = N_A$ (acceptor doping density)

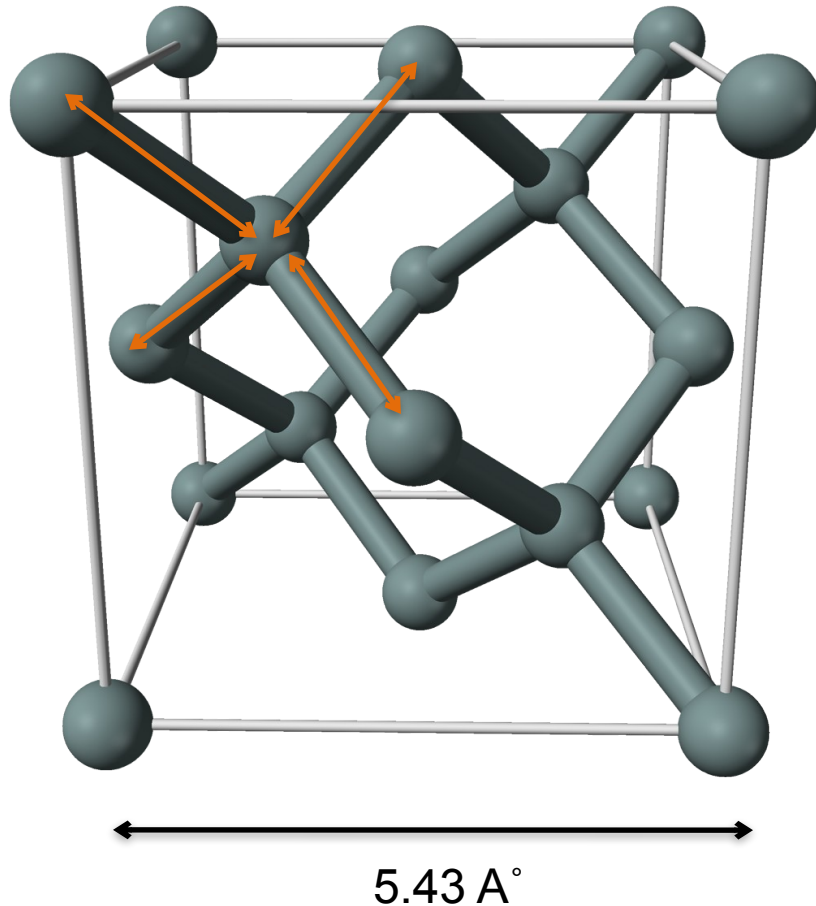
Group III elements have 3 valence electrons. Therefore, if one Si atom is replaced by one group III atom (e.g. B), then 4 electrons are shared among the 4 nearest neighbors which complete the shell, leaving one hole to freely wonder around. Thus each dopant accepts an extra electron leaving one free hole to the material. Thus the name 'Acceptors'.

Summary: Dopants

- When a material is doped with Donors, it has many more mobile electrons than holes. It is called a 'n-type' semiconductor.
- When a material is doped with Acceptors, it has many more mobile holes than electrons. It is called a 'p-type' semiconductor.
- The material is charge neutral. The dopants are charge neutral too. Therefore, even after doping, the material system as a whole remains charge neutral.

Physics of Semiconductors

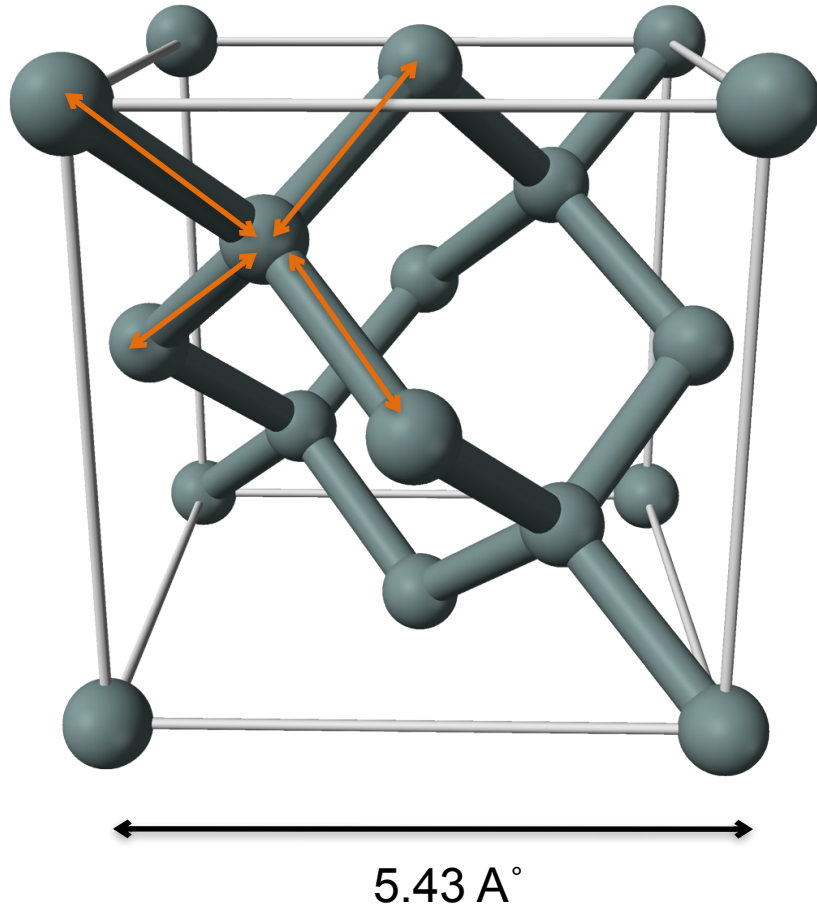
What is a reasonable number (to the higher side) of dopants in $\#/m^3$?



- Atomic Density: $8/(0.543 \times 10^{-9})^3 = 5 \times 10^{28} /m^3$
- Intrinsic Free Carrier: $1.5 \times 10^{16} /m^3$

Physics of Semiconductors

What is a reasonable number (to the higher side) of dopants in $\#/m^3$?



- Atomic Density: $8/(0.543 \times 10^{-9})^3 = 5 \times 10^{28} /m^3$
- Intrinsic Free Carrier: $1.5 \times 10^{16} /m^3$

Highest=0.1 % of the atomic density
($5 \times 10^{25} /m^3$)

Typical: 10^{21} - $5 \times 10^{24}/m^3$