Part II

Semiconductor Devices

Atoms, Bonding and Crystals

Atoms and Bonding

- In order to understand the physics of semiconductor (s/c) devices, we should first learn **how atoms bond together to form the solids**.
- Atom is composed of a nucleus which contains protons and neutrons; **surrounding the nucleus are the electrons**.
- Atoms can combine with themselves or other atoms. The valence electrons, i.e. the **outermost shell electrons govern** the chemistry of atoms.
- Atoms come together and form gases, liquids or solids depending on the strength of the attractive forces between them.
- The atomic bonding can be classified as **ionic, covalent, metallic, van der Waals,** etc.
- In all types of bonding the **electrostatic force acts between charged particles.**

The Periodic Table

1A	2A	2B	3A	4A	5A	6A	7A	8A
Li	Be							He
Na	Mg		B	C	N	O	F	Ne
K	Ca		Al	Si	P	S	Cl	Ar
Rb	Sr	Zn	Ga	Ge	As	Se	Br	Kr
Cs	Ba	Cd	In	Sn	Sb	Te	I	Xe
Fr	Rd	Hg	Ti	Pb	Bi	Po	At	Rn

Groups 3B,4B,5B,6B
7B,8B,1B lie in here

A section of the periodic table

- Ionic solids

  Group 1A (alkali metals) contains Lithium (Li), Sodium (Na), Potassium (K), … and these combine easily with group **7A** (halogens) of Fluorine (F), Chlorine (Cl), Bromine (Br), … and produce ionic solids of NaCl, KCl, KBr, etc.

- Rare (noble) gases

  Group 8A elements of noble gases of Helium (He), Neon (Ne), Argon (Ar), … have a full complement of valence electrons and so do not combine easily with other elements.

- Elemental semiconductors

  Silicon (Si) and Germanium (Ge) belong to **Group 4A**.

- Compound semiconductors

  1) **III-V** compound s/c's; GaP, InAs, AlGaAs **(Group 3A-5A)**
  2) **II-VI** compound s/c's; ZnS, CdS, etc. **(Group 2B-6A)**

Semiconductors are a group of materials having electrical conductivities intermediate between metals and insulators. It is significant that the conductivity of these materials can be varied over orders of magnitude by changes in temperature, optical excitation, and impurity content. This variability of electrical properties makes the semiconductor materials natural choices for electronic device investigations.

Semiconductor materials are found in column IV and neighbouring columns of the periodic table (Table 1-1).The column IV semiconductors, Silicon and Germanium, are called ***elemental semiconductors*** because they are composed of single species of atoms. In addition to the elemental materials, compounds of column III and column V atoms, as well as certain combinations from II and VI, and from IV, make up the ***compound semiconductors***.

Table 1-1. Common semiconductor materials: (a) the portion of the periodic table where semiconductors occur; (b) elemental and compound semiconductors.

(a)	II	III	IV	V	VI
		B	C	N	
		Al	Si	P	S
	Zn	Ga	Ge	As	Se
	Cd	In		Sb	Te

(b)	Elemental	IV compounds	Binary III–V compounds	Binary II–VI compounds
	Si	SiC	AlP	ZnS
	Ge	SiGe	AlAs	ZnSe
			AlSb	ZnTe
			GaN	CdS
			GaP	CdSe
			GaAs	CdTe
			GaSb	
			InP	
			InAs	
			InSb	

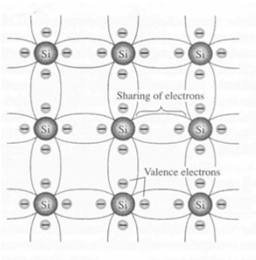
Covalent Bonding

- Elemental semiconductors of **Si**, **Ge** and **diamond** are bonded by this mechanism and these are **purely covalent**.

- The bonding is due to the ***sharing of electrons***.

- Covalently bonded solids are hard, high melting points, and insoluble in all ordinary solids.

- Compound s/c's exhibit a mixture of both ionic and covalent bonding.



Covalent bonding of the silicon atom.

Ionic Bonding

- Ionic bonding is due to the **electrostatic force of attraction between positively and negatively charged ions** (btw. Group 1A and Group 7A).

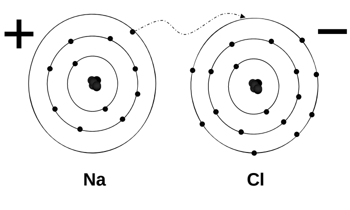
- This process leads to electron **transfer and formation of charged ions**; a ***positively*** charged ion for the atom that has ***lost the electron*** and a *negatively* charged ion for the atom that has ***gained an electron*.**

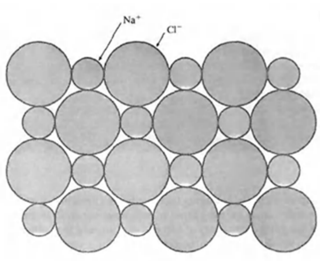
All ionic compounds are ***crystalline solids*** at room temperature.

- **NaCl** and **KCl** are typical examples of ionic bonding.

- Ionic crystals are hard, high melting point, brittle and can be dissolved in ordinary liquids.

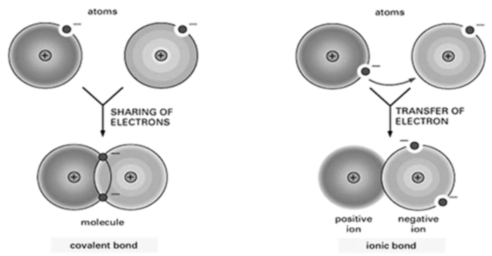
The metallic elements have only up to the valence electrons in their outer shell will lose their electrons and become positive ions, whereas electronegative elements tend to acquire additional electrons to complete their octed and become negative ions, or anions.





An example of ionic bonding in NaCl

Comparison of Ionic and Covalent Bonding

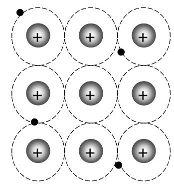


Metallic Bonding

Valance electrons are relatively bound to the nucleus and therefore they move freely through the metal and they are spread out among the atoms in the form of a low-density electron cloud.

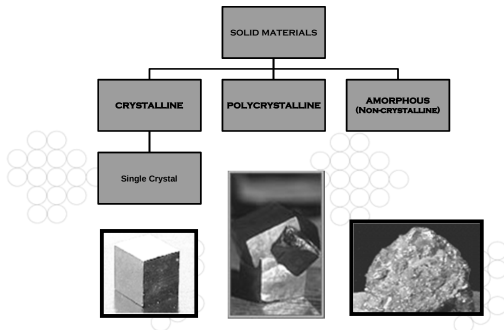
A metallic bond result from the sharing of a variable number of electrons by a variable number of atoms. A metal may be described as a ***cloud of free electrons***.

Therefore, metals have high electrical and thermal conductivity.



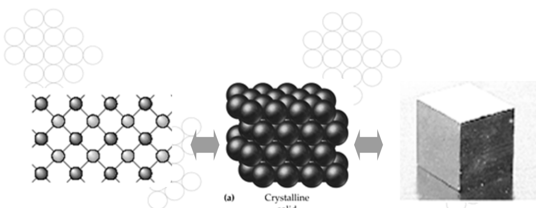
- All valence electrons in a metal combine to form a "sea" of electrons that ***move freely between the atom*** **cores**. The more electrons, the stronger the attraction. This means the melting and boiling points are higher, and the metal is stronger and harder.
- The **positively charged cores** are held together by these **negatively charged electrons**.
- The free electrons act as the bond (or as a "glue") between the positively charged ions.
- This type of bonding is nondirectional and is rather insensitive to structure.
- As a result we have a high ductility of metals - the "bonds" do not "break" when atoms are rearranged – metals can experience a significant degree of plastic deformation.

Classification of solids

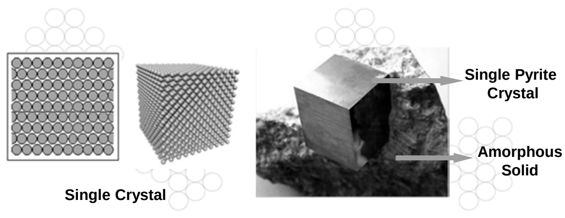


Crystalline Solid

Crystalline Solid is the solid form of a substance in which the atoms or molecules are arranged in a definite, repeating pattern in three dimension.


(a) Crystalline solid

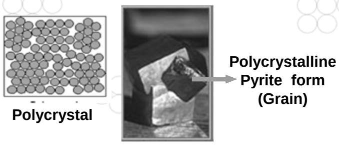
Single crystal has an atomic structure that repeats periodically across its whole volume. Even at infinite length scales, each atom is related to every other equivalent atom in the structure by translational symmetry

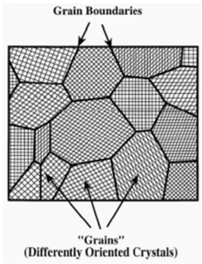


Polycrystalline Solid

Polycrystal is a material made up of an aggregate of many small single crystals (also called crystallites or grains).

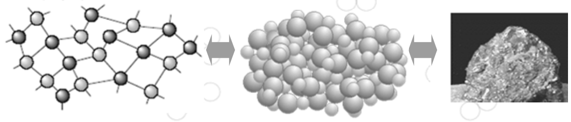
The grains are usually 100 nm - 100 microns in diameter. Polycrystals with grains that are <10 nm in diameter are called *nanocrystalline*





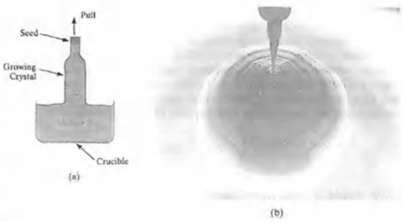
Amorphous Solid

Amorphous (non-crystalline) solid is composed of randomly orientated atoms, ions, or molecules that do not form defined patterns or lattice structures**.**



Si Crystal Growth and Wafers

Figure 1–10
Pulling of a Si crystal from the melt (Czochralski method): (a) schematic diagram of the crystal growth process; (b) an 8-in. diameter, ⟨100⟩ oriented Si crystal being pulled from the melt. (Photograph courtesy of MEMC Electronics Intl.)



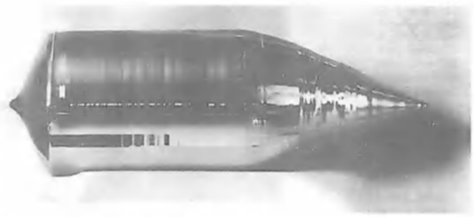


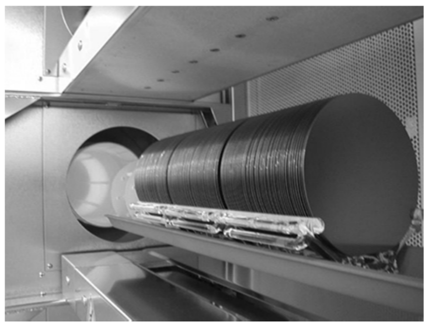
Figure 1–11
Silicon crystal grown by the Czochralski method. This large single-crystal ingot provides 300 mm (12-in.) diameter wafers when sliced using a saw. The ingot is about 1.0 m long (including the tapered regions), and weighs about 140 kg. (Photograph courtesy of MEMC Electronics Intl.)

After the single-crystal ingot is grown, it is then mechanically processed to manufacture **wafers**. The first step involves mechanically grinding the more-or-less cylindrical ingot into a perfect cylinder with a precisely controlled diameter. This is important because in a modern integrated circuit fabrication facility many processing tools and wafer handling robots require tight tolerances on the size of the wafers.

Figure 1–12
Steps involved in manufacturing Si wafers: (a) A 300 mm Si cylindrical ingot, with a notch on one side, being loaded into a wire saw to produce Si wafers; (b) a technician holding a cassette of 300 mm wafers. (Photographs courtesy of MEMC Electronics Intl.)

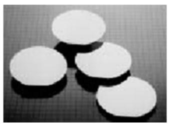
(a)

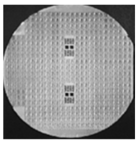
(b)

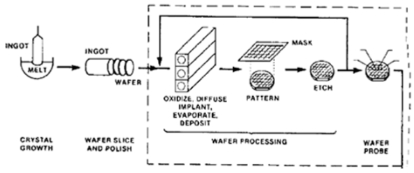


Showing silicon wafers waiting to be pushed into the furnace for device fabrication

Bulk Si Wafer to IC Chip

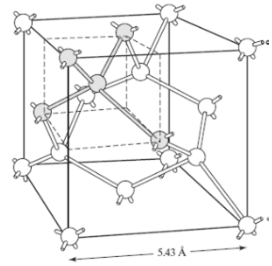




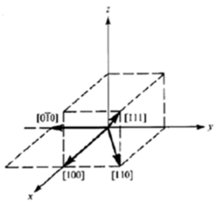


Silicon Crystal Structure

- ***Unit cell*** of silicon crystal is cubic.
- ***Each Si atom has 4 nearest neighbours.***



Miller Indices
Crystallographic Notation

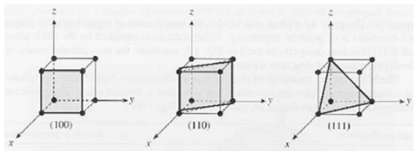


Notation	Interpretation
(*h k l*)	crystal plane
{ *h k l* }	equivalent planes
[*h k l*]	crystal direction
< *h k l* >	equivalent directions

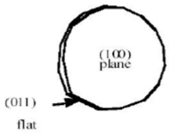
h: inverse *x*-intercept
k: inverse *y*-intercept
l: inverse *z*-intercept

(Intercept values are in multiples of the lattice constant; *h*, *k* and *l* are reduced to 3 integers having the same ratio.)

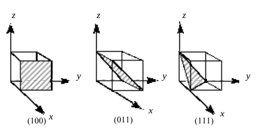
Crystallographic Planes and Si Wafers



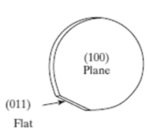
Silicon wafers are usually cut along the (100) plane with a flat or notch to orient the wafer during IC fabrication

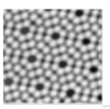


Silicon Wafers and Crystal Planes



- The standard notation for crystal planes is based on the cubic unit cell.
- Silicon wafers are usually cut along the (100) plane with a flat or notch to help orient the wafer during IC fabrication.

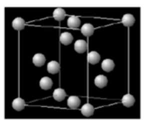




Si (111) plane

Crystallographic Planes

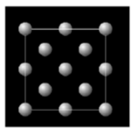
Unit cell:



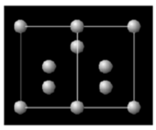
Si lattice constant = 5.431Å

→ **5 x 10^{22} atoms/cm^3**

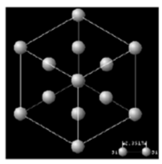
View in <100> direction



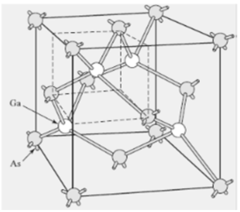
View in <110> direction

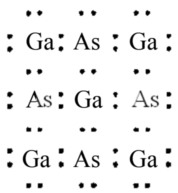


View in <111> direction



GaAs (Group III-V) Compound Semiconductors





- GaAs has the same crystal structure as Si.
- GaAs, GaP, GaN are III-V compound semiconductors, important for optoelectronics.

Physical Constants and Conversion Factors

Avogadro's number	$N_A = 6.02 \times 10^{23}$ molecules/mole
Boltzmann's constant	$k = 1.38 \times 10^{-23}$ J/K
	$= 8.62 \times 10^{-5}$ eV/K
Electronic charge (magnitude)	$q = 1.60 \times 10^{-19}$ C
Electronic rest mass	$m_0 = 9.11 \times 10^{-31}$ kg
Permittivity of free space	$\epsilon_0 = 8.85 \times 10^{-14}$ F/cm
	$= 8.85 \times 10^{-12}$ F/m
Planck's constant	$h = 6.63 \times 10^{-34}$ J-s
	$= 4.14 \times 10^{-15}$ eV-s
Room temperature value of kT	$kT = 0.0259$ eV
Speed of light	$c = 2.998 \times 10^{10}$ cm/s

	Prefixes:		
1 Å (angstrom) $= 10^{-8}$ cm	milli-,	m-	$= 10^{-3}$
1 μm (micron) $= 10^{-4}$ cm	micro-,	μ-	$= 10^{-6}$
1 nm = 10 Å $= 10^{-7}$ cm	nano-,	n-	$= 10^{-9}$
2.54 cm = 1 in.	pico-,	p-	$= 10^{-12}$
1 eV $= 1.6 \times 10^{-19}$ J	kilo-,	k-	$= 10^{3}$
	mega-,	M-	$= 10^{6}$
	giga-,	G-	$= 10^{9}$

A wavelength λ of 1 μm corresponds to a photon energy of 1.24 eV.

Properties of Semiconductor Materials

		E_g (eV)	μ_n (cm^2/V-s)	μ_p (cm^2/V-s)	m^*_n/m_0 (m_l, m_t)	m^*_p/m_0 (m_{lh}, m_{hh})	a (Å)	ϵ_r	Density (g/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 (α)	(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

All values at 300 K. *Vaporizes

Electrical Resistivity and Conductivity of Selected Materials at 293 K

Table 11.1 Electrical Resistivity and Conductivity of Selected Materials at 293 K

Material	Resistivity (Ω · m)	Conductivity ($\Omega^{-1} \cdot m^{-1}$)
Metals		
Silver	1.59×10^{-8}	6.29×10^{7}
Copper	1.72×10^{-8}	5.81×10^{7}
Gold	2.44×10^{-8}	4.10×10^{7}
Aluminum	2.82×10^{-8}	3.55×10^{7}
Tungsten	5.6×10^{-8}	1.8×10^{7}
Platinum	1.1×10^{-7}	9.1×10^{6}
Lead	2.2×10^{-7}	4.5×10^{6}
Alloys		
Constantan	4.9×10^{-7}	2.0×10^{6}
Nichrome	1.5×10^{-6}	6.7×10^{5}
Semiconductors		
Carbon	3.5×10^{-5}	2.9×10^{4}
Germanium	0.46	2.2
Silicon	640	1.6×10^{-3}
Insulators		
Wood	10^{8}–10^{11}	10^{-8}–10^{-11}
Rubber	10^{13}	10^{-13}
Amber	5×10^{14}	2×10^{-15}
Glass	10^{10}–10^{14}	10^{-10}–10^{-14}
Quartz (fused)	7.5×10^{17}	1.3×10^{-18}

Resistivity vs. Temperature

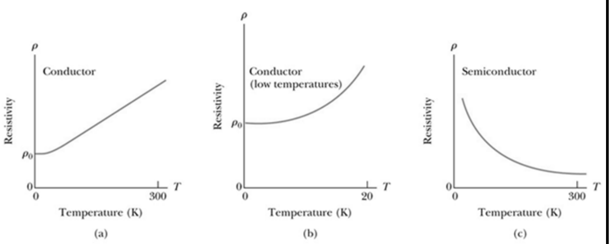


Figure 11.1: (a) Resistivity versus temperature for a typical conductor. Notice the linear rise in resistivity with increasing temperature at all but very low temperatures. (b) Resistivity versus temperature for a typical conductor at very low temperatures. Notice that the curve flattens and approaches a nonzero resistance as $T \to 0$. (c) Resistivity versus temperature for a typical semiconductor. The resistivity increases dramatically as $T \to 0$.

Temperature

Temperature used in the equations would be in Kelvin unit. The kelvin is a unit of measurement for temperature its unit symbol is K. The 0K temperature is called the **absolute zero**, the temperature at which all thermal motion ceases in the classical description of thermodynamics.

The kelvin is not referred to or typeset as a degree. Its relationship with the degree Celcius (°C) is given by

$$[K] = [°C] + 273.15 \cong [°C] + 273$$

$$[°C] = [K] - 273.15 \cong [K] - 273$$

For example, 300K is 27°C, 0K is −273°C or 25°C is 298K.