

B39SE Semiconductor Physics

Semiconductor Fundamentals (Week 1)

Week 1: Fundamentals of semiconductors

Week 2: Atomic models

Week 3: Doping and carrier transport phenomena

Semiconductor
fundamentals

1) Semiconductor Material

1. Type of solids
2. Space lattices
3. Imperfections and impurities in Solids
4. Growth from a Melt

2) Fundamental Physics

1. Photoelectric Effect
2. Quantification of energy
3. Duality particle-wave

1. Semiconductors Physics and Devices, by Donald Neamen, McGrawHill (main textbook)
(Useful for Weeks 1 to 5)

Semiconductor materials – basics---Chap 1

1. Semiconductor Material
2. Type of solids----- (three classifications)
3. Space lattices
 - a. Primitive and unit cell
 - b. Basic Crystal Structure
 - c. Crystal planes and Miller indices
 - d. Diamond structure
4. Imperfections and impurities in Solids
5. Growth from a Melt

Semiconductor Material

- **Conductivities** between metal and insulator
- **Elemental semiconductor materials**, Group IV
- **Compound semiconductor**, mostly combination group III and V

Table 1.1 | A portion of the periodic table

III	IV	V
5 B Boron	6 C Carbon	
13 Al Aluminum	14 Si Silicon	15 P Phosphorus
31 Ga Gallium	32 Ge Germanium	33 As Arsenic
49 In Indium		51 Sb Antimony

Semiconductor Materials - Basics

- **Elemental semiconductor materials**: single species, mainly Silicon and germanium, but also carbon and tin. **Silicon is the most common.**
- Gallium arsenide is one of the more common **compound semiconductor**. Useful in optical device and high speed devices.

Table 1.1 | A portion of the periodic table

III	IV	V
5 B Boron	6 C Carbon	
13 Al Aluminum	14 Si Silicon	15 P Phosphorus
31 Ga Gallium	32 Ge Germanium	33 As Arsenic
49 In Indium		51 Sb Antimony

Table 1.2 | A list of some semiconductor materials

Elemental semiconductors	
Si	Silicon
Ge	Germanium
Compound semiconductors	
AlP	Aluminum phosphide
AlAs	Aluminum arsenide
GaP	Gallium phosphide
GaAs	Gallium arsenide
InP	Indium phosphide

Semiconductor Materials - Extended

1
IA
1A

2
IIA
2A

3
IIIB
3B

4
IVB
4B

5
VB
5B

6
VIB
6B

7
VIIB
7B

8
VIII
8

9
VIII
9

10
VIII
10

11
IB
1B

12
IIB
2B

13
IIIA
3A

14
IVA
4A

15
VA
5A

16
VIA
6A

17
VIIA
7A

18
VIIIA
8A

1
H
Hydrogen
1.008

3
Li
Lithium
6.941

11
Na
Sodium
22.990

19
K
Potassium
39.098

37
Rb
Rubidium
84.468

55
Cs
Cesium
132.905

87
Fr
Francium
223.020

4
Be
Beryllium
9.012

12
Mg
Magnesium
24.305

20
Ca
Calcium
40.078

38
Sr
Strontium
87.62

56
Ba
Barium
137.328

88
Ra
Radium
226.025

5
B
Boron
10.811

13
Al
Aluminum
26.982

21
Sc
Scandium
44.956

29
Cu
Copper
63.546

39
Y
Yttrium
88.906

47
Ag
Silver
107.868

57-71
Lanthanide Series

67
Ho
Holmium
164.930

77
Ir
Iridium
192.217

81
Tl
Thallium
204.38

85
At
Astatine
209.987

91
Pa
Protactinium
231.036

95
Am
Americium
243.061

99
Es
Einsteinium
[254]

103
Lr
Lawrencium
[262]

6
C
Carbon
12.011

14
Si
Silicon
28.086

22
Ti
Titanium
47.867

30
Zn
Zinc
65.38

38
Sr
Strontium
87.62

46
Pd
Palladium
106.42

54
Xe
Xenon
131.294

62
Sm
Samarium
150.36

70
Yb
Ytterbium
173.055

78
Pt
Platinum
195.085

86
Rn
Radon
222.018

94
Pu
Plutonium
244.064

102
No
Nobelium
259.101

110
Ds
Darmstadtium
[269]

116
Lv
Livermorium
[293]

7
N
Nitrogen
14.007

15
P
Phosphorus
30.974

23
V
Vanadium
50.942

31
Ga
Gallium
69.723

39
Y
Yttrium
88.906

47
Ag
Silver
107.868

55
Cs
Cesium
132.905

63
Eu
Europium
151.964

71
Lu
Lutetium
174.967

79
Au
Gold
196.967

87
Fr
Francium
223.020

93
Np
Neptunium
237.048

101
Md
Mendelevium
258.1

109
Mt
Meitnerium
[268]

115
Uut
Ununtrium
unknown

8
O
Oxygen
15.999

16
S
Sulfur
32.066

24
Cr
Chromium
51.996

32
Ge
Germanium
72.631

40
Zr
Zirconium
91.224

48
Cd
Cadmium
112.411

56
Ba
Barium
137.328

64
Gd
Gadolinium
157.25

72
Hf
Hafnium
178.49

80
Hg
Mercury
200.592

88
Ra
Radium
226.025

96
Cm
Curium
247.070

104
Rf
Rutherfordium
[261]

112
Cn
Copernicium
[277]

9
F
Fluorine
18.998

17
Cl
Chlorine
35.453

25
Mn
Manganese
54.938

33
As
Arsenic
74.922

41
Nb
Niobium
92.906

49
In
Indium
114.818

57-71
Lanthanide Series

65
Tb
Terbium
158.925

73
Ta
Tantalum
180.948

81
Tl
Thallium
204.38

89
Ac
Actinium
227.028

97
Bk
Berkelium
247.070

105
Nh
Nihonium
[284]

113
Uut
Ununtrium
unknown

10
Ne
Neon
20.180

18
Ar
Argon
39.948

26
Fe
Iron
55.845

34
Se
Selenium
78.971

42
Mo
Molybdenum
95.95

50
Sn
Tin
118.71

58
Ce
Cerium
140.116

66
Dy
Dysprosium
162.500

74
W
Tungsten
183.84

82
Pb
Lead
207.2

90
Th
Thorium
232.038

98
Cf
Californium
251.080

106
Sg
Seaborgium
[266]

114
Fl
Flerovium
[289]

11
Na
Sodium
22.990

19
K
Potassium
39.098

27
Co
Cobalt
58.933

35
Br
Bromine
79.904

43
Tc
Technetium
98.907

51
Sb
Antimony
121.760

59
Pr
Praseodymium
140.908

69
Tm
Thulium
168.934

77
Ir
Iridium
192.217

85
At
Astatine
209.987

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Neptunium
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12
Mg
Magnesium
24.305

20
Ca
Calcium
40.078

28
Ni
Nickel
58.693

36
Kr
Krypton
84.798

44
Ru
Ruthenium
101.07

52
Te
Tellurium
127.6

60
Nd
Neodymium
144.243

68
Er
Erbium
167.259

76
Os
Osmium
190.23

84
Po
Polonium
[208.982]

92
U
Uranium
238.029

100
Fm
Fermium
257.095

108
Hs
Hassium
[269]

116
Lv
Livermorium
[293]

III-V

II-VI

Atomic Number

Symbol

Name

Atomic Mass

Alkali Metal

Alkaline Earth

Transition Metal

Basic Metal

Semimetal

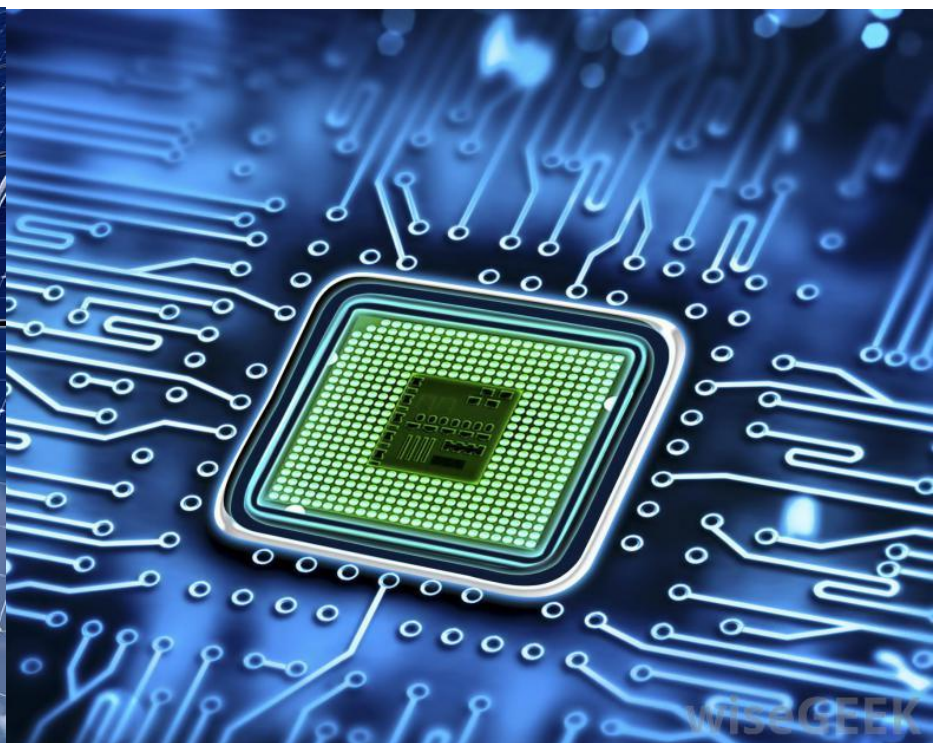
Nonmetal

Halogen

Noble Gas

Lanthanide

Actinide



WISGEEK

Type of solids

- **Amorphous:** have order only within a few atomic or molecular dimensions
- **Polycrystalline:** have a high degree of order over many atomic or molecular dimensions
- **Single crystal (monocrystalline):** are also called **grains**, have a high degree of order through the entire volume of the material.

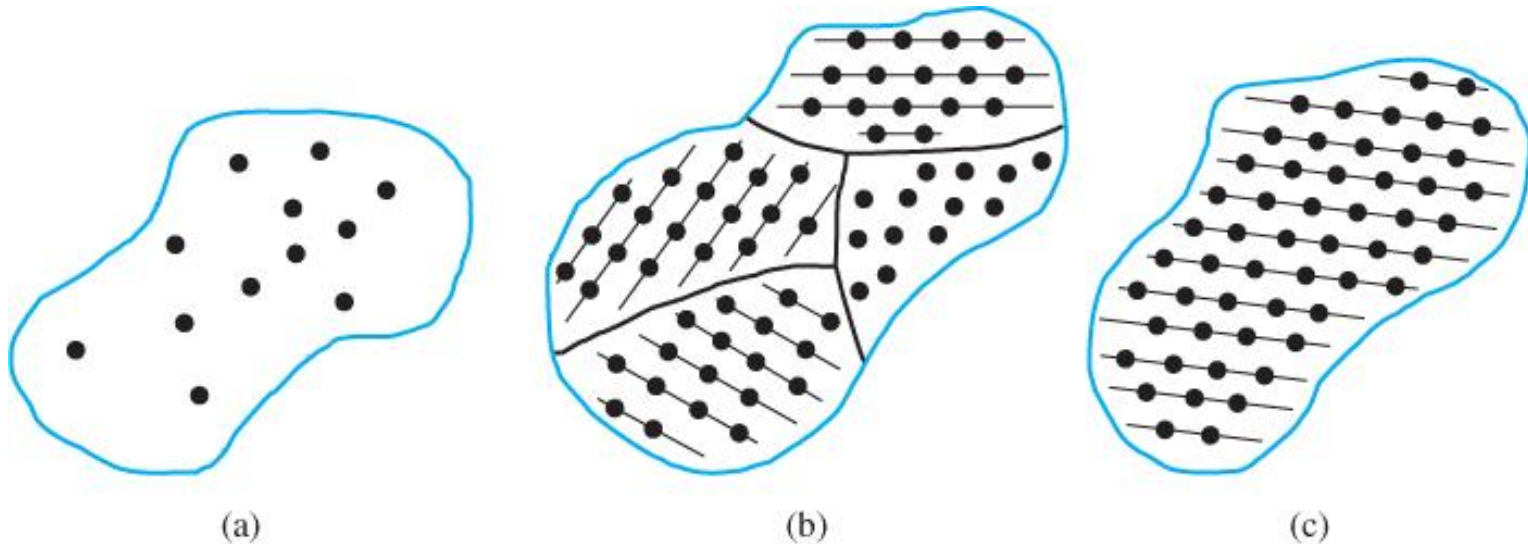


Figure 1.1 | Schematics of three general types of crystals: (a) amorphous, (b) polycrystalline, (c) single.

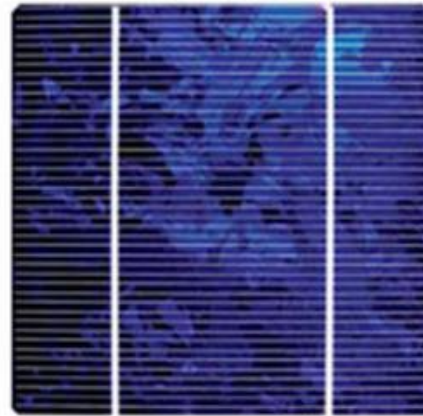
Quartz:



Silicon:



Mono



Poly

<https://www.zhihu.com/question/25006152>

Space lattices(single-crystal)

- Lattice: The periodic arrangement of atoms in a crystal.
- lattice point: Each dot represents a particular atom.
- The Simplest way of repeating atomic array is by translation.

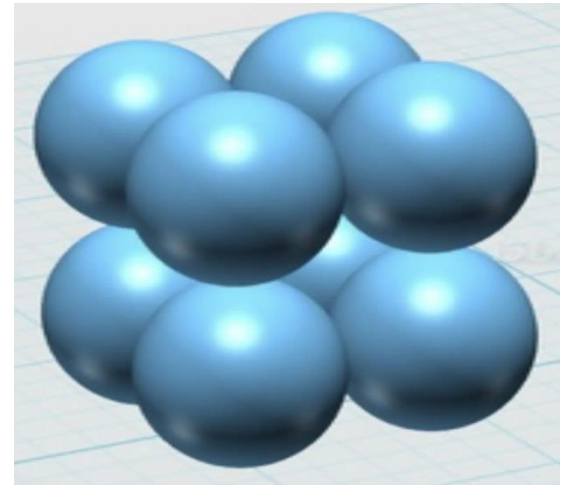
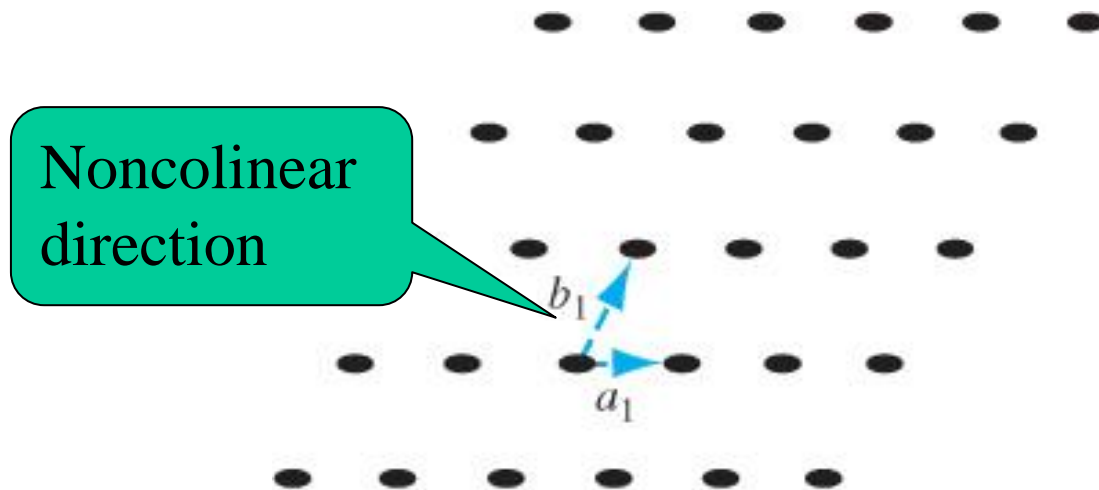


Figure 1.2 | Two-dimensional representation of a single-crystal lattice.

Primitive and unit cell

- **Unit cell:** a small volume of the crystal that can be used to reproduce the entire crystal.
- **Primitive cell:** The smallest unit cell that can be repeated to form the lattices. $\vec{r} = p\vec{a} + q\vec{b} + s\vec{c}$ (p, q and s positive integers)
- \vec{a}, \vec{b} and \vec{c} need **not** be perpendicular.

Lattice constant (or lattice parameter): is the length of the unit cell. A 3D lattice will have 3 constants: a, b, c . (magnitudes of the vector)

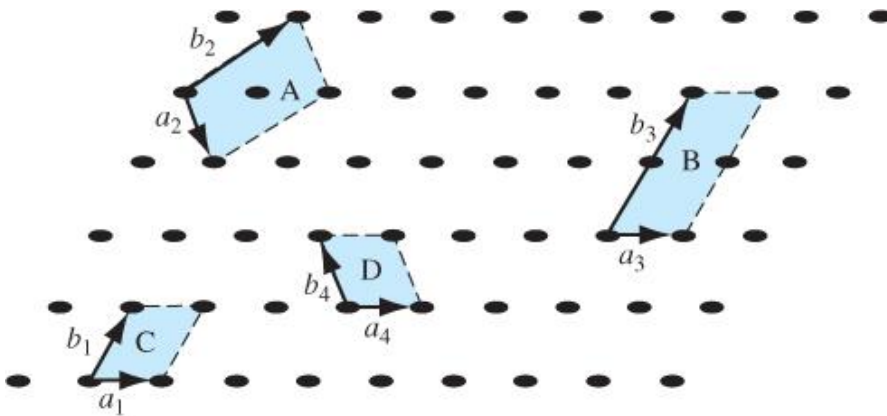


Figure 1.3 | Two-dimensional representation of a single-crystal lattice showing various possible unit cells.

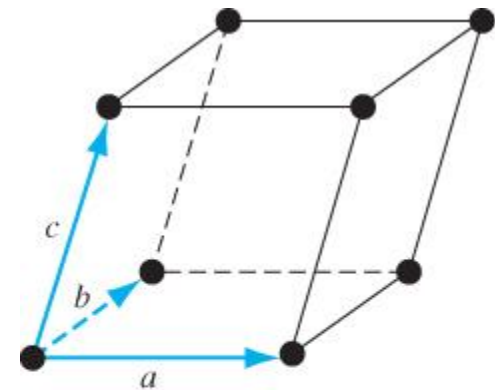


Figure 1.4 | A generalized primitive unit cell.

Basic Crystal Structure

- **Simple cubic**: an atom at each corner.
- **Body-centred cubic**: an additional atom at the center.
- **Face-centred cubic**: additional atoms on each face plane.

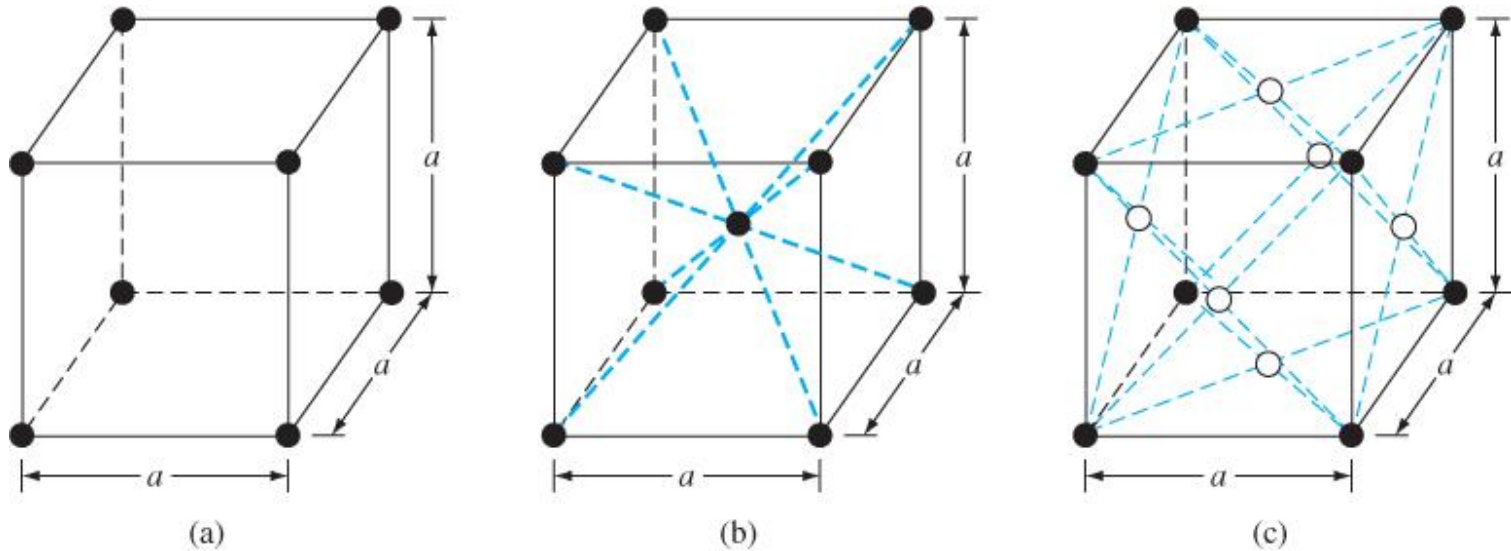


Figure 1.5 | Three lattice types: (a) simple cubic, (b) body-centered cubic, (c) face-centered cubic.

Basic Crystal Structure

- Simple cubic: an atom at each corner.
- Body-centred cubic: an additional atom at the center.
- Face-centred cubic: simple cubic with additional atoms on each face plane.

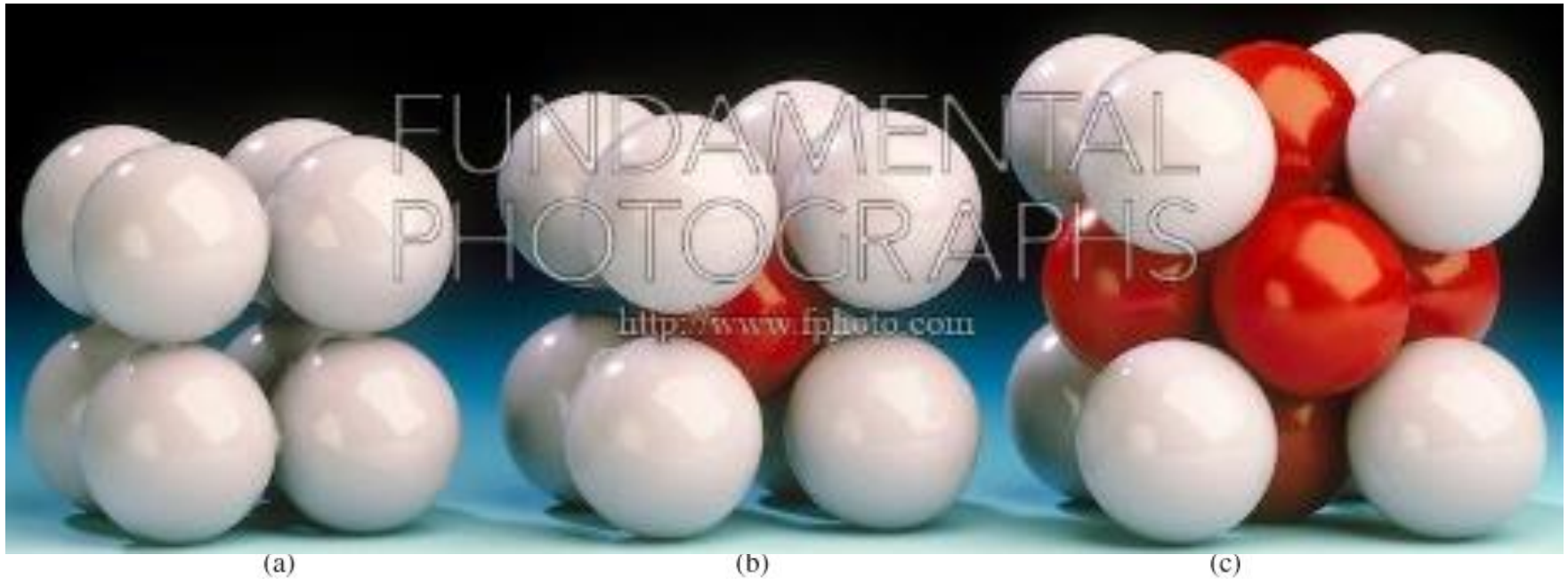


Figure 1.5 | Three lattice types: (a) simple cubic, (b) body-centered cubic, (c) face-centered cubic.

The Atomic Mac™

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GREGORY TETRAULT
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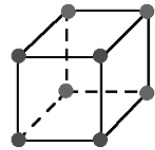
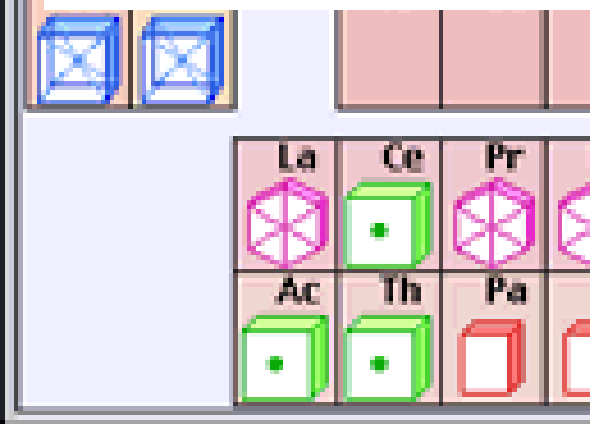
- | | |
|---|---|
|  Hexagonal |  Cubic face centered |
|  Cubic body centered |  Monoclinic |
|  Rhombohedral |  Orthorhombic |
|  Cubic |  Tetragonal |

H																		He
Li	Be												B	C	N	O	F	Ne
Na	Mg												Al	Si	P	S	Cl	Ar
K	Ca	Sc	Ti	V	Cr	Mn	Fe	Co	Ni	Cu	Zn		Ga	Ge	As	Se	Br	Kr
Rb	Sr	Y	Zr	Nb	Mo	Tc	Ru	Rh	Pd	Ag	Cd		In	Sn	Sb	Te	I	Xe
Cs	Ba		Hf	Ta	W	Re	Os	Ir	Pt	Au	Hg		Tl	Pb	Bi	Po	At	Rn
Fr	Ra		Rf	Db	Sg	Bh	Hs	Mt	Uun	Uuu	Uub		Uut	Uuq	Uup	Uuh	Uus	Uuo

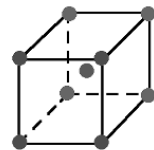
La	Ce	Pr	Nd	Pm	Sm	Eu	Gd	Tb	Dy	Ho	Er	Tm	Yb	Lu
Ac	Th	Pa	U	Np	Pu	Am	Cm	Bk	Cf	Es	Fm	Md	No	Lr



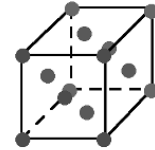
Additional info: in total there are 14 basic structures, called Bravais lattices, but in this course we will study only 3.



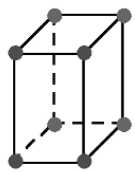
simple cubic



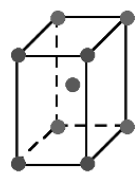
body-centered cubic



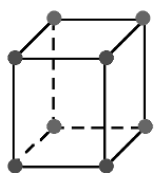
face-centered cubic



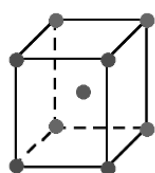
simple tetragonal



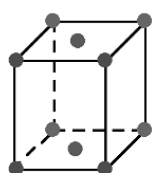
body-centered tetragonal



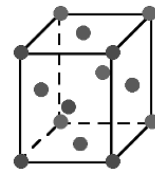
simple orthorhombic



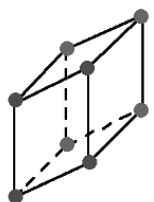
body-centered orthorhombic



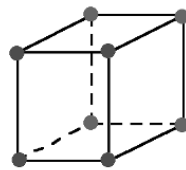
base-centered orthorhombic



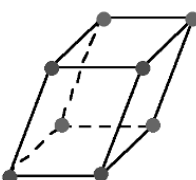
face-centered orthorhombic



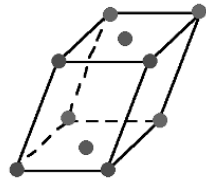
rhombohedral



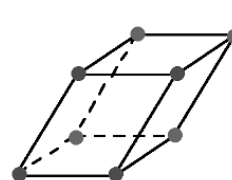
hexagonal



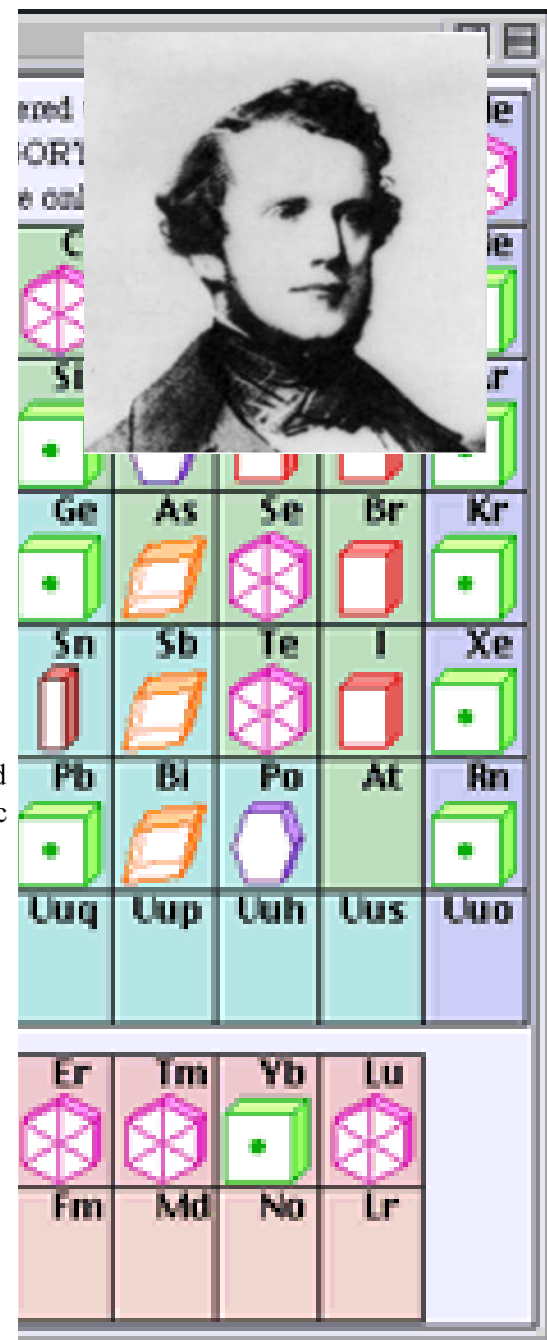
simple monoclinic



base-centered monoclinic



triclinic



Units

- the preferred length unit in crystallography is the “Angstrom”, represented by Å, although sometimes “nm” is also used.

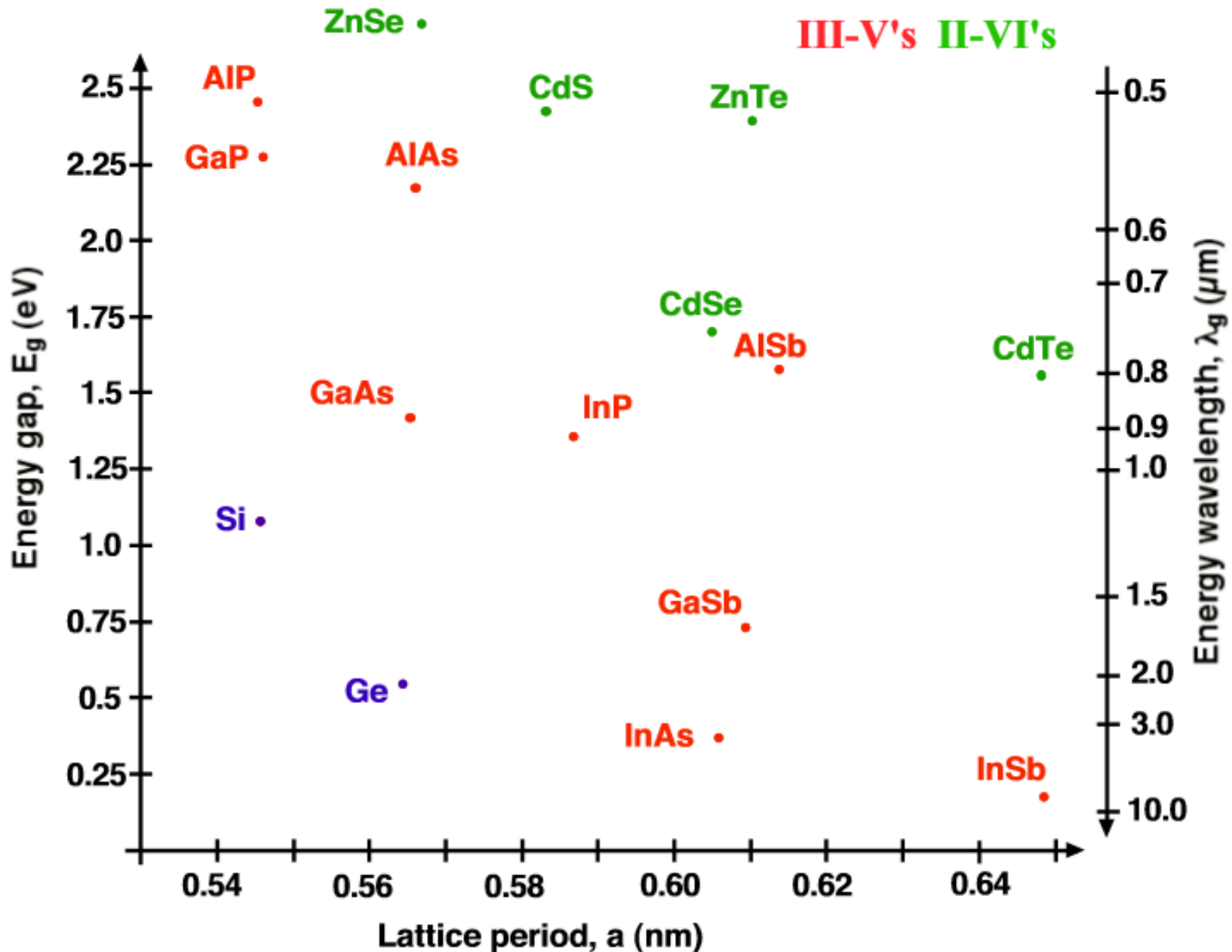
$$10 \text{ Å} = 1 \text{ nm}$$

Metal	Spacing
	In-plane (Å)
Ru	2.729
Os	2.761
Co	2.456
Rh	2.718
Ir	2.745
Ni	2.484
Pd	2.794
Pt	2.816
Cu	2.567
Ag	2.934
Au	2.950



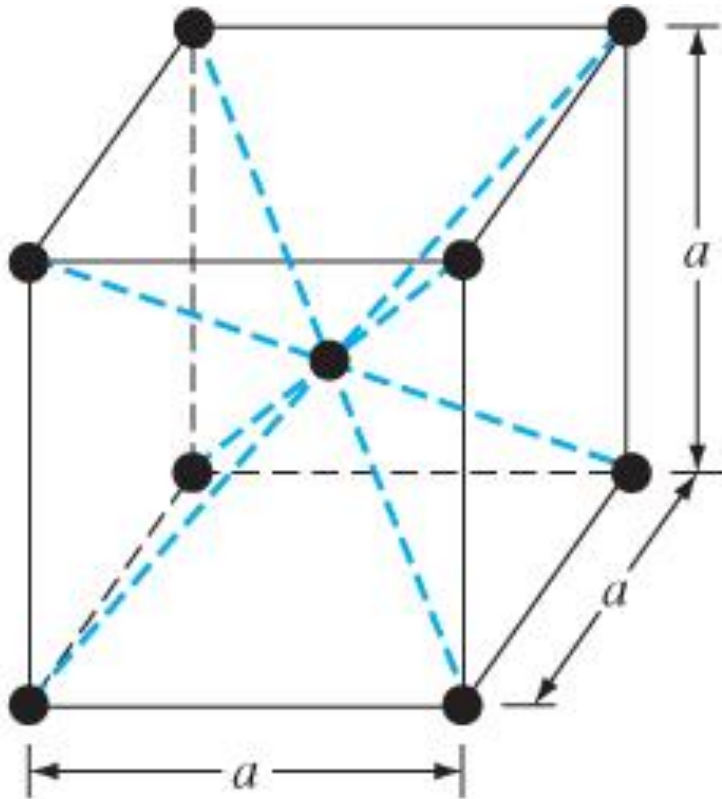
It was named after Anders Jonas Ångström (1814 –1874), a famous Swedish physicist

Example of lattice constants

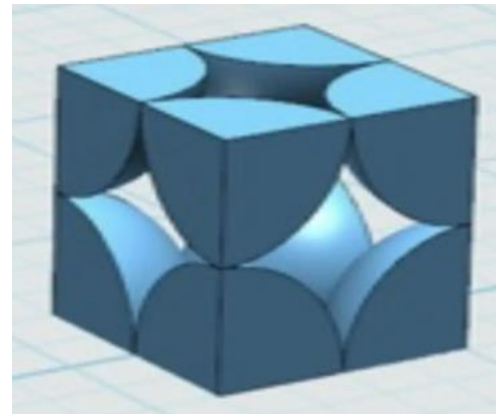


Example 1.1: volume density of atoms

- Consider a single-crystal material that is a body-centred cubic with a lattice constant $a = 5\text{\AA}$. What is the **volume density** of atoms?



$$\text{Volume Density} = \frac{\# \text{ atoms per unit cell}}{\text{volume of unit cell}}$$



Solution

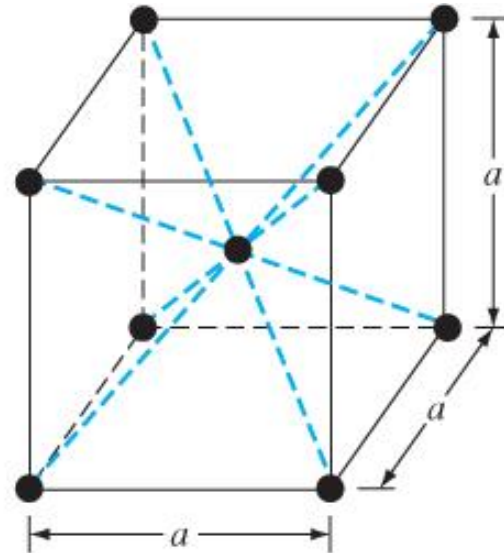
Example 1.1

- Consider a single-crystal material that is a body-centred cubic with a lattice constant $a = 5\text{\AA}$. What is the volume density of atoms?

- Answer:**

- 8 corner atoms atom $\times 1/8 = 1$ atom
- 1 enclosed atom = 1 atom

Total of 2 atoms per unit cell



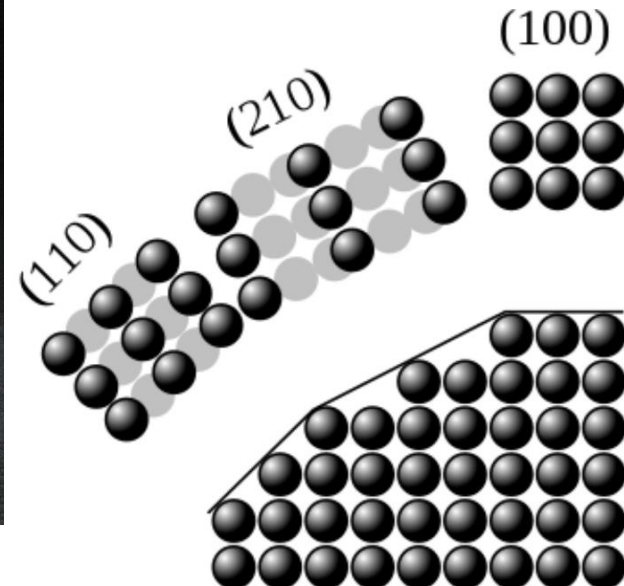
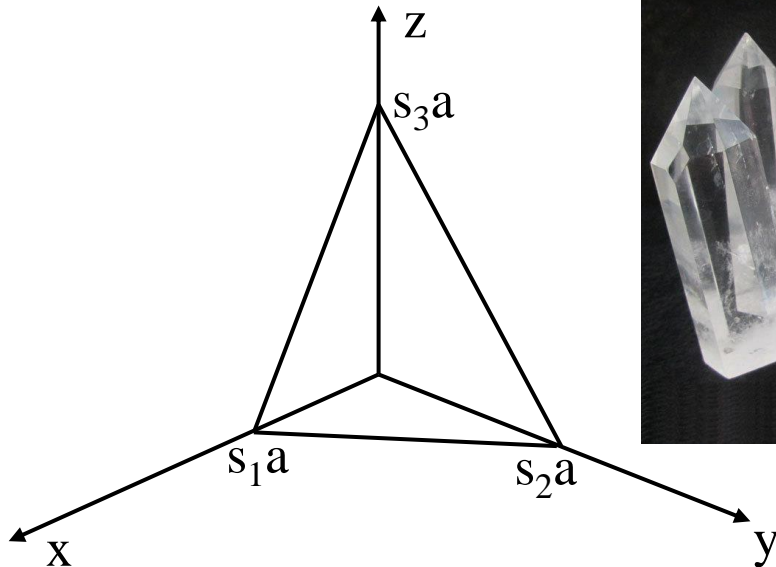
- Density = $\frac{2 \text{ atoms}}{a^3} = \frac{2}{(5 \times 10^{-8})^3} = 1.6 \times 10^{22} \text{ atoms per cm}^3$

Semiconductor materials - basics

1. Semiconductor Material
2. Type of solids
3. Space lattices
 - a. Primitive and unit cell
 - b. Basic Crystal Structures
 - c. Crystal planes and Miller indices
 - d. Diamond structure
4. Imperfections and impurities in Solids
5. Growth from a Melt

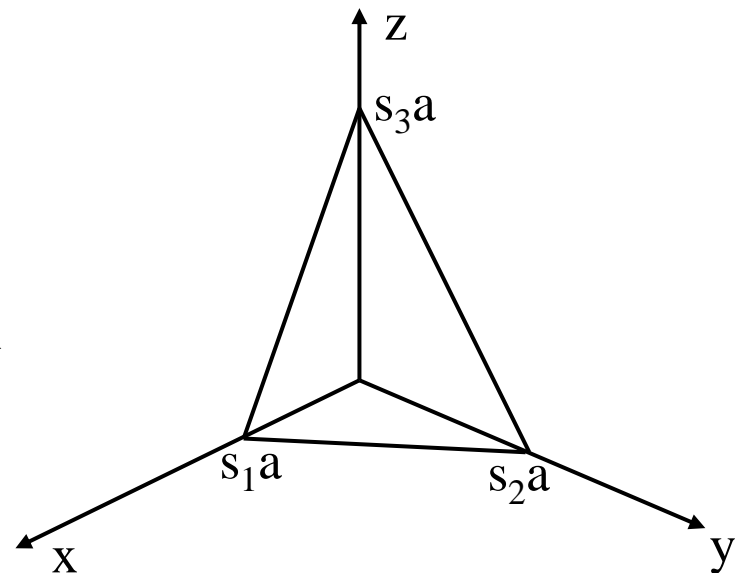
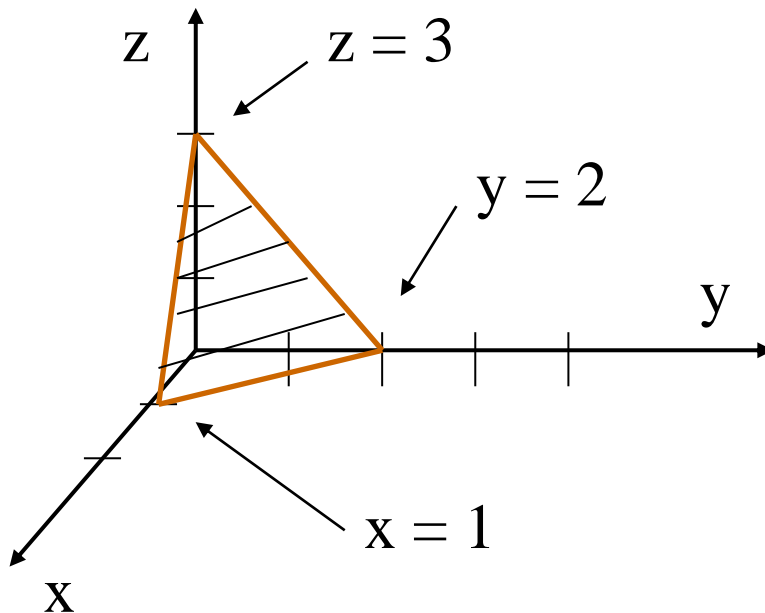
Crystal planes

- Because crystals are usually **anisotropic** (their properties differ along different directions) it is useful to regard a crystalline solid as a collection of parallel planes of atoms. **Miller notation** is used for defining planes and directions in a crystal.
- For example as shown in the figure below, x , y , and z are three axes parallel to the edges of the unit cell of a cubic crystal with a lattice point as their origin, s_1a , s_2a , and s_3a are their interception on the axes with indices of s_1 , s_2 and s_3



Miller Indices

- Named after William Hallowes Miller, British mineralogist and professor at Cambridge that proposed them in 1839.
- The Miller indices **h**, **k** and **l** of the crystal plane are determined by taking the **reciprocals** of s_1 , s_2 and s_3 and clearing the fractions by multiplying them by their **common denominator**.
- The crystal plane is then denoted by (**hkl**).



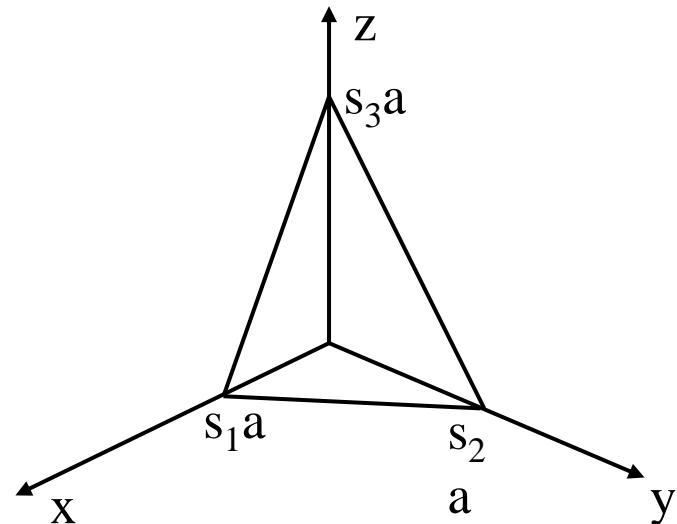
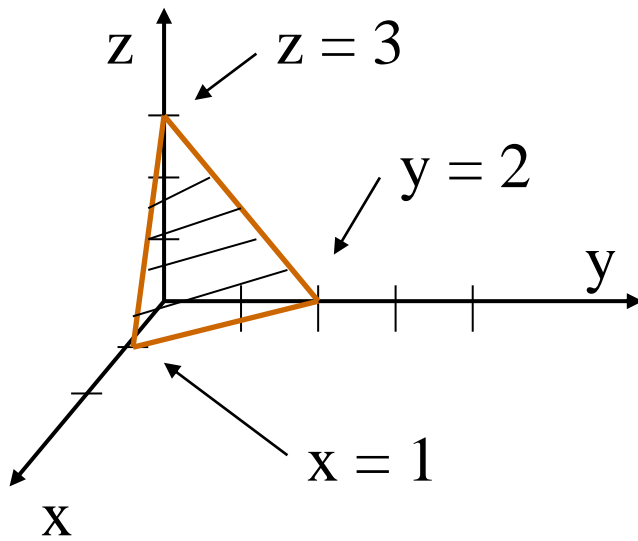
Example 1.2 : Miller Indices

- Find the Miller indices (hkl) for the plane of the image below.

Solution:

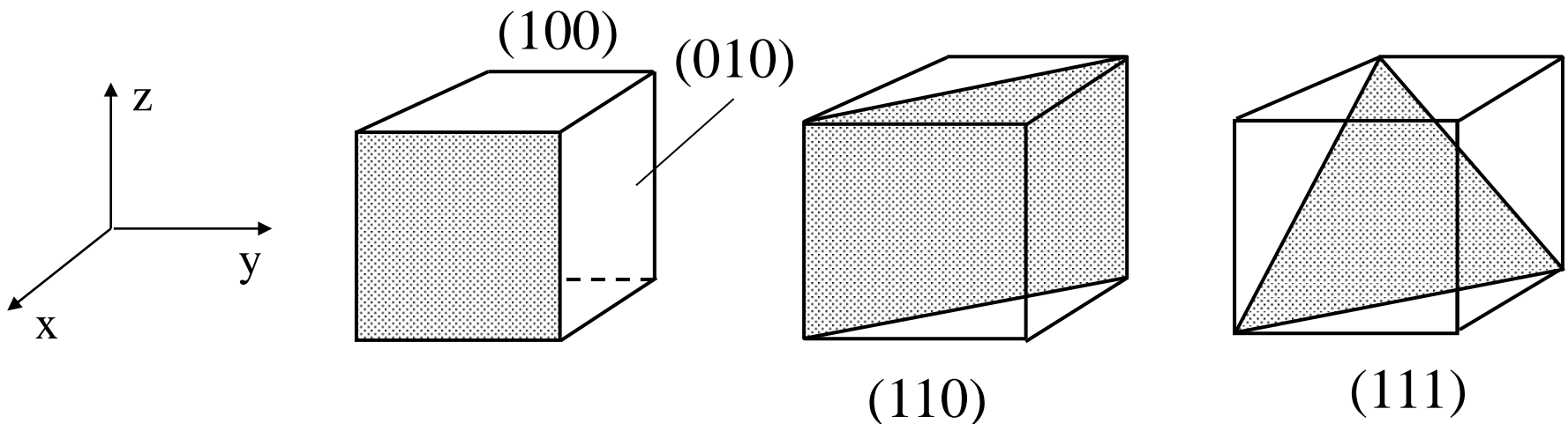
1. We take the intersections: $s_1=1$, $s_2=2$, and $s_3=3$,
2. Calculate the reciprocals, this is: $(1, 1/2, 1/3)$
3. Multiply by their lowest common denominator, to clear out the fractions (in this case by 6).

$$(6*1, 6*1/2, 6*1/3) = (6 \ 3 \ 2) = (h,k,l)$$



Crystal planes in cubic crystals

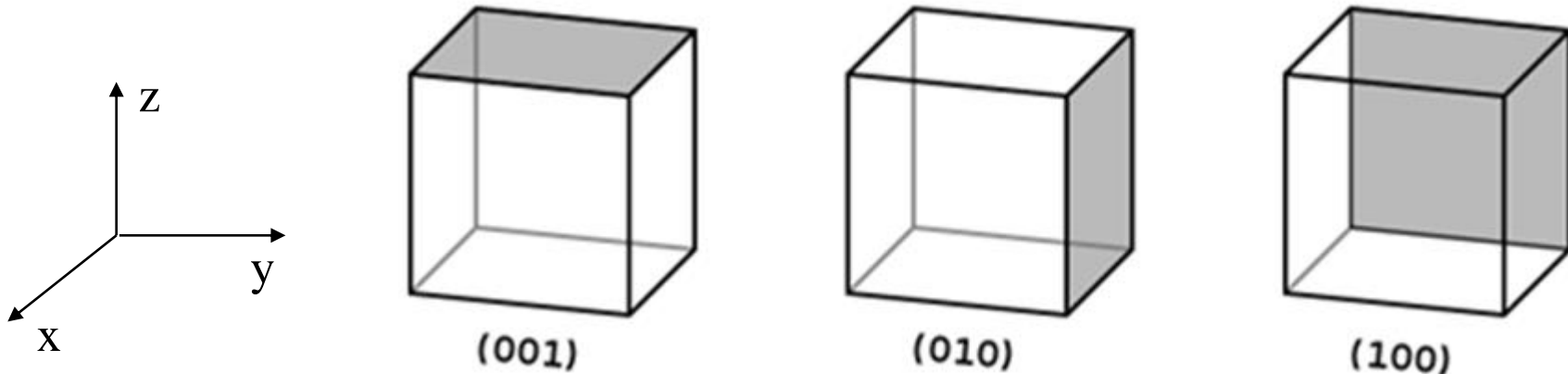
- The following figure shows crystal planes of a cubic crystal.
- Although each crystal plane has its own Miller indices, some of the crystal planes are **equivalent**, that is, *a plane with given Miller indices can be shifted about in the lattice simply by choice of the position and orientation of the unit cell.*
- The indices of such equivalent planes are enclosed in **braces** $\{ \}$ instead of parentheses



- For example in the cubic lattice, all the cubic faces are crystallographically equivalent in that the unit cell can be rotated in various directions and still appear the same. The six equivalent faces are collectively designated as $\{100\}$.

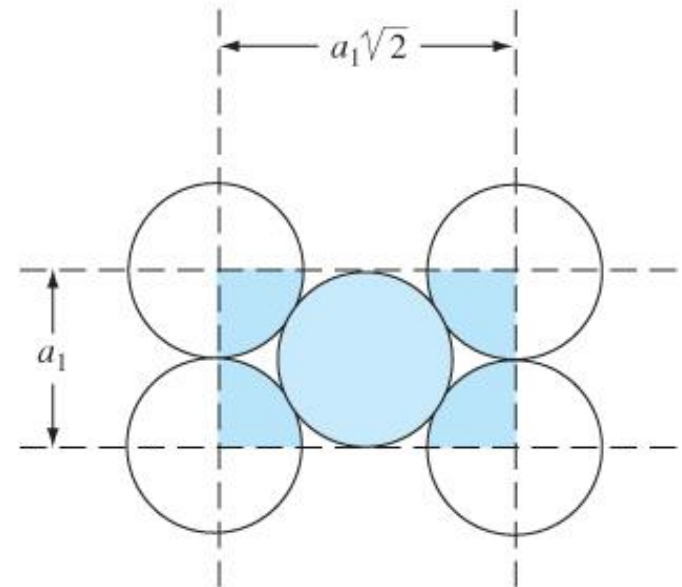
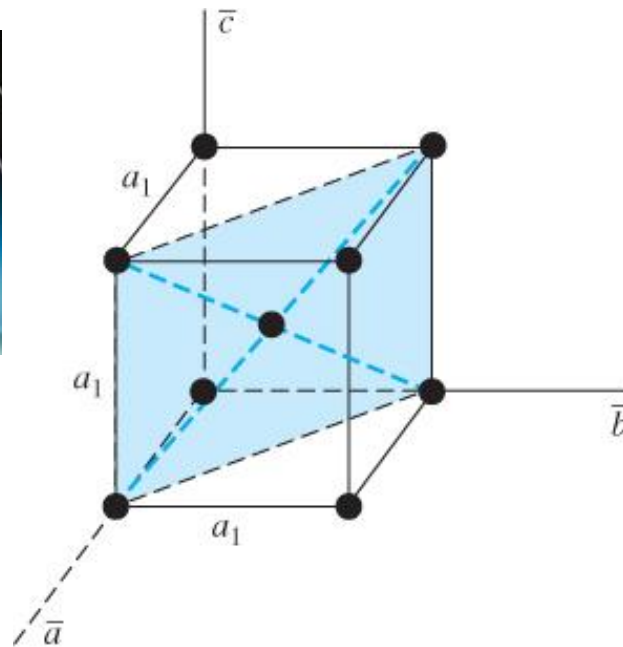
Note: (hkl) = a single plane; $\{hkl\}$ = a family of symmetry-equivalent planes

Crystallographically equivalent planes and directions are planes and directions which encompass the same pattern of lattice points. They may be transformed into each other by the symmetry of the crystal system.



Example 1.3: Surface Density

- Consider the body-centered cubic structure and the (110) plane in the figure. Assume the atoms can be represented as hard spheres with closest atoms touching each other. Assume the lattice constant is a $a_1 = 5\text{\AA}$. Calculate the surface density of the plane in a unit cell?

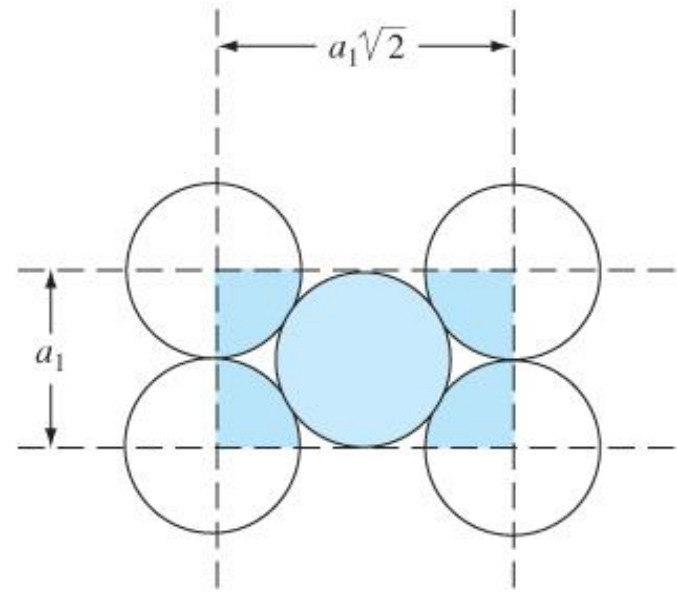
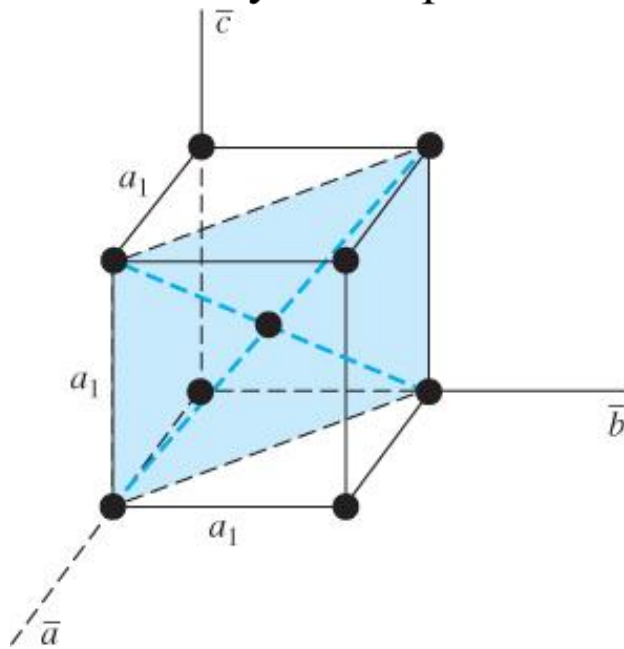


$$\text{Surface Density} = \frac{\text{\# of atoms per lattice plane}}{\text{area of lattice plane}}$$

Solution

Example 1.3

- Consider the body-centered cubic structure and the (110) plane in the figure. Assume the atoms can be represented as hard spheres with closest atoms touching each other. Assume the lattice constant is $a_1 = 5\text{\AA}$. Calculate the surface density of the plane in a unit cell?



$$\text{Surface density} = \frac{2 \text{ atoms}}{(a_1)(a_1\sqrt{2})} = \frac{2}{(5 \times 10^{-8})^2 (\sqrt{2})^2} = 5.66 \times 10^{14} \text{ atoms per cm}^2$$

Crystal Direction

Crystal direction is defined by noting the **coordinates** of the **nearest lattice point** on the line and expressing them as multiples of the basic unit vector **a**, **b**, and **c**. The direction index of a vector $\mathbf{r} = h\mathbf{a} + k\mathbf{b} + l\mathbf{c}$ drawn from the origin, is written as **[hkl]**.

- For cubic lattices, the direction [hkl] is perpendicular to the (hkl) plane. This perpendicularity may not be true in noncubic lattices

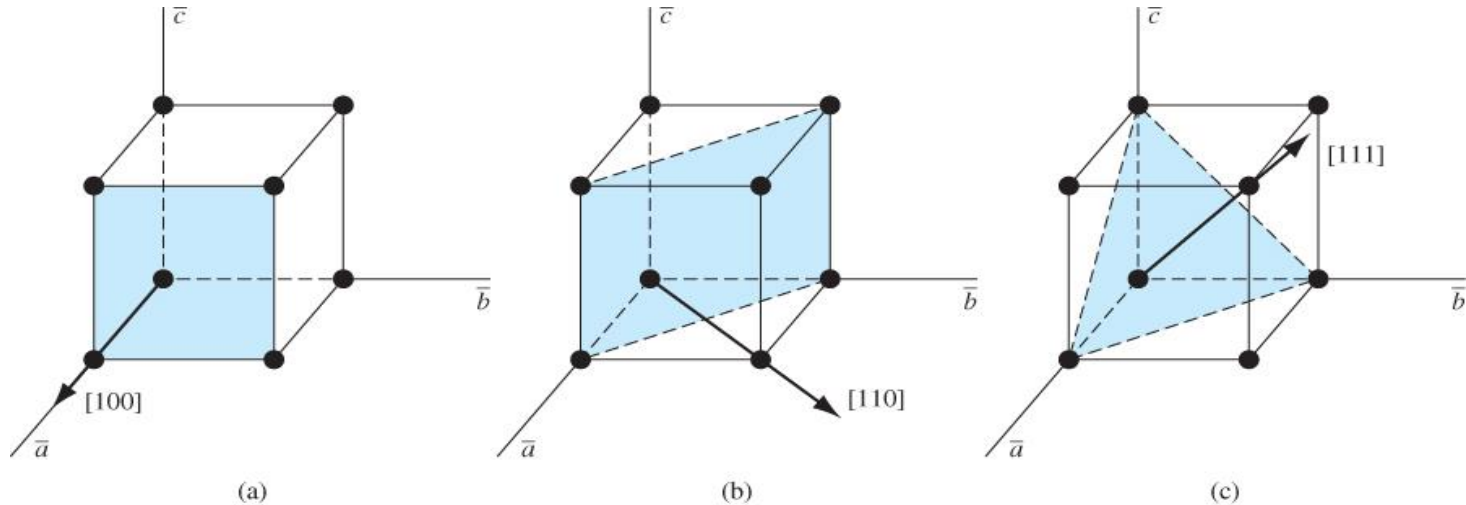


Figure 1.10 | Three lattice directions and planes: (a) (100) plane and [100] direction, (b) (110) plane and [110] direction, (c) (111) plane and [111] direction.

Crystal Planes and Directions

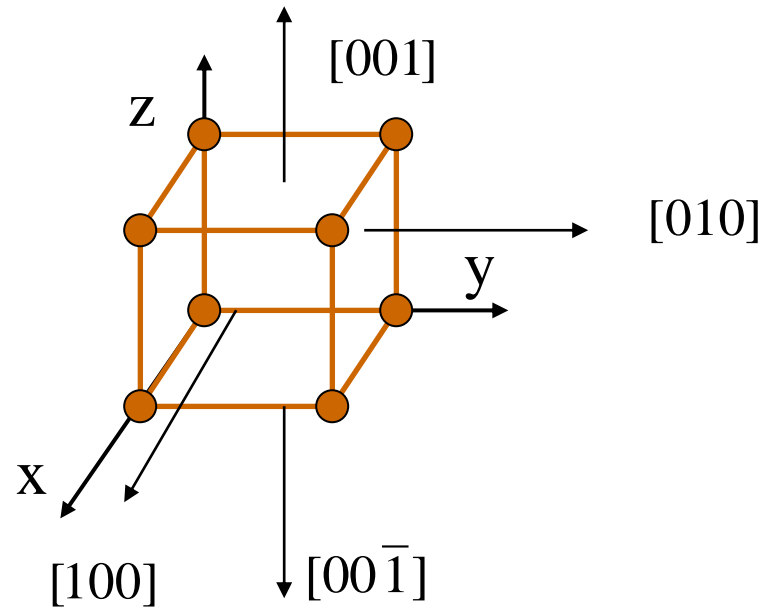
As in the case of crystal planes, many directions in a crystal lattice are **equivalent**. depending on the **arbitrary choice or orientation for the axes**. Such **equivalent direction** indices are placed in $\langle \rangle$. For example the crystal directions in the cubic lattice $[100]$, $[010]$ and $[001]$ are all equivalent and are called $\langle 100 \rangle$ directions.

Note:

$[hkl]$ = a specific direction;

$\langle hkl \rangle$ = a family of symmetry-equivalent directions

Note that for cubic lattices, the direction $[hkl]$ is perpendicular to the (hkl) plane



Negative integers are traditionally written with a bar, as in $\bar{2}$ for -2 .

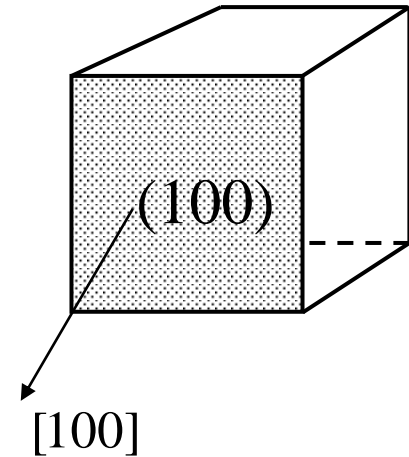
- Summary of notation:

Planes:

(hkl) = a single plane;

$\{hkl\}$ = a family of symmetry-equivalent planes

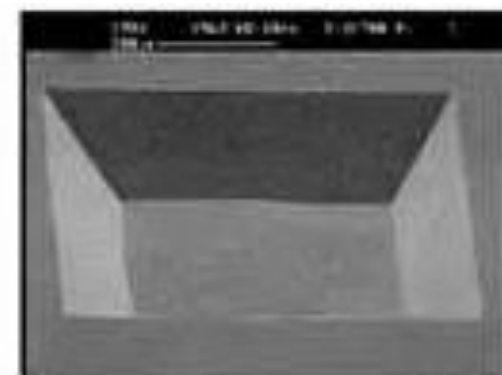
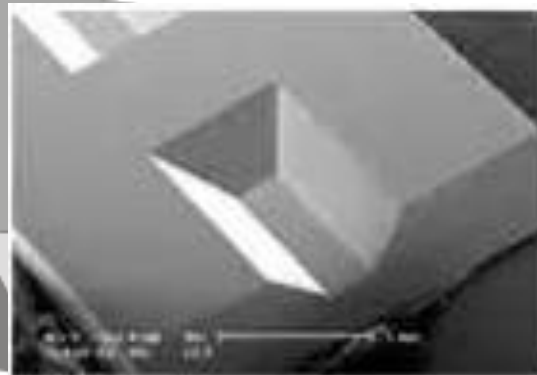
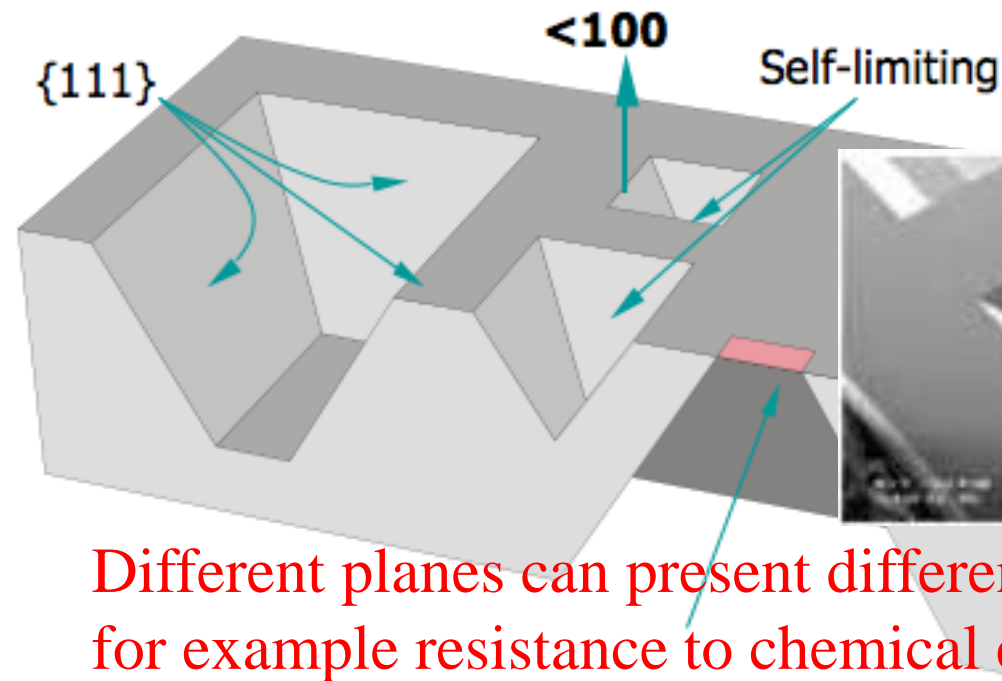
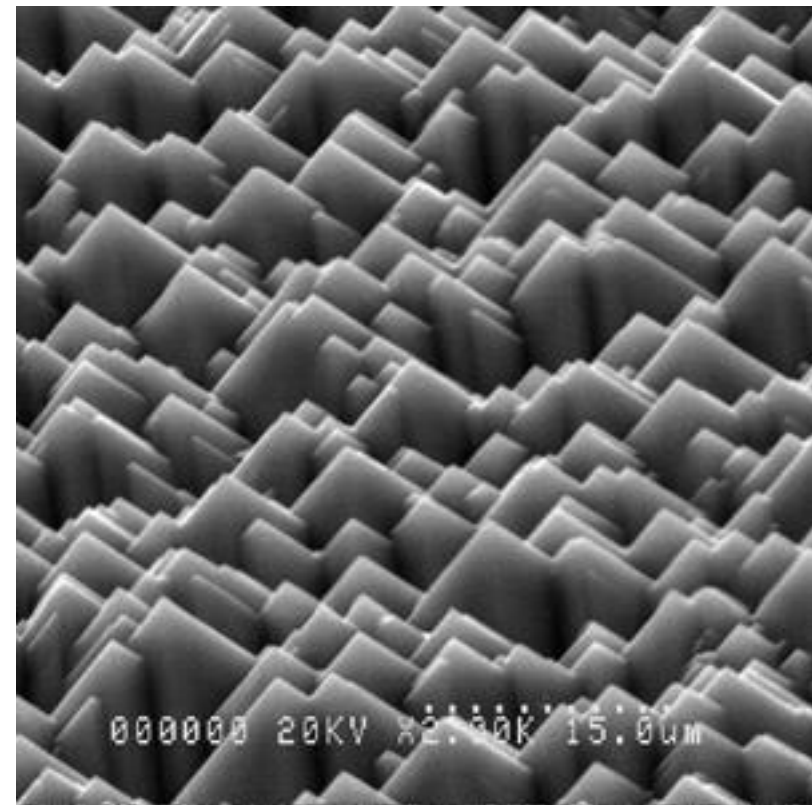
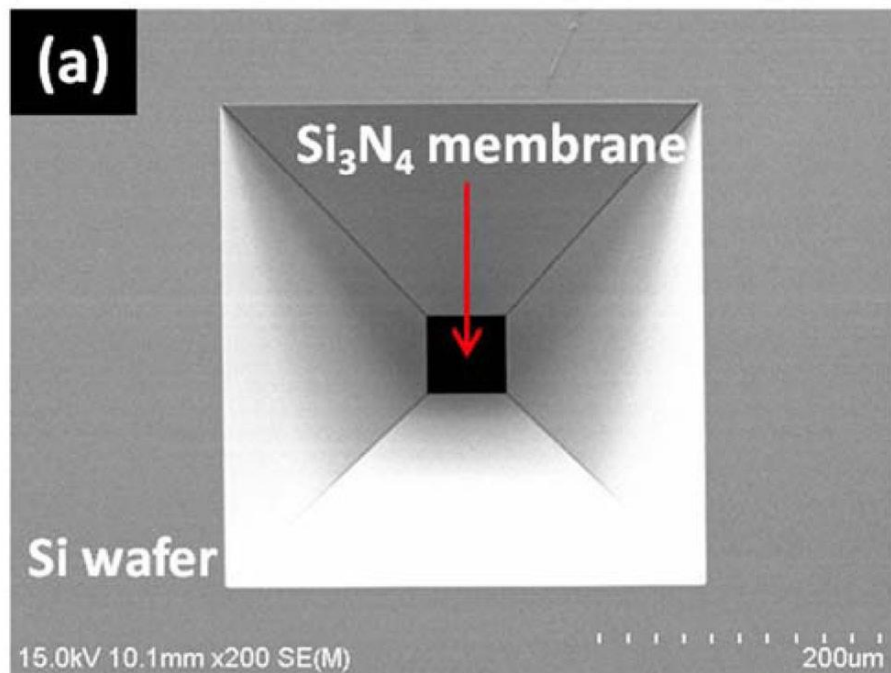
$\{100\} = (100), (010), (001), (-100), (0-10), (00-1)$



Directions:

$[hkl]$ = a specific direction;

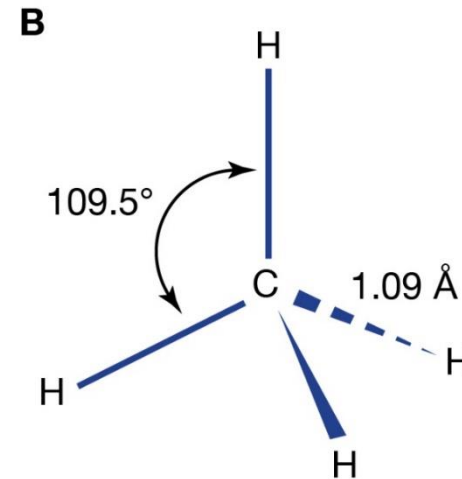
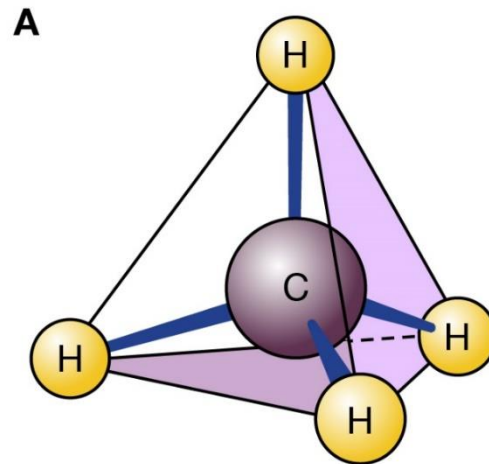
$\langle hkl \rangle$ = a family of symmetry-equivalent directions



Different planes can present different properties,
for example resistance to chemical etching

Diamond structure

- Silicon and germanium have **diamond structure** formed by covalent bonds, which is more complicated than the simple cubic structure.
- This structure is generated from the position of the orbitals (bonds) of the carbon atom.



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Methane molecule displaying the position of the bonds

Diamond structure

- **Tetrahedral structure** is the basic building block of the diamond lattice.
- Tetrahedral structure is like a body-centered cubic but with four of the corner atoms missing.

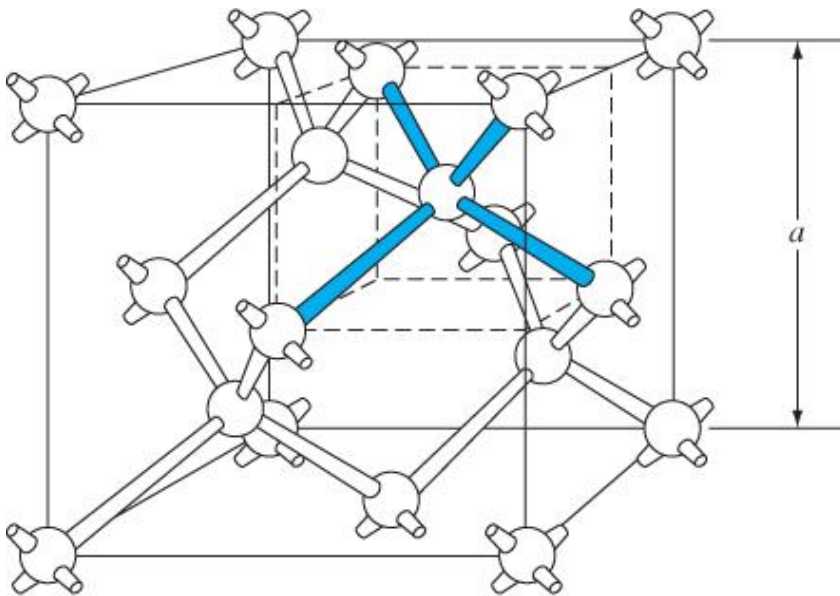


Fig1.11Diamond unit cell

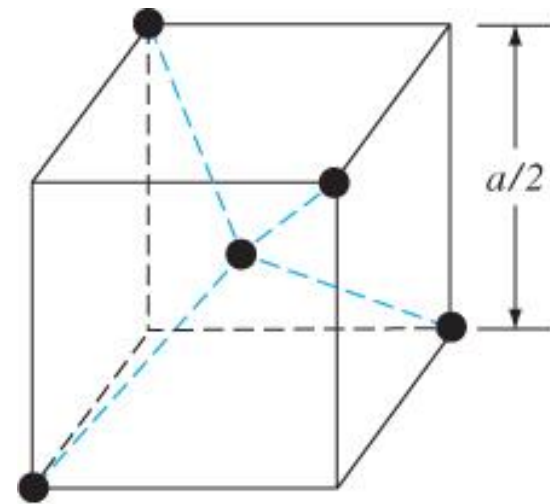


Fig 1.12 Tetrahedral structure

Diamond structure

- Any atom will have four nearest neighboring atoms.

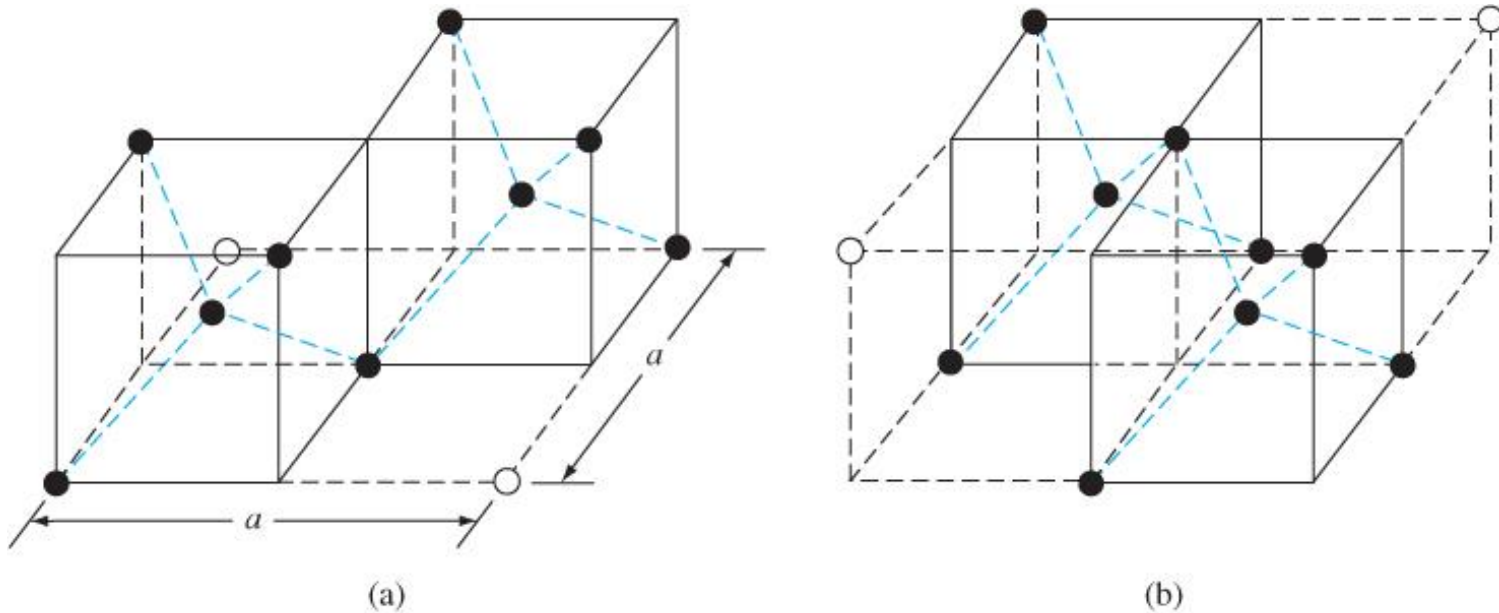
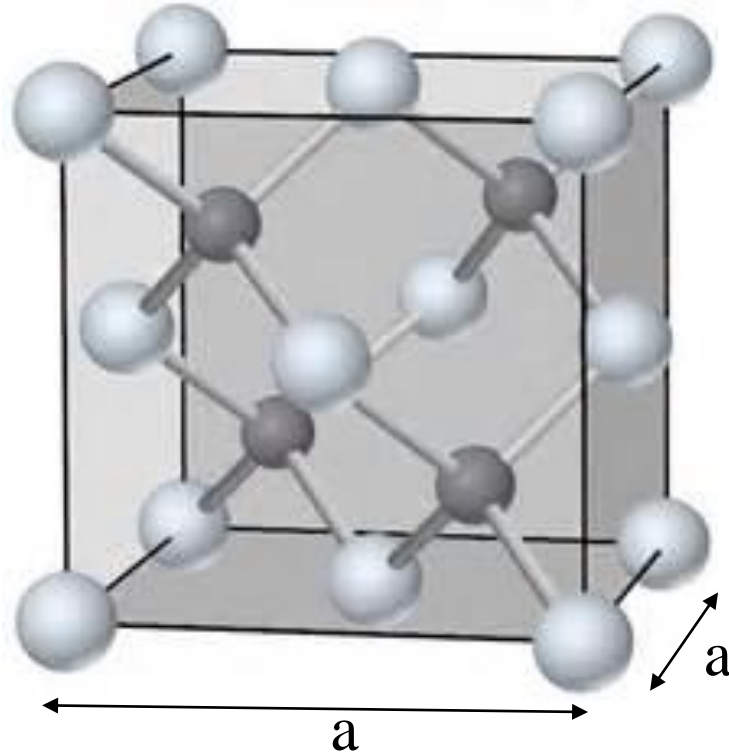


Figure 1.13 | Portions of the diamond lattice: (a) bottom half and (b) top half.

Diamond structure

- It follows a **face centered lattice** (but with 4 extra atoms inside):



Material	Lattice constant “a” (Å)
C (Diamond)	3.567
Si	5.431
Ge	5.658

Diamond structure of compound semiconductor (zincblende)

- It has tetrahedral structure.
- In GaAs, each Ga atom has four nearest As neighbors and each As has four nearest Ga neighbors.
- It is the most common for binary semiconductors: GaAs, GaP, GaSb, InP, InAs, InSb, CdS, CdSe, CdTe, ZnS...

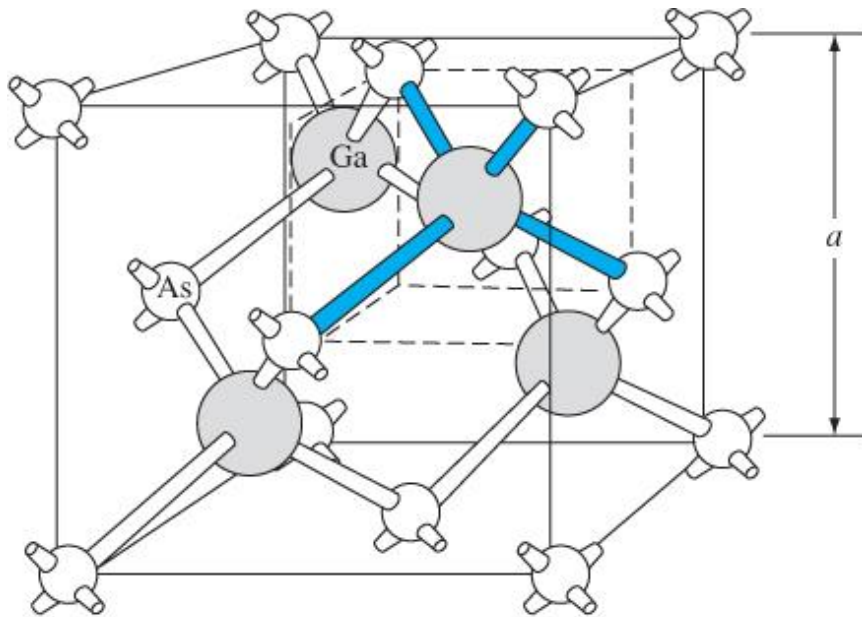


Figure 1.14 | The zincblende (sphalerite) lattice of GaAs.

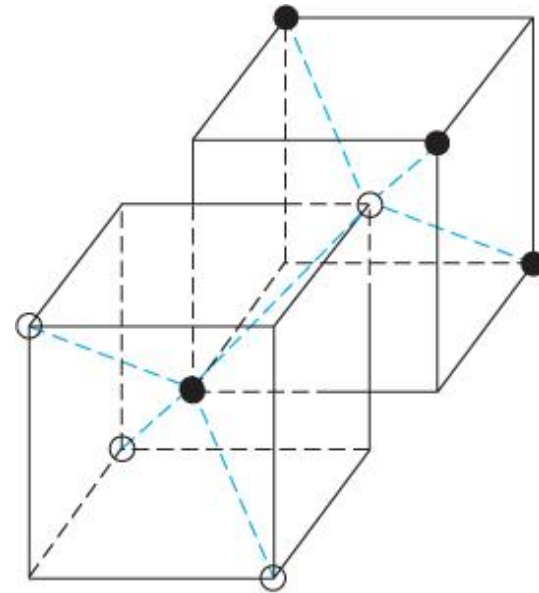


Figure 1.15 | The tetrahedral structure of closest neighbors in the zincblende lattice.

Semiconductor materials - basics

1. Semiconductor Material
2. Type of solids
3. Space lattices
 - a. Primitive and unit cell
 - b. Basic Crystal Structure
 - c. Crystal planes and Miller indices
 - d. Diamond structure
4. Imperfections and impurities in Solids
5. Growth from a Melt

Imperfections and impurities in Solids

- In a real crystal, the lattice is not perfect, but contains imperfections or defects.
- Imperfections tend to alter the **electrical properties** of a material and, in some cases, electrical parameters can be dominated by these defects or impurities

Imperfections in Solids

- **Lattice vibration:** Thermal energy → vibration of lattice in random manner → randomly fluctuation of distance between atoms → disrupting the perfect geometric arrangement of atoms → affect some electrical parameters
- **Point defects:** Change the electrical properties of the material.
 - **Vacancy:** when an atom is missing from a particular lattice site.
 - **Interstitial:** an atom located between lattice sites.
 - **Frenkel defect:** when a vacancy and interstitial are in close enough proximity to exhibit an interaction between the two points.

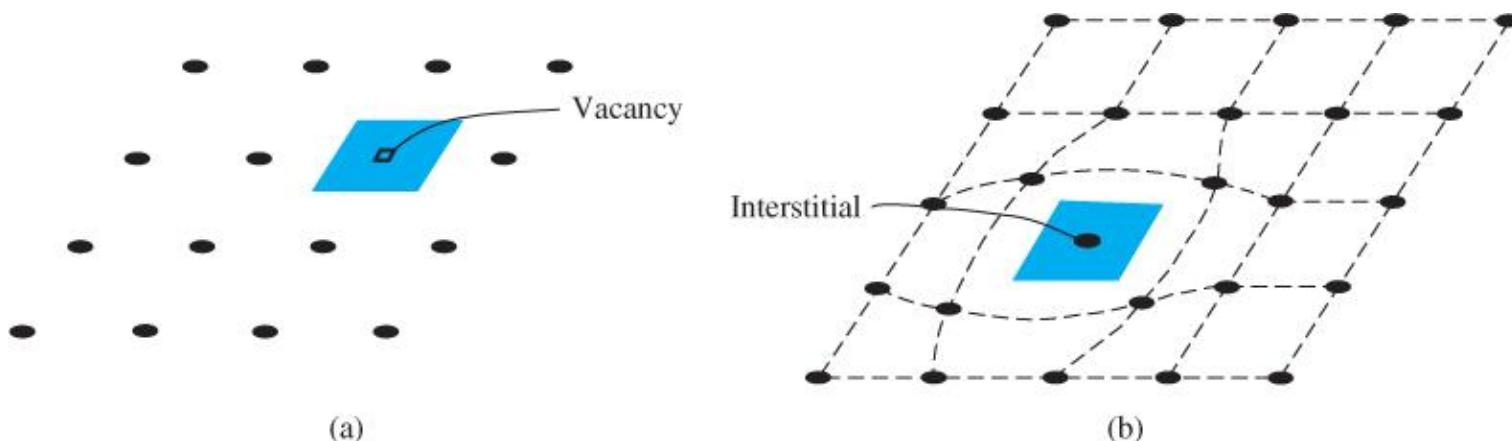


Figure 1.18 | Two-dimensional representation of a single-crystal lattice showing (a) a vacancy defect and (b) an interstitial defect.

Imperfections in Solids

- **Line dislocation:** an entire row of atoms is missing.

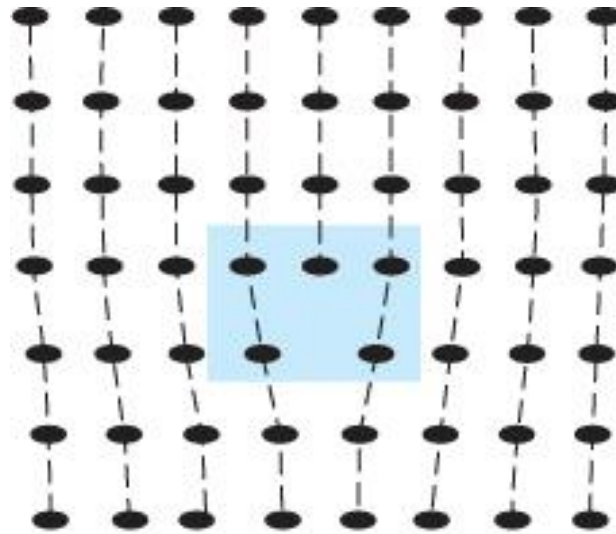


Figure 1.19 | A two-dimensional representation of a line dislocation.

Impurities in Solids

- Foreign atoms, or impurity atoms, may be present in a crystal lattice.
- **Substitutional impurities:** located at normal lattice sites.
- **Interstitial impurities:** located between normal sites.
- Some impurities, such as oxygen in silicon, tend to be essentially inert.
- Other impurities, such as gold or phosphorous in silicon, can drastically alter the electrical properties of the material.

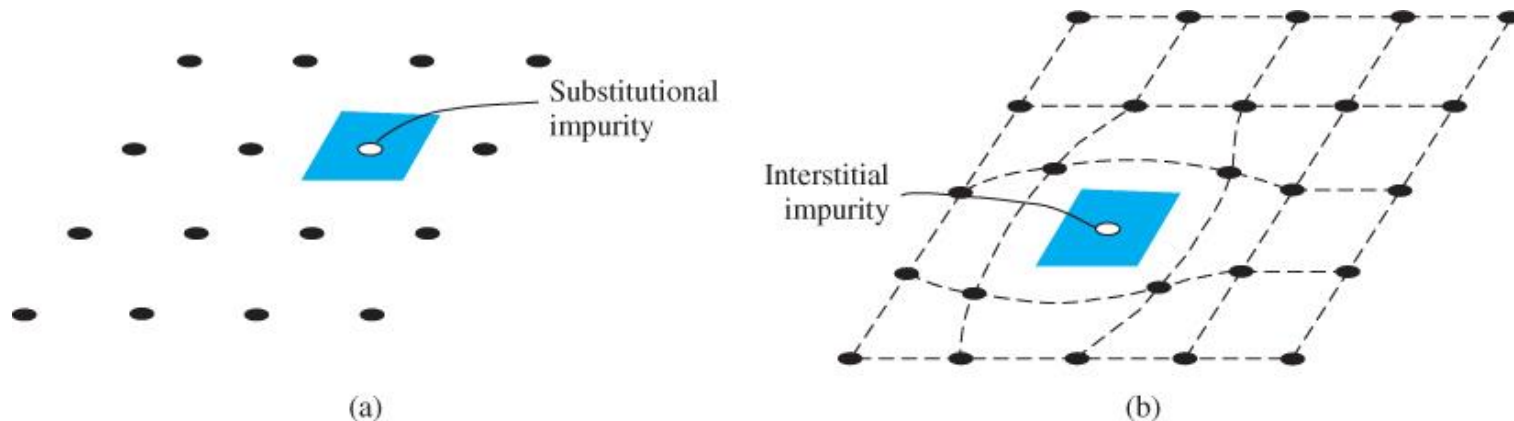


Figure 1.20 | Two-dimensional representation of a single-crystal lattice showing (a) a substitutional impurity and (b) an interstitial impurity.

Impurities in Solids: Doping

- By adding a **controlled amount** of a particular impurity atoms, the electric characteristics of a semiconductor material can be favourably altered.
- **Doping:** is the technique of adding impurity atoms to a semiconductor material in order to change its conductivity.
- There are two general methods of doping:
 - impurity diffusion,
 - ion implantation
- **Impurity diffusion:** Semiconductor crystal is placed in a high temperature gaseous atmosphere containing the desired impurity atom. Impurity particles move from a region of high concentration near the surface to a region of low concentration. When the temperature decreases, the impurity atoms become permanently frozen into the substitutional lattice sites.



Impurities in Solids

- **Ion implantation:** At lower temperature than diffusion.
- A beam of impurity ions is accelerated to kinetic energies in the range of 50 keV or greater, and then directed to the surface of the semiconductor. Ions enter the crystal and rest at some average depth.
- **Advantage:** control over the number of impurity atoms and depth.
- **Disadvantage:** the incident impurity atoms collide with the crystal atoms, causing lattice-displacement damage.

Semiconductor Grade Si

Typical Impurity Level	
Boron	< 0.1 ppba
Phosphorous	< 0.1 ppba
Other Donors	< 0.03 ppba
Carbon	< 0.15 ppma
Transition Metals (Total Cu, Ni, Fe)	< 1 ppba

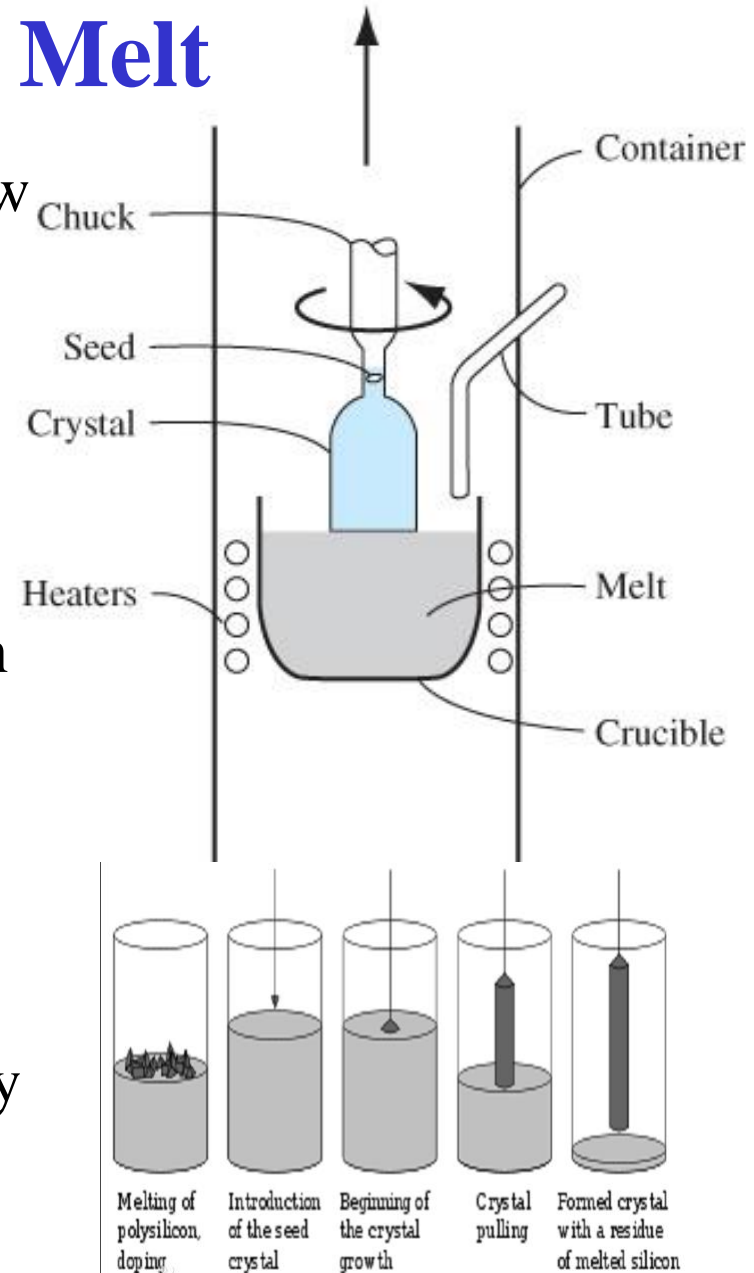
How can we get a **large** crystal?

Growth from a Melt

Czochralski: a common technique to grow single-crystal materials.

A small piece of single-crystal material, known as a **seed**, is brought into contact with the surface of the same material in liquid phase, and then slowly pulled from the melt.

As the seed is slowly pulled, solidification occurs along the plane between the solid-liquid interface. Usually the crystal is also **rotated** slowly as it is being pulled, to provide a slight stirring action to the melt, resulting in a more uniform temperature. Controlled amounts of specific impurity atoms, such as **boron** or **phosphorus**, may be added to the melt so that the grown semiconductor crystal is intentionally doped with the impurity atom.



Floating zone

Technique to **refine the material**:

A coil melts only a region

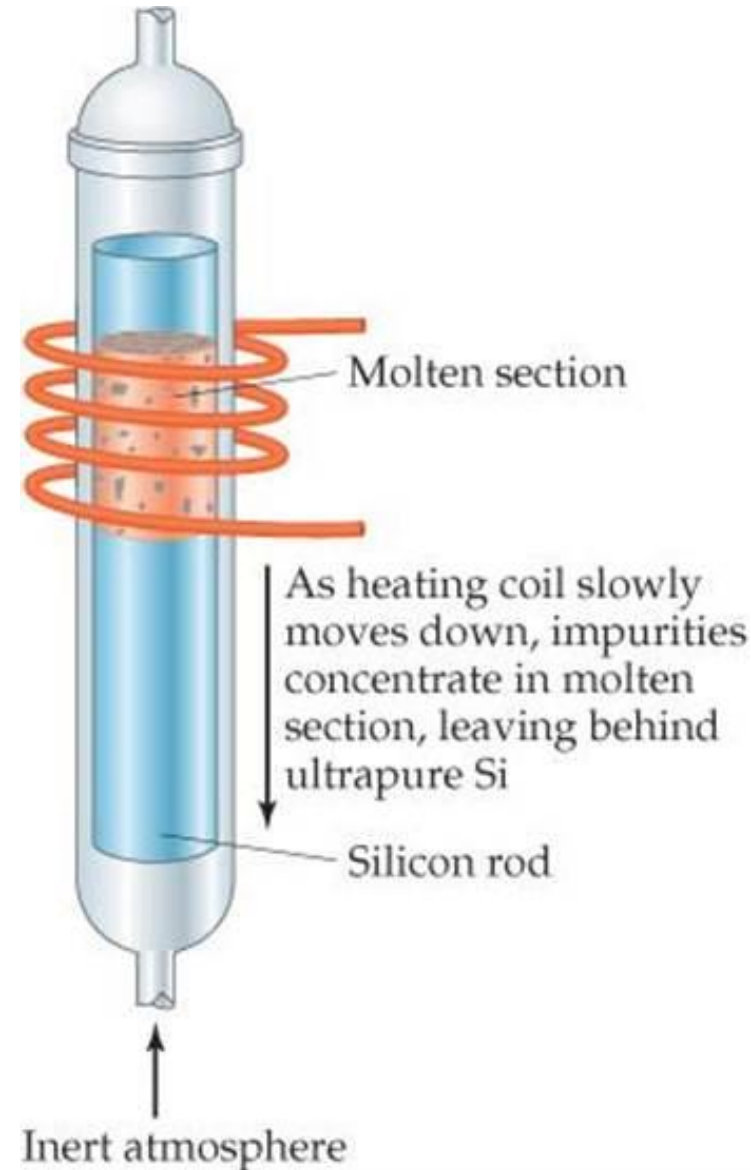
The coil moves down

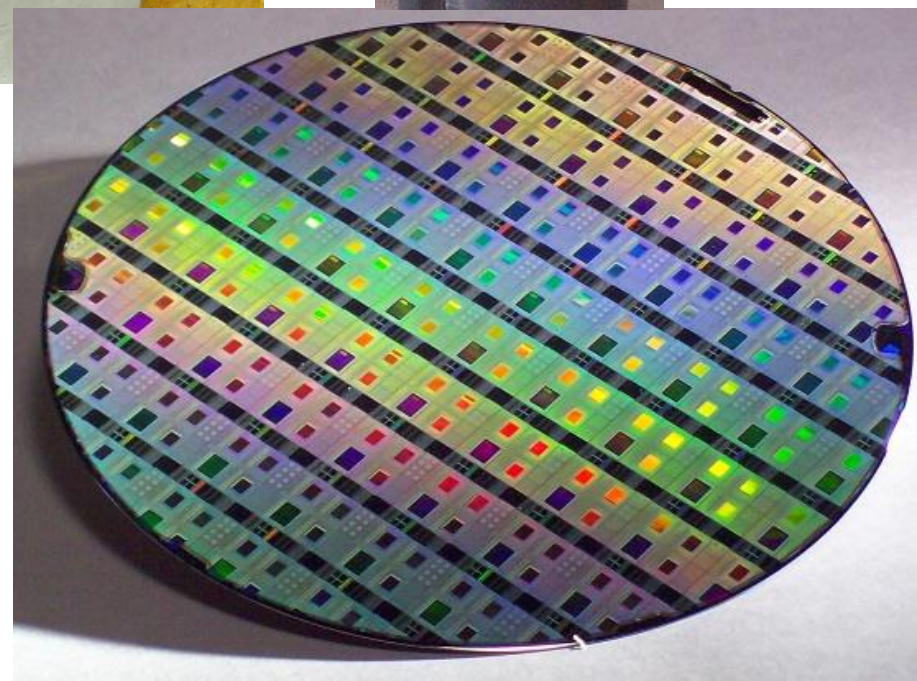
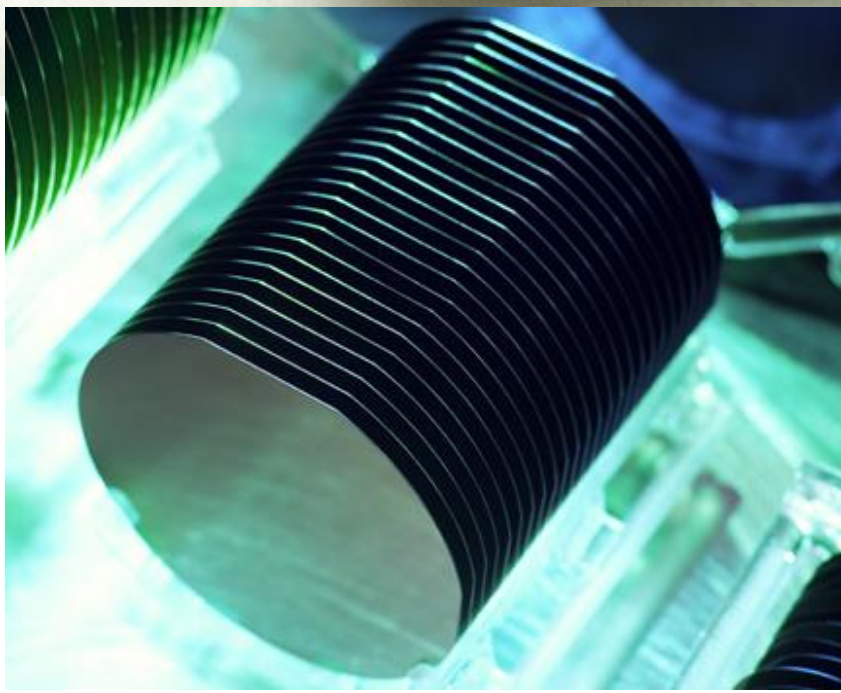
The impurities concentrate at the bottom section

The bottom is discarded

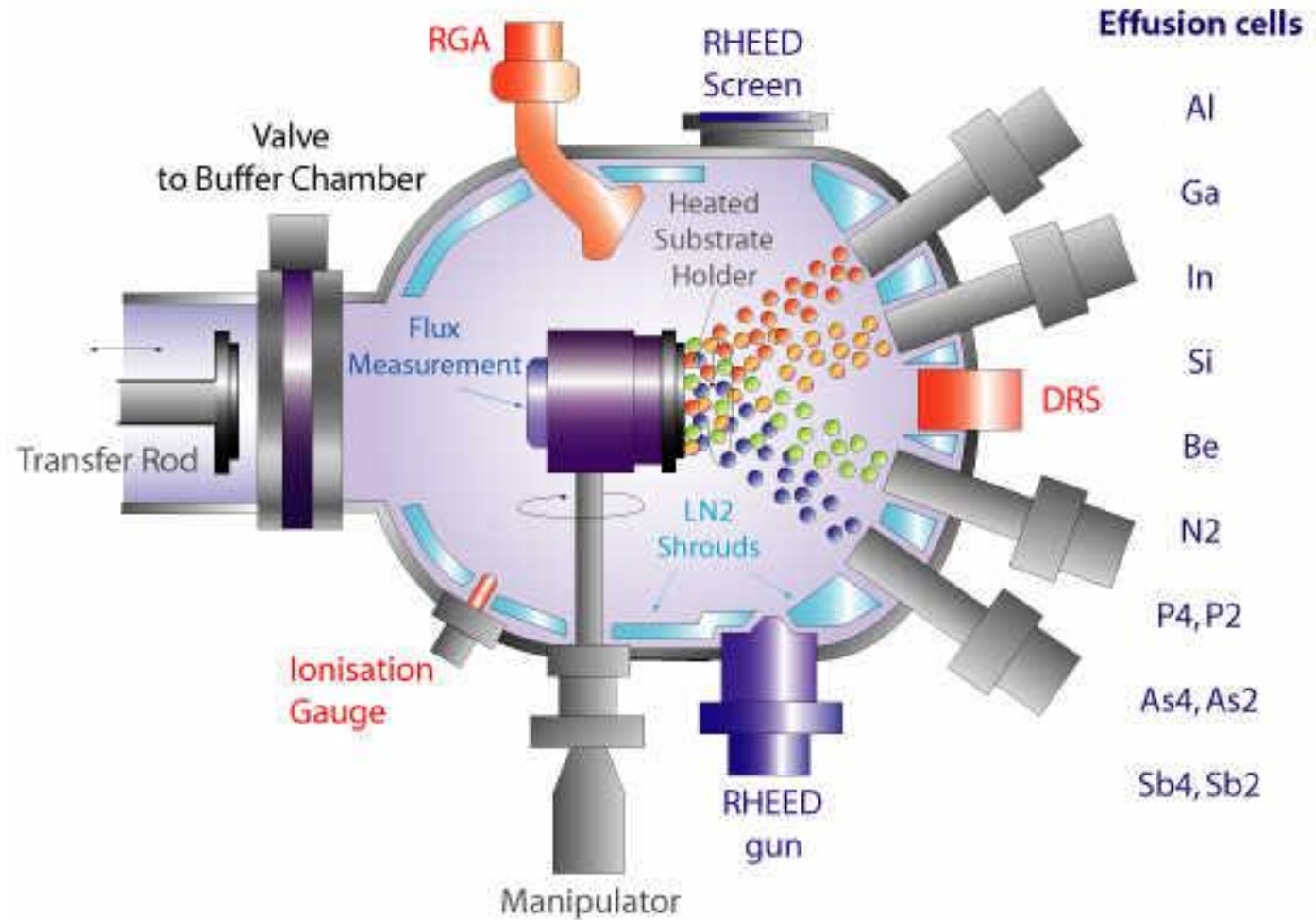
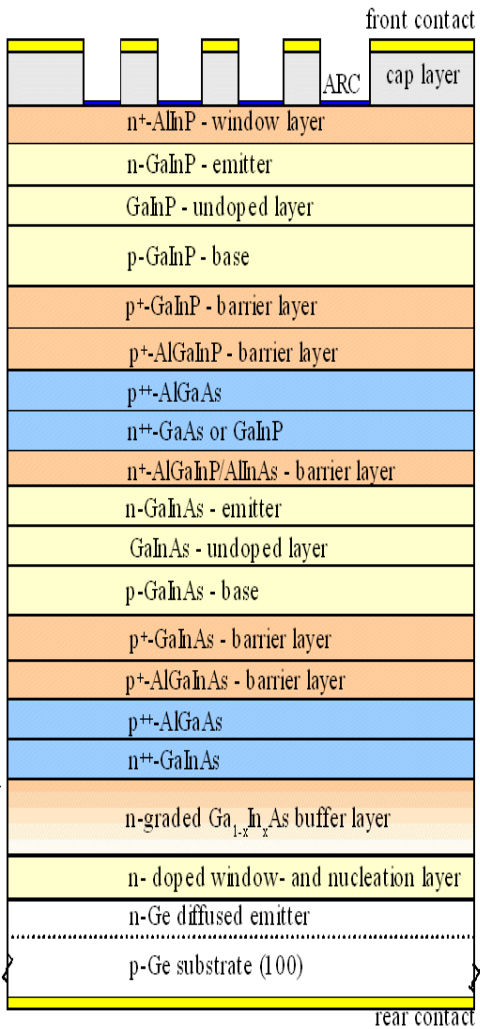
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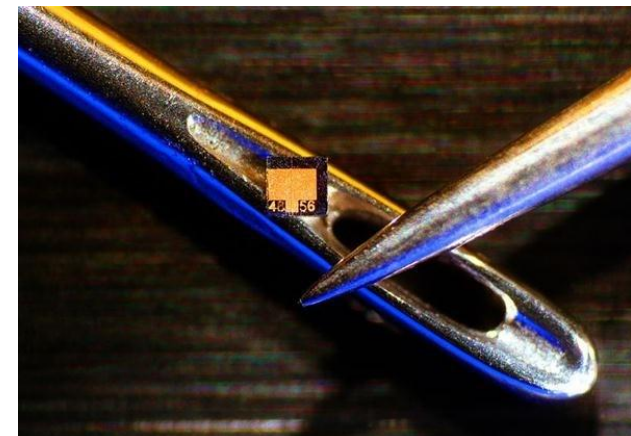
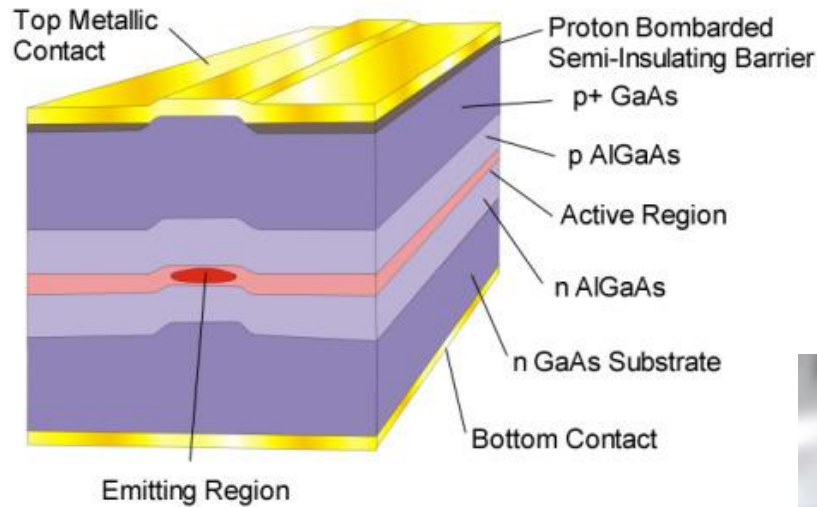
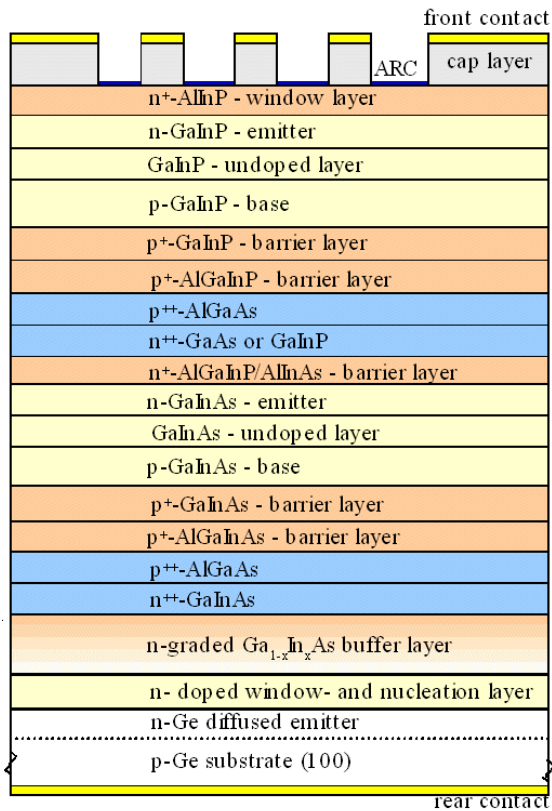




Molecular Beam Epitaxy (MBE)

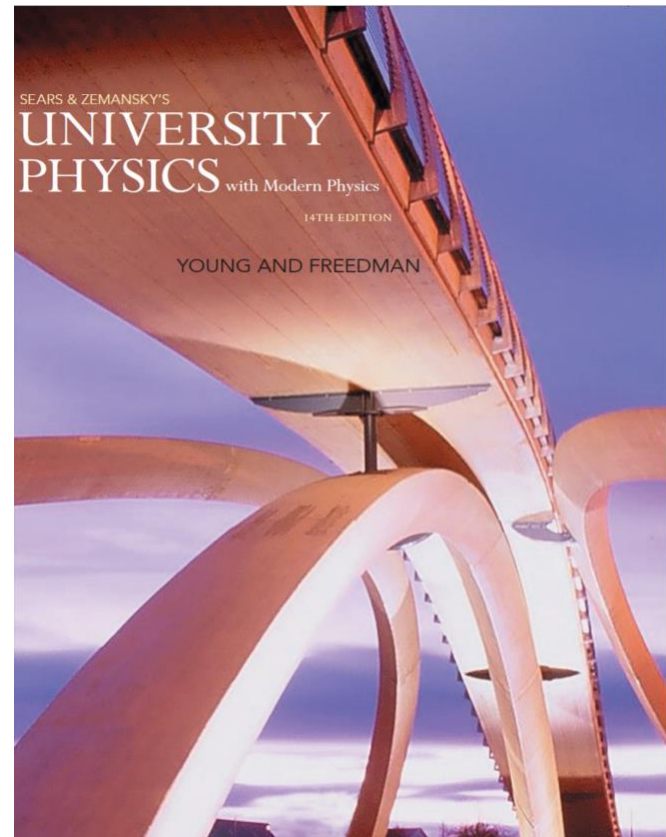


Molecular Beam Epitaxy (MBE)



Fundamental Physics

- 1) Photoelectric Effect
- 2) Quantification of energy
- 3) Duality particle-wave



Light Nature

- **Pre – 1900 – Classical Theories**

- **Light** was thought of as purely a **wave phenomenon** and its properties could be explained by Maxwell type of equations.
- **Electrons and Nuclei** possess charge and mass, and their properties could be explained by Newtonian Mechanics.

- **Post – 1900 - Quantum Mechanical Theories**

Phenomena such as **black body radiation** and **photoelectric effect** could not be explained satisfactorily by classical theory.

- **Wave – Particle duality** is fundamental to understand modern physical electronics.

HISTORY OF QUANTUM PHYSICS

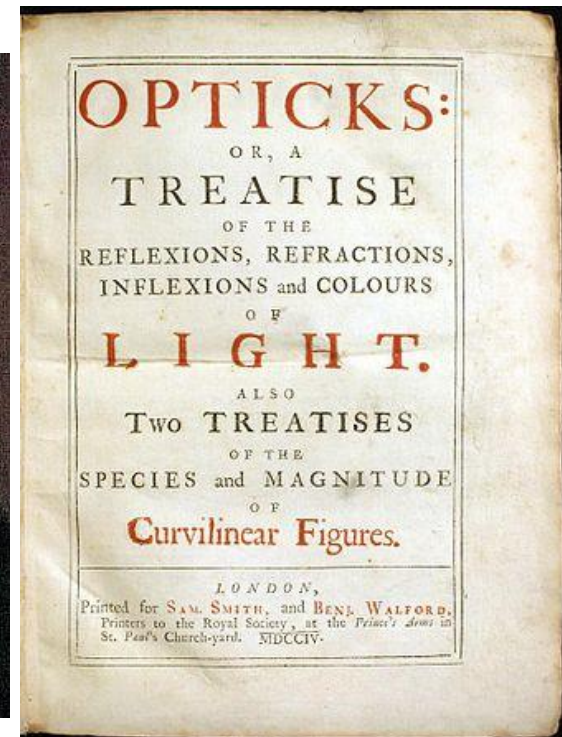
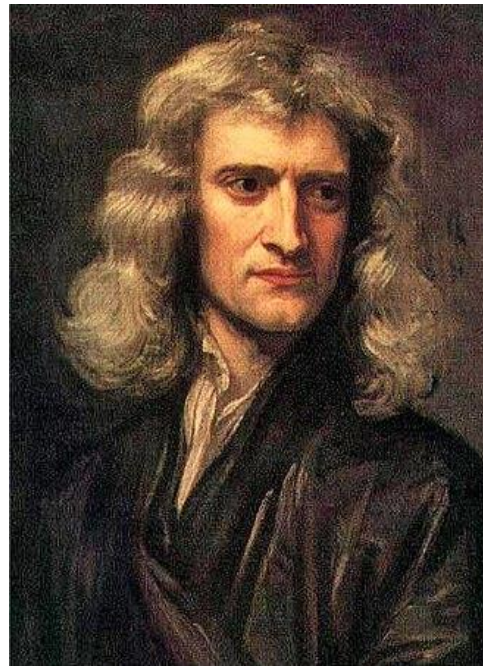
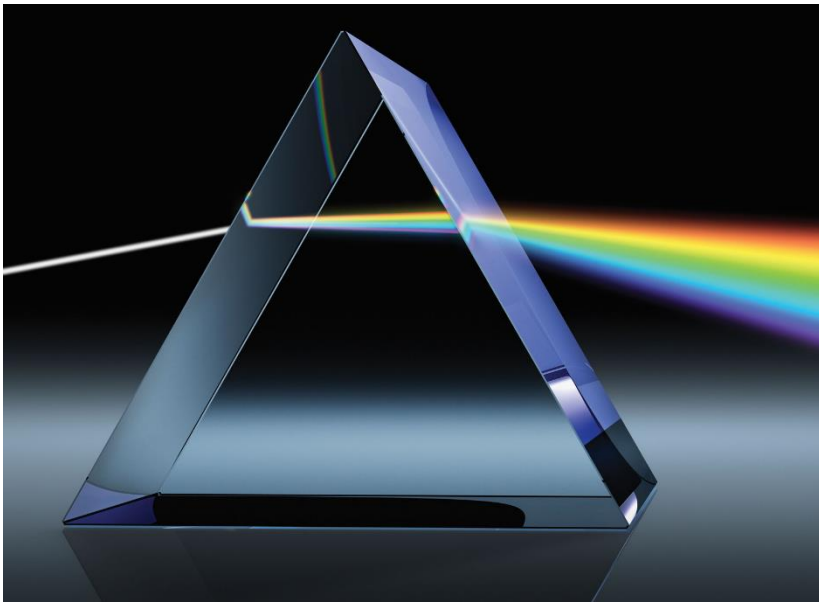
量子 「物理史话」 上帝掷骰子吗

曹天元(Capo)/著

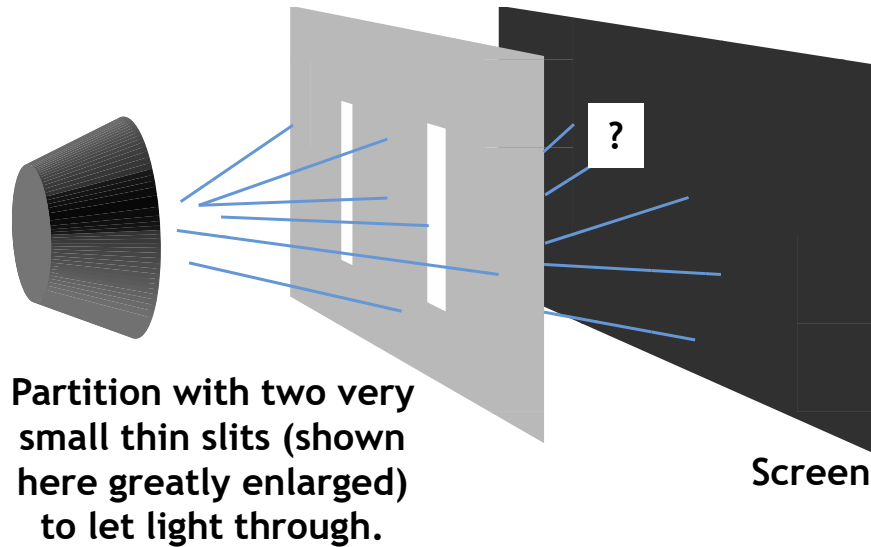
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Classical theories

- Before 1800, there was not much evidence about light nature.
- Isaac Newton assumed that light was formed of extremely small corpuscles, smaller than matter particles.
- In 1704 he published his corpuscular theory of light in his book *Opticks*.



Thomas Young's Double Slit Experiment



Young demonstrated in 1801 that light behaves a wave, showing diffraction and interference

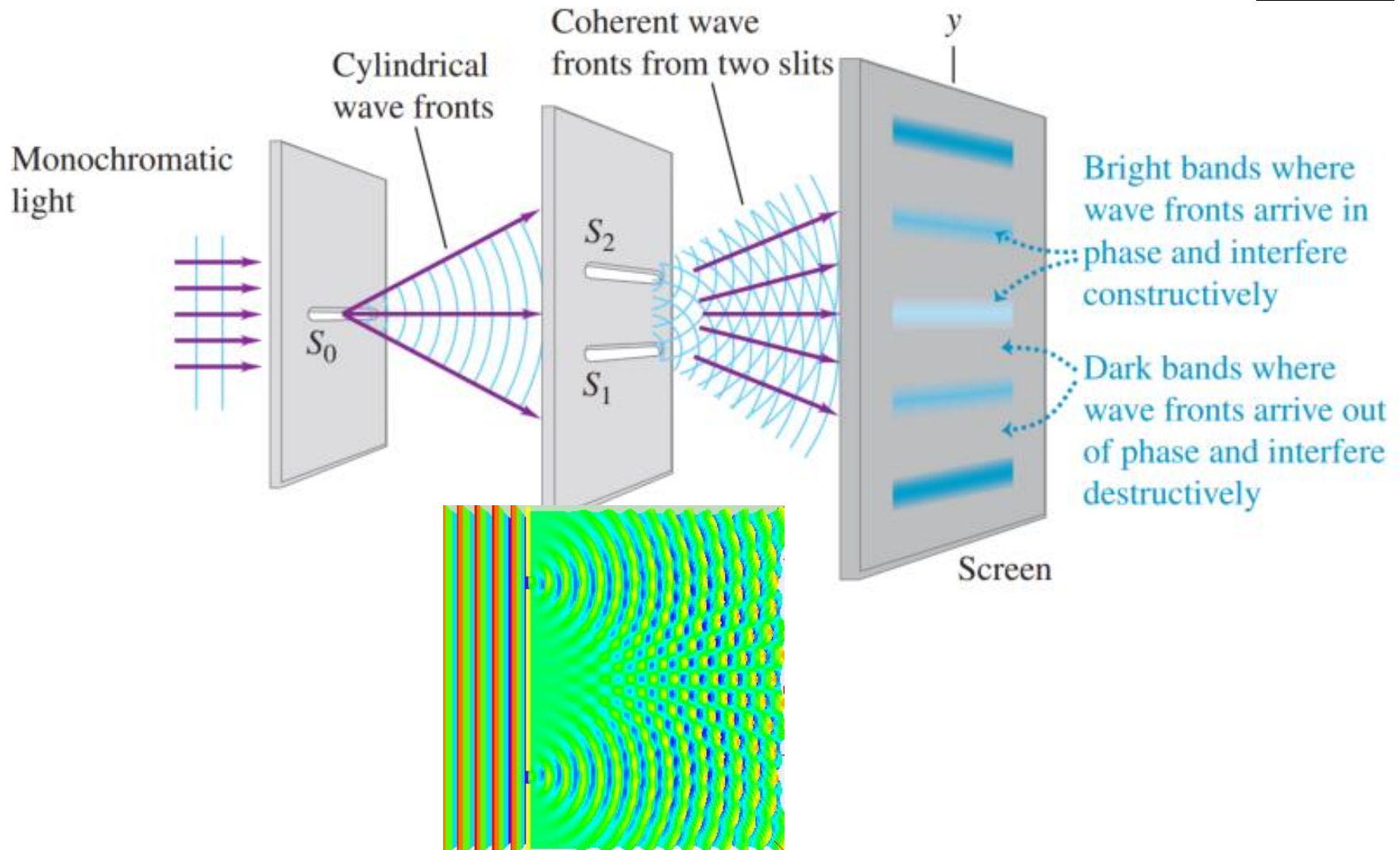


Image is in the public domain

Figure 35.5a shows one of the earliest quantitative experiments to reveal the interference of light from two sources, first performed in 1800 by the English scientist Thomas Young.

(a) Interference of light waves passing through two slits

Interference is the defining characteristic of waves



Classical theories: by 1800 Light was supposed a wave

1. It shows interferences.

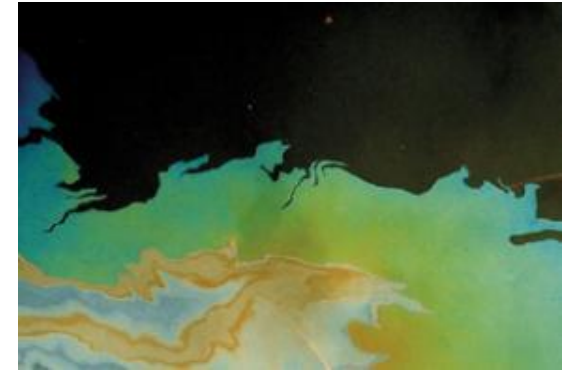
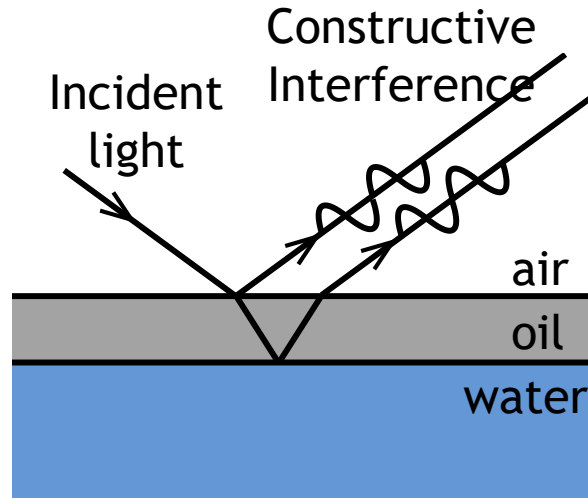
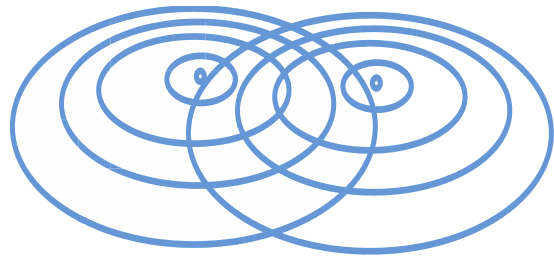
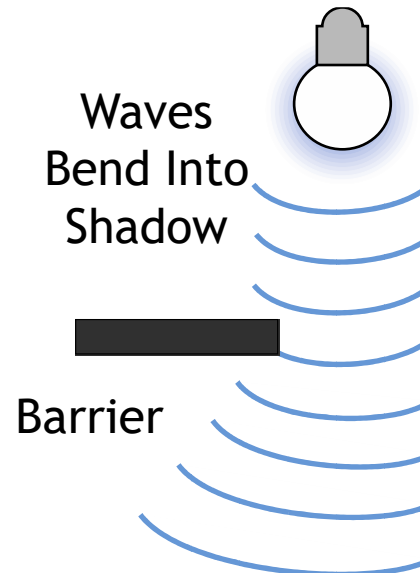
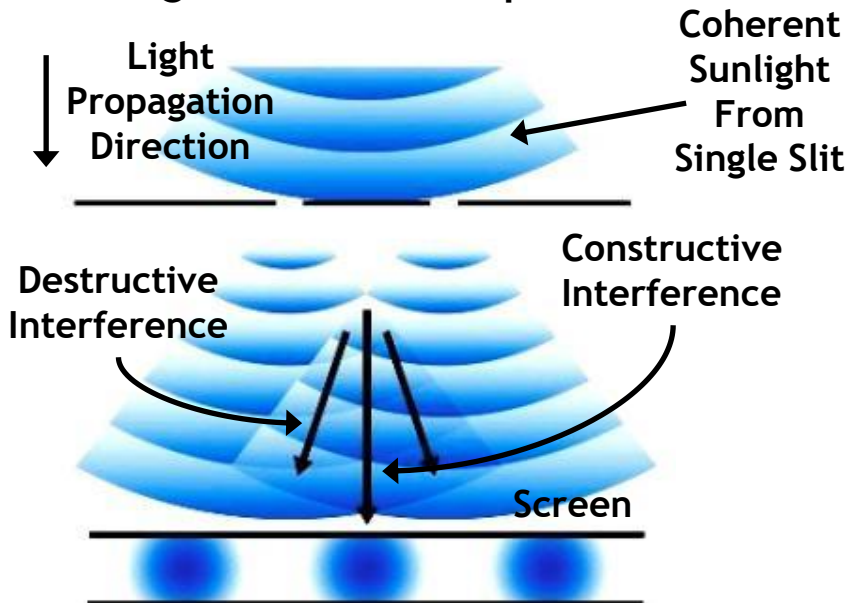


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Young's Double Slit Experiment



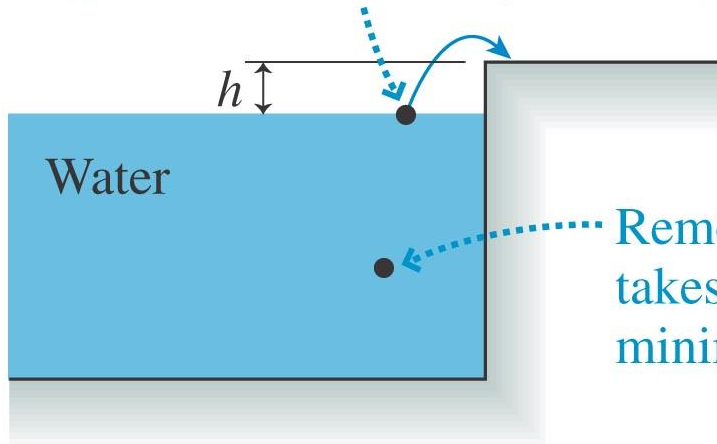
2. It is diffracted.

How would light interact with matter?

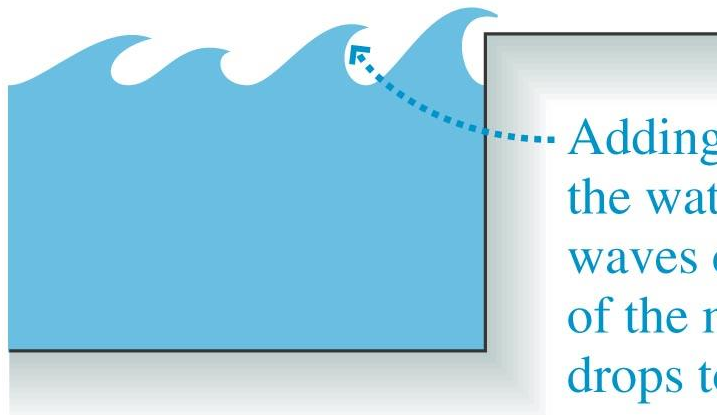
The Photoelectric Effect

What would make an electron leave a solid?

The *minimum* energy to remove a drop of water from the pool is mgh .

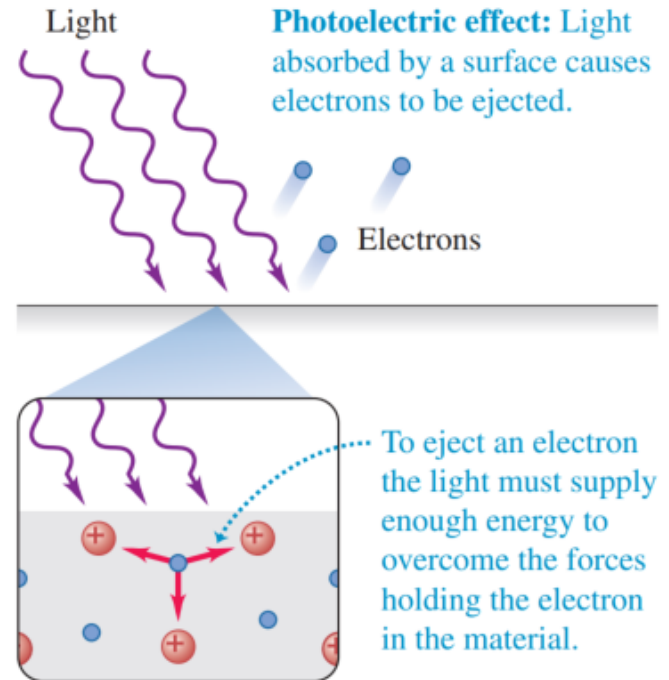


Removing this drop takes more than the minimum energy.



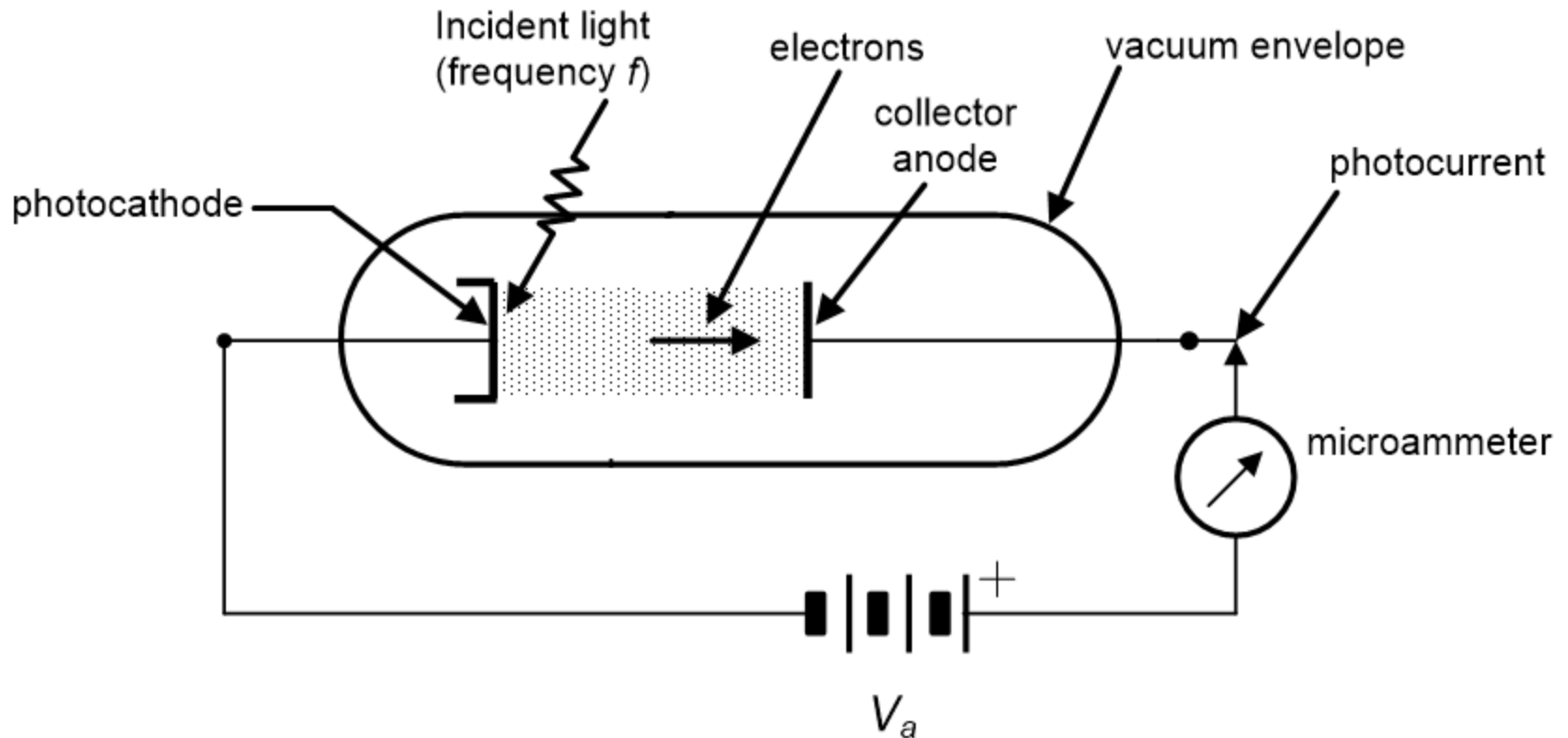
Adding energy to the water and making waves can cause a few of the most energetic drops to escape.

38.1 The photoelectric effect.



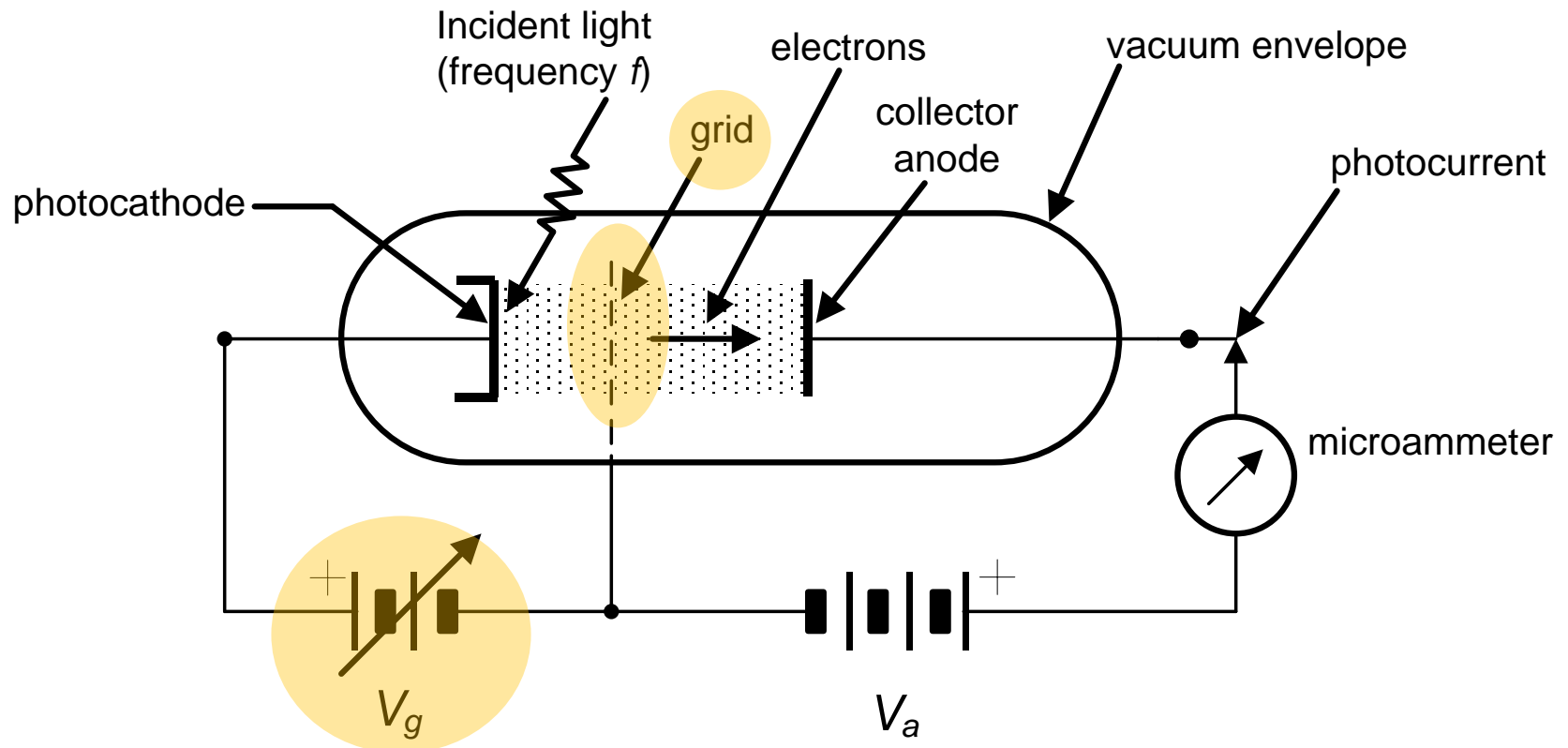
The Photoelectric Effect

- First observed by Heinrich Hertz in 1887.
- If light of sufficiently short wavelength impinges on the surface of certain solids, (usually metals), then it is possible for electrons to be emitted from the solid. This is called the *Photoelectric Effect*. The effect may be demonstrated by using an apparatus of the type shown in the diagram



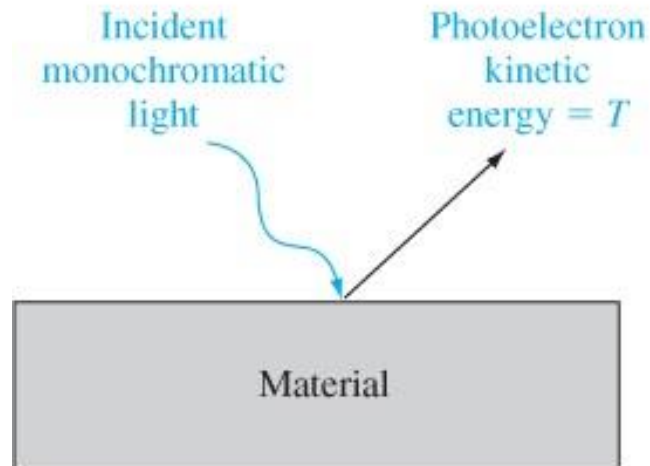
The Photoelectric Effect

- By placing a grid with a reversed voltage (V_g) creates a **potential barrier** that allows to measure the kinetic energy of the electrons.
- Only electrons with kinetic energy higher than V_g will be able to go through the barrier.



The Photoelectric Effect

- A diagram illustrating the emission of electrons from a metal plate, requiring **energy** gained from an incoming photon to be more than the **work function** of the material.

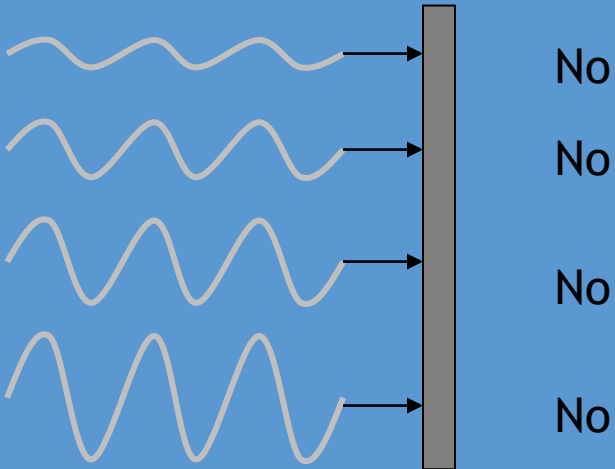


Observation of the Photoelectric Effect

“Classical” Method

Increase energy by
increasing amplitude

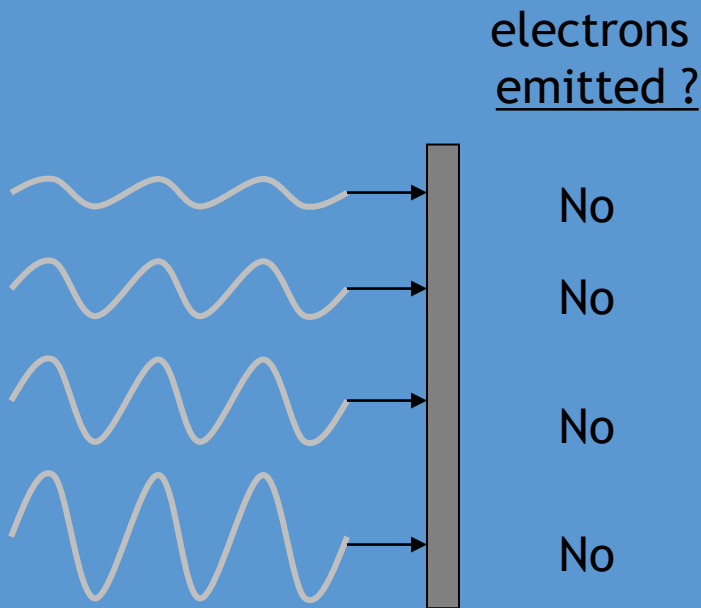
electrons
emitted ?



Observation of the Photoelectric Effect

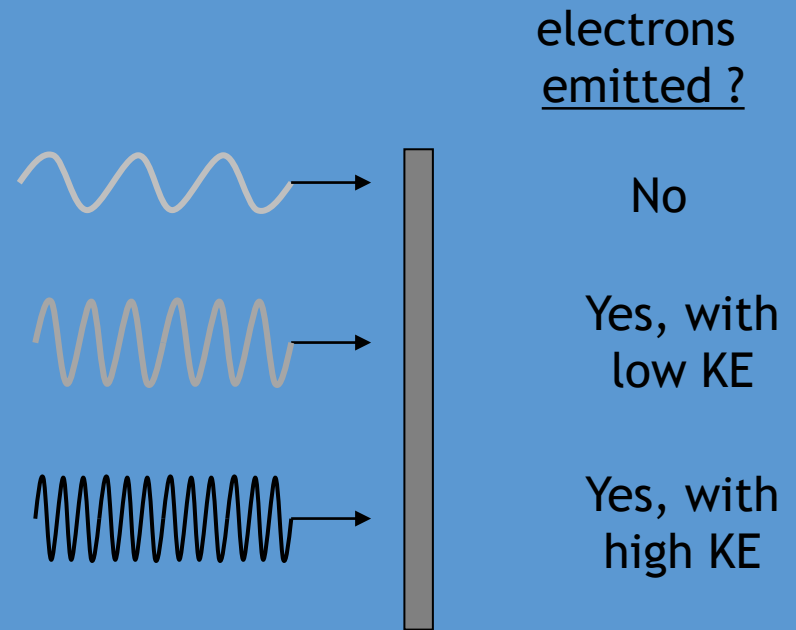
“Classical” Method

Increase energy by
increasing amplitude



What if we try this ?

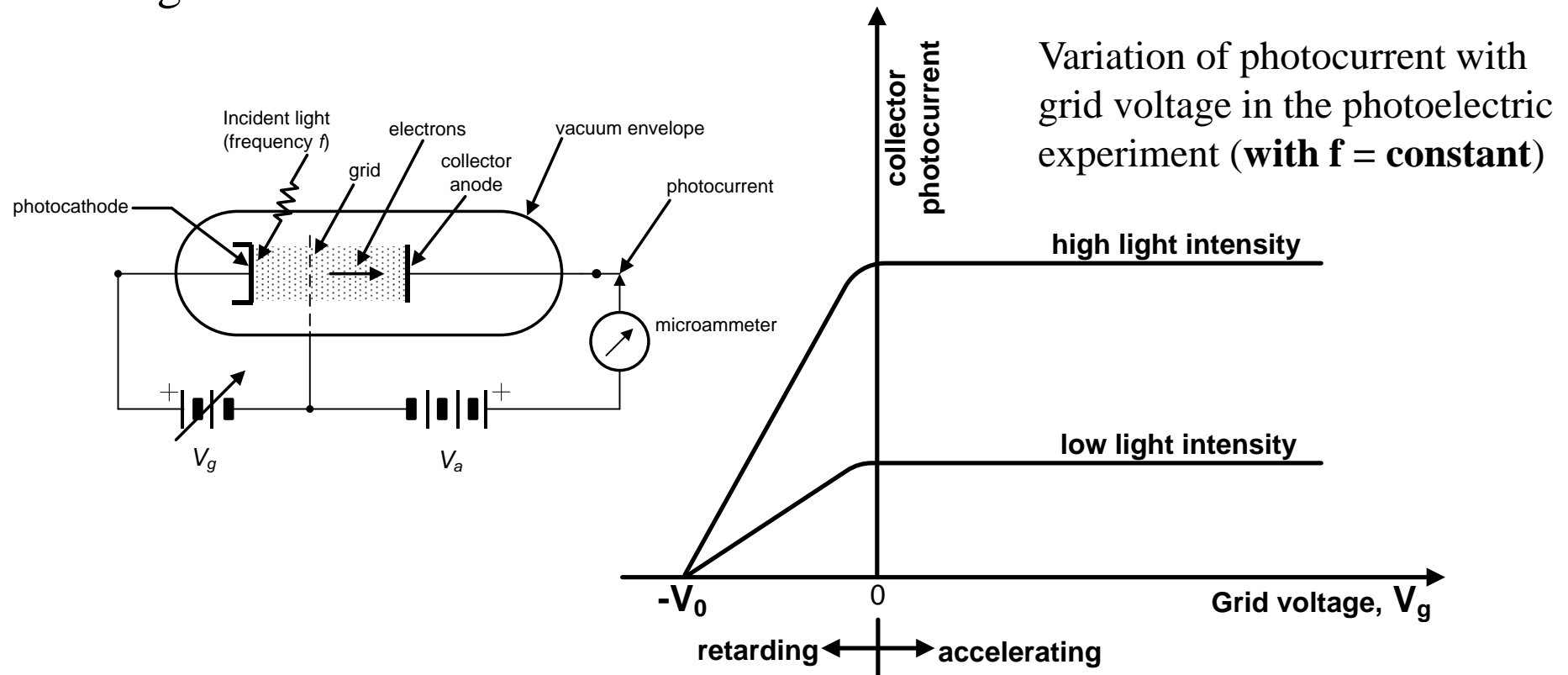
Vary wavelength, fixed amplitude



No electrons were emitted until the frequency of the light exceeded a critical frequency (f_0), at which point electrons were emitted from the surface !
(Recall: small $\lambda \rightarrow$ large ν)

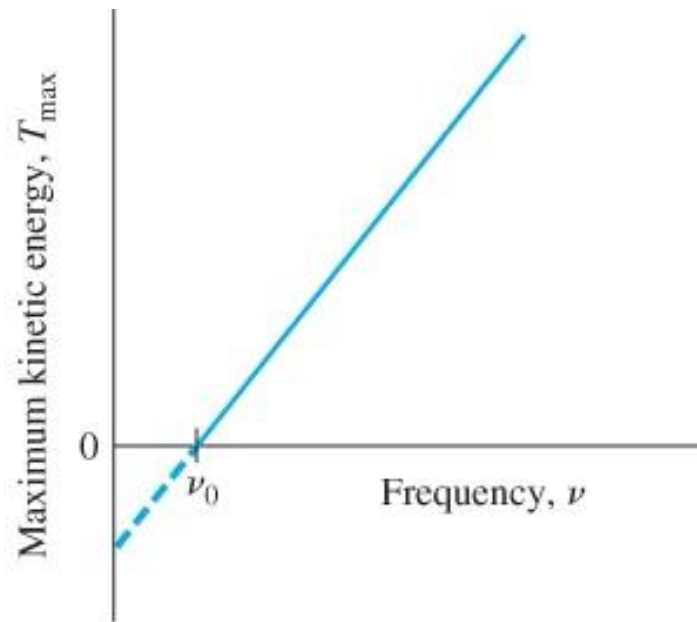
The Photoelectric Effect

- Unless the frequency of the incident light is greater than some critical value f_0 , no emission is observed, no matter how intense the light.
- f_0 is dependant on the cathode material.
- If $f > f_0$, **the photocurrent** can be measured as a function of grid voltage V_g and of light intensity keeping collector voltage constant to give the collector current.



The Photoelectric Effect

- For each f , there is a constant retarding voltage, which entirely inhibits emission ($-V_0$, stopping potential). No matter what the intensity of the light is.
- This implies that the maximum kinetic energy of emitted electrons is independent of the intensity of the incident light.
- If we plot the stopping potential against incident light frequency, a straight line is produced with a slope of h/e



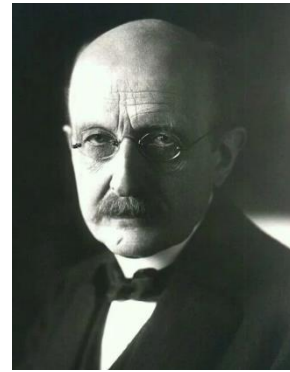
Classical Theory Explanation

- According to the Classical Theory... if light is a wave... electrons should gain sufficient energy to be emitted if the light is bright enough (ie., if it is of sufficient intensity).

Contradictions to Classical Theory

- Electrons are emitted instantaneously, $\sim 10^{-14}$ s , providing the frequency is high enough.
- There is no explanation for the threshold frequency, f_0 .
- The maximum energy of emitted photoelectrons is not dependent on the intensity of the incoming radiation.

Fundamental Concepts



- **Electromagnetic Radiation**

The electromagnetic spectrum covers an extremely large frequency range. The energy of the photons or quanta is given by

$$E = hf$$

where h is Planck's constant equal to $6.63 \times 10^{-34} \text{ J}\cdot\text{s}$ and f is the frequency.

Photons or quanta always travel at the velocity of light, c , which in free space or vacuum can be taken to be $3 \times 10^8 \frac{\text{m}}{\text{s}}$.

A diagram showing the equation $E = hf = \frac{hc}{\lambda}$ on a light yellow background. The equation is written in black. Surrounding the equation are four labels in blue text, each with a dotted blue arrow pointing to a specific part of the equation: 'Planck's constant' points to h ; 'Frequency' points to f ; 'Speed of light in vacuum' points to c ; and 'Wavelength' points to λ . To the left of the equation, the text 'Energy of a photon' is written in blue, with a dotted blue arrow pointing to the E on the left side of the equation.

$$E = hf = \frac{hc}{\lambda}$$

Labels and arrows in the diagram:

- Planck's constant (points to h)
- Frequency (points to f)
- Speed of light in vacuum (points to c)
- Wavelength (points to λ)
- Energy of a photon (points to E)

Quantum Explanation of Einstein – 1905

- Each photon has an **energy equal to hf** and this is the total energy used in the interaction. Some of the energy is used **to overcome** the binding forces of the material (*work function*) and the remainder is **converted to kinetic energy** of the emitted electron.

K.E. of emitted electron = photon energy – work function

$$\frac{1}{2}mv^2 = hf - \phi = eV_0$$

The **limiting case** when the photon energy is equal to the work function and an electron is just emitted with zero kinetic energy. Then

$$hf_0 = \phi$$

$f_0 = \frac{\phi}{h}$, f_0 is the critical frequency or threshold frequency.

The wave theory of light and the quantum theory of light complement each other.

Einstein's postulates

Einstein framed **three postulates** about light quanta and their interaction with matter:

1. Light of frequency f consists of **discrete quanta**, each of energy $E = hf$, where h is Planck's constant $h = 6.63 \times 10^{-34}$ J s. Each photon travels at the speed of light $c = 3.00 \times 10^8$ m/s.
2. Light quanta are emitted or absorbed on an **all-or-nothing** basis. A substance can emit 1 or 2 or 3 quanta, but not 1.5. Similarly, an electron in a metal can absorb only an integer number of quanta.
3. A light quantum, when absorbed by a metal, delivers its entire energy to **one** electron.

Work function

$$\frac{1}{2}mv^2 = hf - \phi = eV_0$$

Units:

1 electron volt (eV) = $1.6 \cdot 10^{-19}$ Joules
and is the energy gained by an
electron in going through a potential
difference of 1 volt.

Reminder of other units:

1 Watt = 1 Joule per sec

1 Amp = 1 Coulomb per sec

TABLE 38.1 Work Functions of
Several Elements

Element	Work Function (eV)
Aluminum	4.3
Carbon	5.0
Copper	4.7
Gold	5.1
Nickel	5.1
Silicon	4.8
Silver	4.3
Sodium	2.7

Compare with
ionization energy
for H, 13.6 eV

Photoelectric yield

- The photoelectric yield is the number of photoelectrons given off or emitted by a single photon or quantum. It is a measure of *efficiency*.
- Common yields for a photodetector are in the range 0.05-0.2 (=5%-20%)

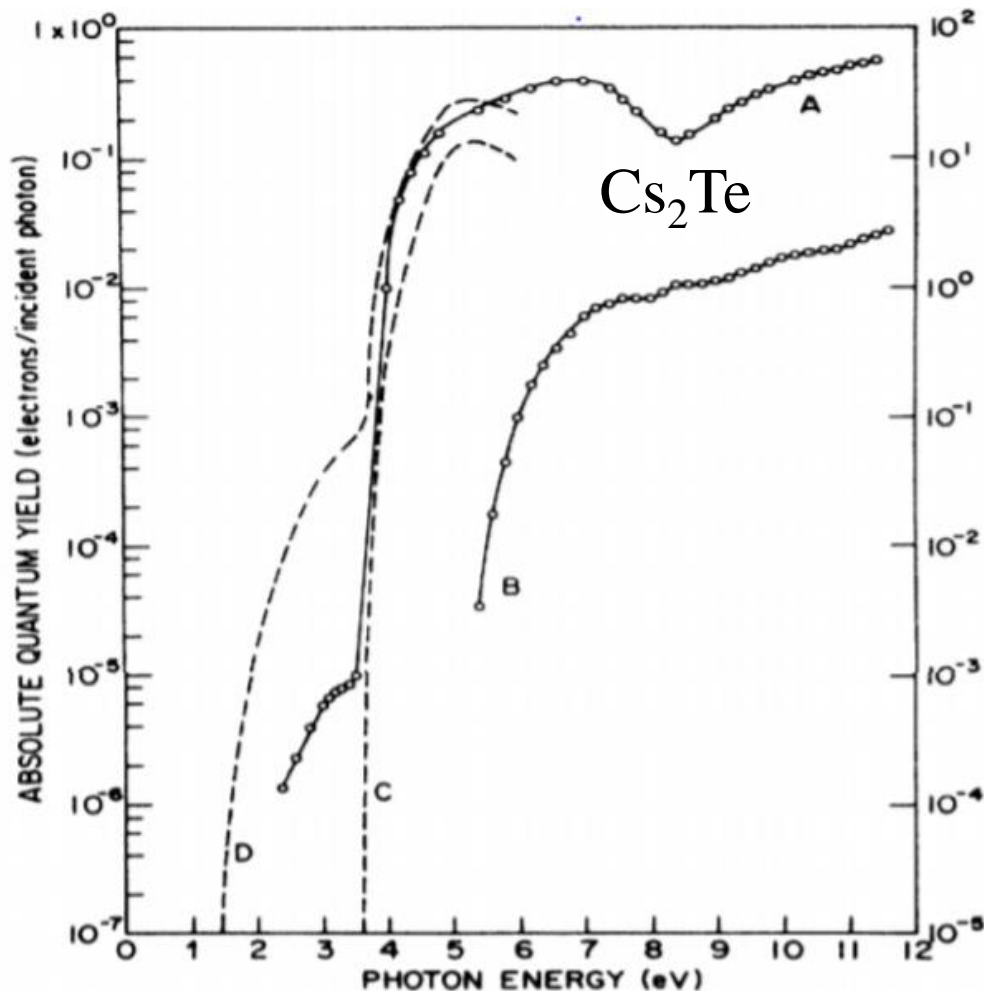
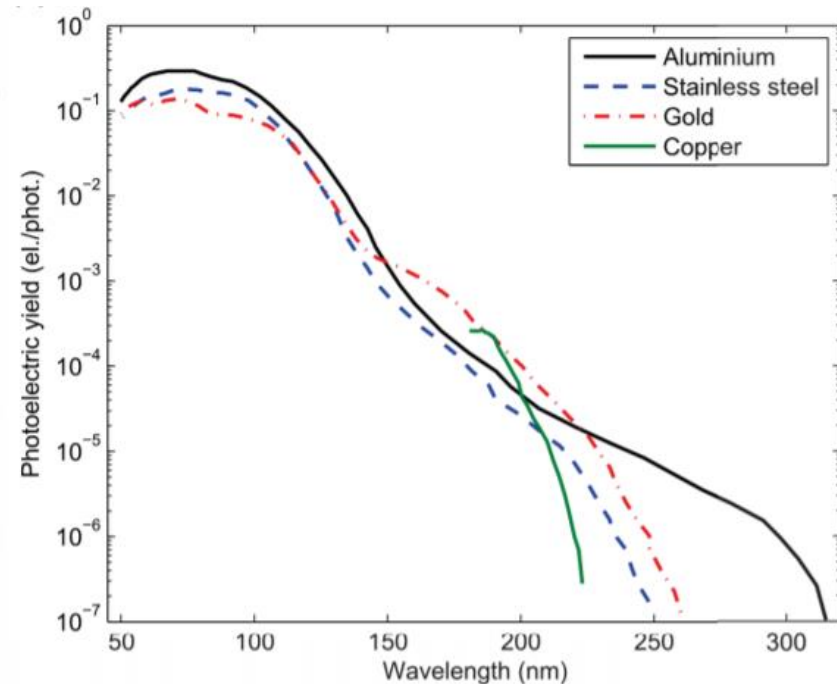


FIG. 1. Spectral distribution of the photoelectric yield from (A) Cs_2Te ; (B) evaporated Te before reaction with Cs. Also shown are the data of Taft and Apker (Ref. 1). In their work, curve C was reported to be from a surface containing excess Cs while curve D was exposed to less Cs.

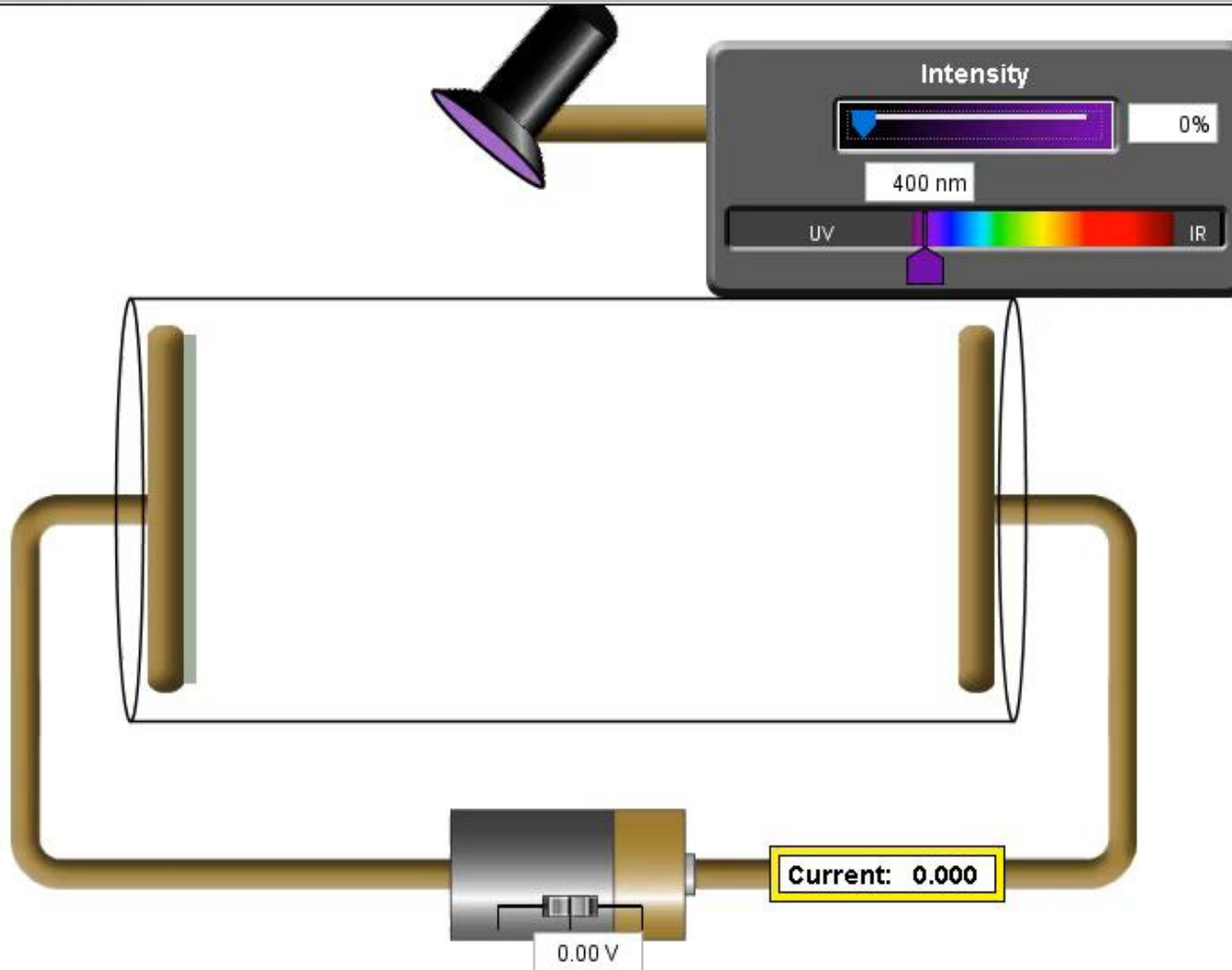


Lab 1: Photoelectric effect

<https://phet.colorado.edu/en/simulation/photoelectric>

Photoelectric Effect (1.10)

File Options Help



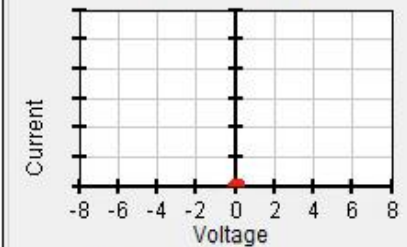
Target

Sodium

☐ Show only highest energy electrons

Graphs

☒ Current vs battery voltage



☐ Current vs light intensity

☐ Electron energy vs light frequency



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Photoelectric Effect



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Topics

- Light
- Quantum Mechanics
- Photons



Sample Learning Goals

- Visualize and describe the photoelectric effect experiment.
- Correctly predict the results of experiments of the photoelectric effect: e.g. how changing the intensity of light will affect the current and the energy of electrons, how changing the wavelength of light will affect the current and the energy of electrons, how changing the voltage of light will affect the current and the energy of electrons, how changing the material of the target will affect the current and the energy of electrons.
- Describe how these results lead to the photon model of light: e.g. argue that only a photon model of light can explain why, when light is shining on the metal but there is no current, increasing the frequency will lead to a current, but increasing the intensity of light or the voltage between the plates will not.

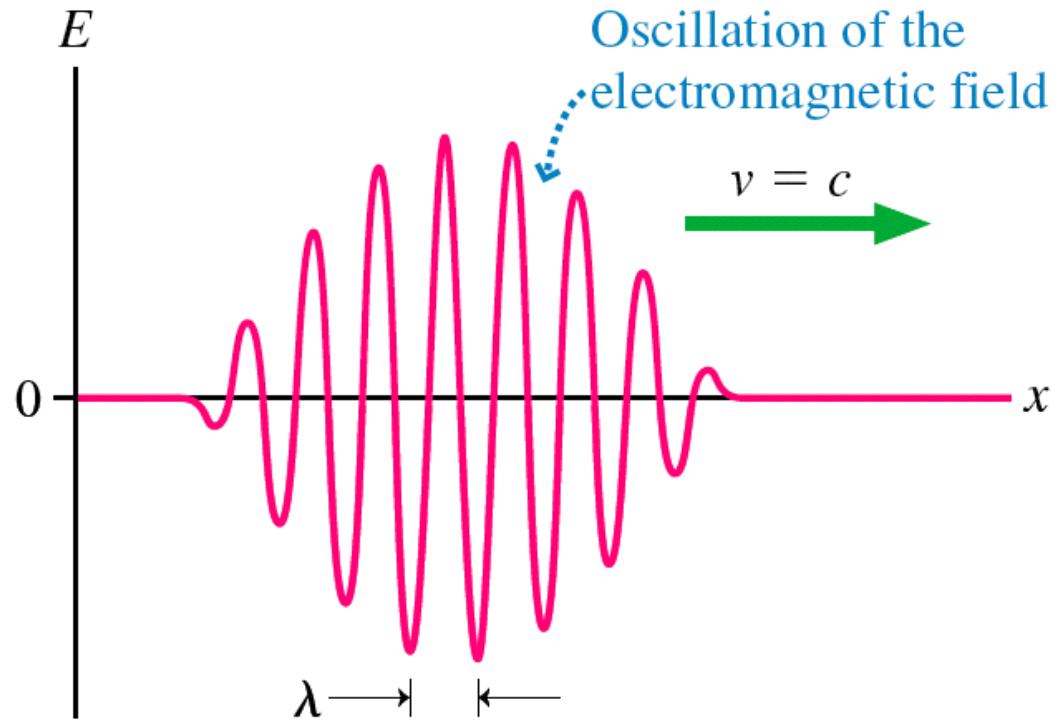
Photons: duality wave-particle

Planck and Einstein showed that photons present qualities of **particles**.

But also of **waves** (Young's experiment).

Photons can be visualized as **wave packets**. The electromagnetic wave shown has a wavelength and a frequency, yet it is also discrete and fairly localized.

$$c = f \cdot \lambda$$

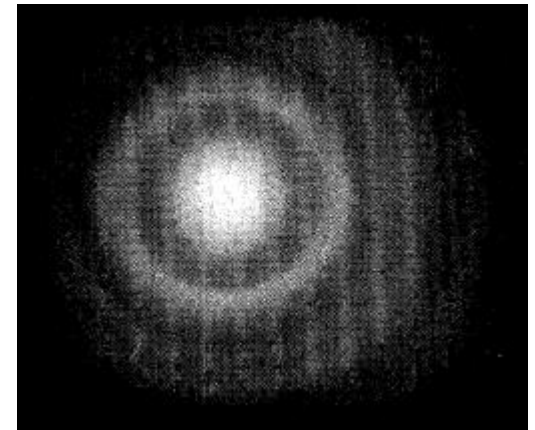


Duality wave-particle

1924 – De Broglie hypothesizes: **ANYTHING** behaves as a wave, but this is noticeable only for microscopic entities.

1927 - George Paget Thomson (University of Aberdeen) demonstrated that **electrons also behave as waves**, because they produce a diffraction pattern when they travel through a very thin gold film

1927 - Davisson–Germer also showed the wave nature of electrons by recording the diffraction pattern from electrons on a nickel crystal



Thomson, G. P.
(1927). "[Diffraction of Cathode Rays by a Thin Film](#)" *Nature*. **119** (3007): 890, 1927

Example 1

The Aurora Borealis is a night display in the Northern latitudes caused by ionizing radiation interacting with the Earth's magnetic field and the upper atmosphere. The distinctive green color is caused by the interaction of the radiation with oxygen and has a frequency of 5.38×10^{14} Hz. What is the wavelength of this light?



Solution Example1:

The speed of light, c , is equal to the product of the wavelength, λ , and the frequency, ν .

Therefore

$$\lambda = c/\nu$$

$$\lambda = 3 \times 10^8 \text{ m/sec}/(5.38 \times 10^{14} \text{ Hz})$$

$$\lambda = 5.576 \times 10^{-7} \text{ m}$$

$$1 \text{ nm} = 10^{-9} \text{ m}$$

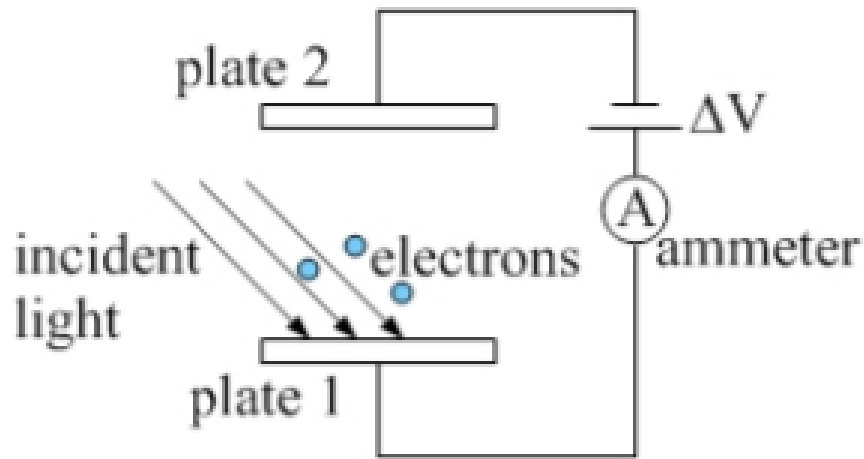
$$\lambda = 557.6 \text{ nm}$$

Answer:

The wavelength of the green light is $5.576 \times 10^{-7} \text{ m}$ or 557.6 nm.

Example 2

Using the experimental apparatus shown, when **ultraviolet light** with a wavelength of 240 nm shines on a particular metal plate, electrons are emitted from plate 1, crossing the gap to plate 2 and causing a current to flow through the wire connecting the two plates. The battery voltage is gradually increased until the current in the ammeter drops to zero, at which point the battery voltage is 1.40 V.



- (a) What is the energy of the photons in the beam of light, in eV?
- (b) What is the maximum kinetic energy of the emitted electrons, in eV?
- (c) What is the work function of the metal, in eV?
- (d) What is the longest wavelength that would cause electrons to be emitted, for this particular metal?
- (e) Is this wavelength in the visible spectrum? If not, in what part of the spectrum is this light found?

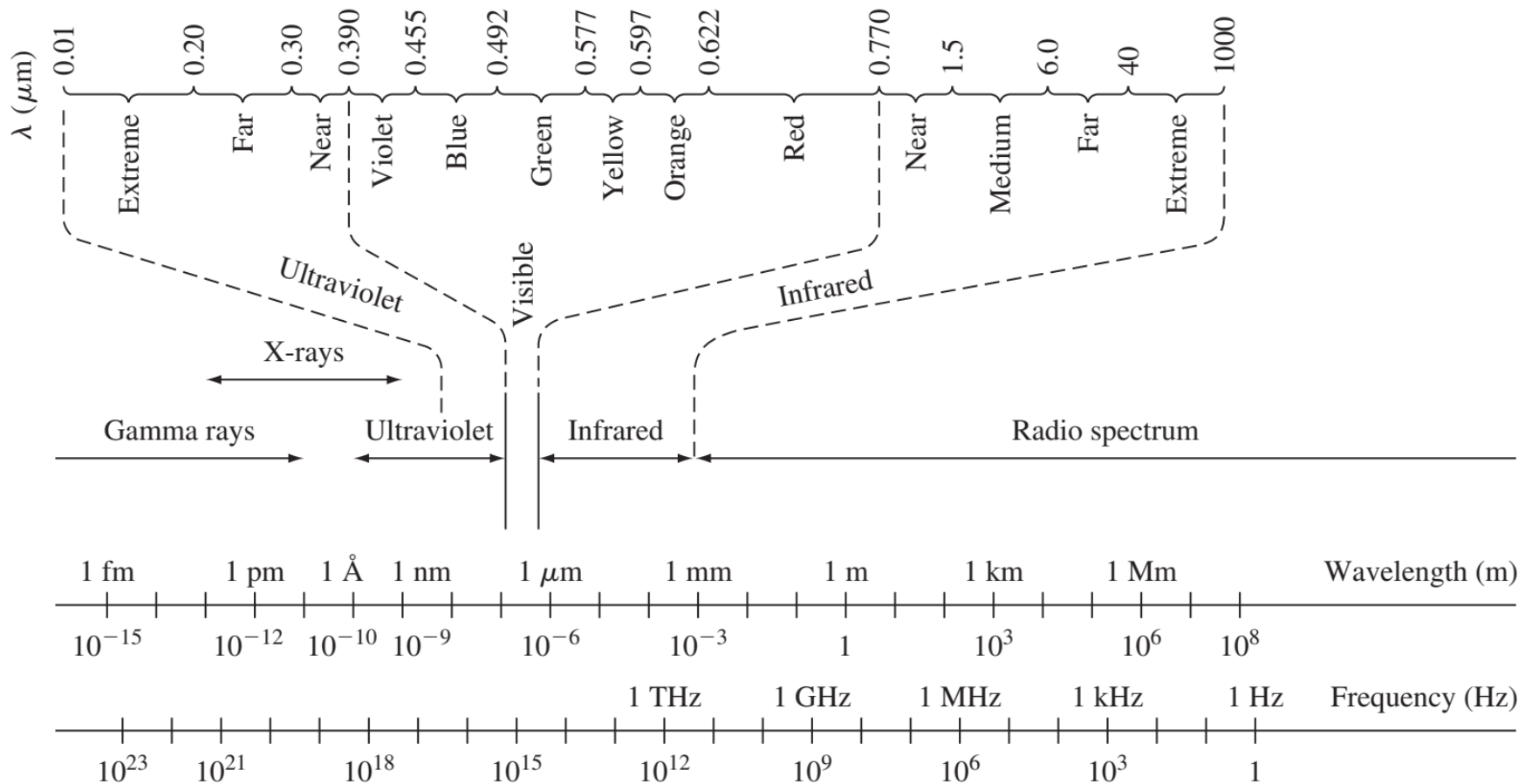


Figure 2.4 | The electromagnetic frequency spectrum.

Solutions Example2

a)
$$f = \frac{c}{\lambda} = \frac{3.00 \times 10^8 \text{ m/s}}{2.40 \times 10^{-7} \text{ m}} = 1.25 \times 10^{15} \text{ Hz} .$$

$$E = hf = (4.136 \times 10^{-15} \text{ eV s}) \times (1.25 \times 10^{15} \text{ Hz}) = 5.17 \text{ eV} .$$

b) The stopping potential is 1.40 V, so the maximum kinetic energy of the electrons is 1.40 eV

c)
$$W_0 = hf - K_{\max} = 5.17 \text{ eV} - 1.40 \text{ eV} = 3.77 \text{ eV} .$$

d)
$$W_0 = hf_0, \quad \text{so} \quad f_0 = \frac{W_0}{h} = \frac{3.77 \text{ eV}}{4.136 \times 10^{-15} \text{ eV s}} = 9.12 \times 10^{14} \text{ Hz} .$$

$$\lambda_{\max} = \frac{c}{f_0} = \frac{3.00 \times 10^8 \text{ m/s}}{9.12 \times 10^{14} \text{ Hz}} = 3.29 \times 10^{-7} \text{ m} .$$

e) This wavelength is 329 nm, less than the 400 nm (violet) wavelength that marks the lower bound of the visible spectrum. This light is beyond violet, in the ultraviolet

End of Week1