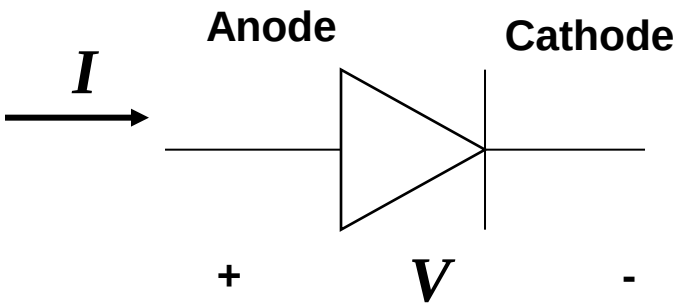
Crystal Structure

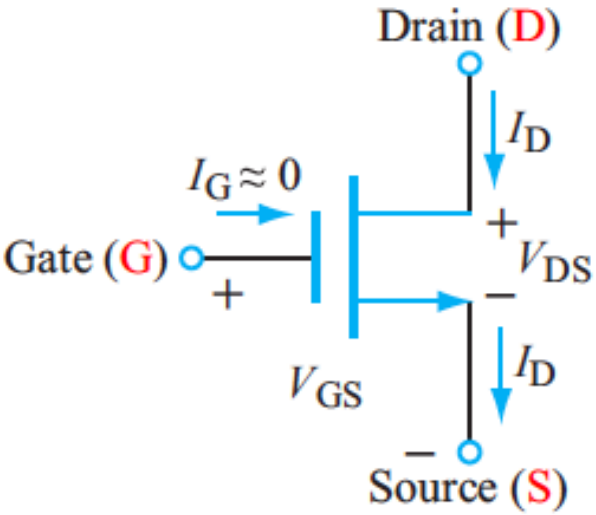
EECS 320

Introduction to Semiconductor Devices

Electronic Devices

- **We learned about electronic devices in EECS 215**
- **How do they work?**
- **How do they control electrical current/voltage?**

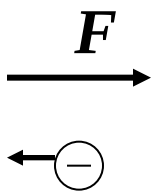




Let's start with examining electrical current flow in a solid material

Response of Electron to Electric Field

What happens to an electron when we apply a voltage/electric field?



$$\text{Force} = -qF = m_0 \frac{dv}{dt}$$

("-" sign for electron)

m_0=electron rest mass

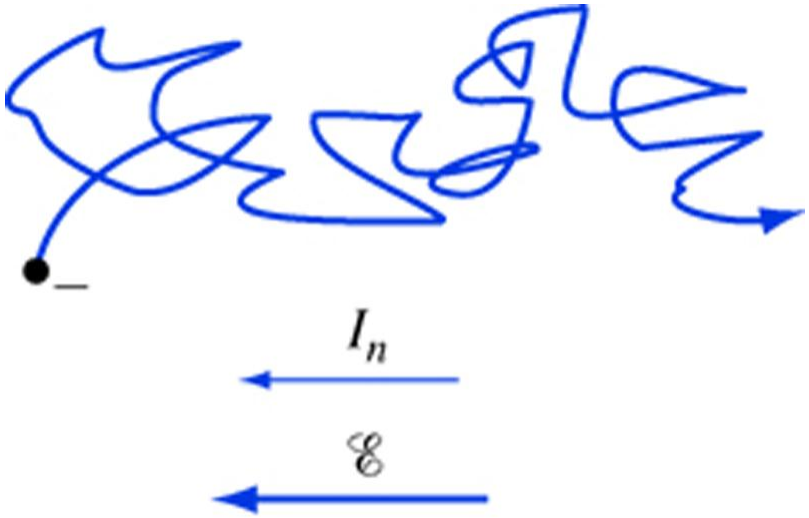
q=charge on an electron (1.6×10^{-19} C)

F=electric field

v=velocity

What is the velocity of the electron in vacuum?
What is the velocity of the electron in a solid?

Scattering Events Determine Velocity



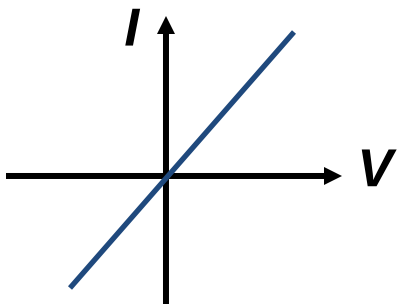
- **Carriers are accelerated by electric field**
- **Carriers scatter from imperfections in material**
- **Average electron velocity for a given electric field**
- **Need velocity-field relation for given material!**

Ohm's Law

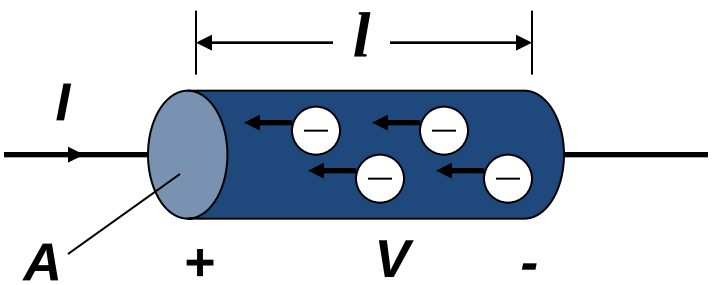
Voltage across resistor is proportional to current

$$V = IR$$

$$R = \frac{V}{I}$$



Resistance: ability to resist flow of electric current



$$R = \frac{\rho l}{A} = \frac{l}{\sigma A}$$

ρ =**resistivity**

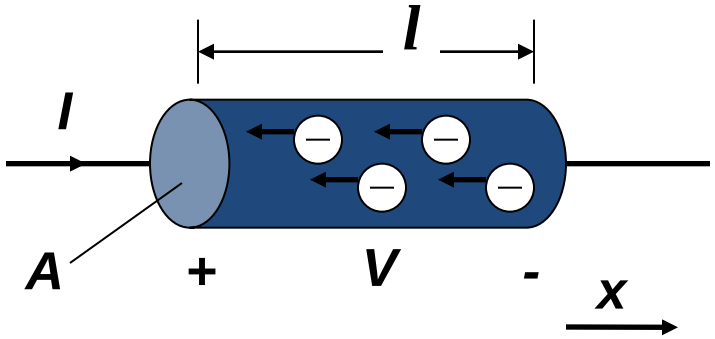
σ =**conductivity**

Looks like should be related to average electron velocity

Resistivity and conductivity are material parameters

Can We Relate Conductivity and Velocity?

Application of electric field produces current flow



$$R = \frac{V}{I} = \frac{\rho L}{A} = \frac{EL}{JA}$$

$$J = \sigma E = \frac{E}{\rho}$$

***J=I/A* = current density**
typical units A/cm^2

I **is charge crossing per unit time ΔQ/Δt in units of A or C/s**

Electrons are moving at a velocity v = Δx/Δt

q **is charge of electron, n is number of electrons per unit volume**

ΔQ is number of electrons crossing Δx times charge, *qnA*Δx

What is expression for *I* in terms of *v*?
What is expression for σ in terms of *v*?
Units of σ?

Electrical Conduction

What we now need to determine:

- **What is velocity of electrons in a solid (for given electric field)?**
- **What is the number of electrons per unit volume that contribute to conduction?**
- **Ideas?**

Electrons In Solids

How do electrons behave in solids?

Ohm's Law

$$V = IR = AJR$$

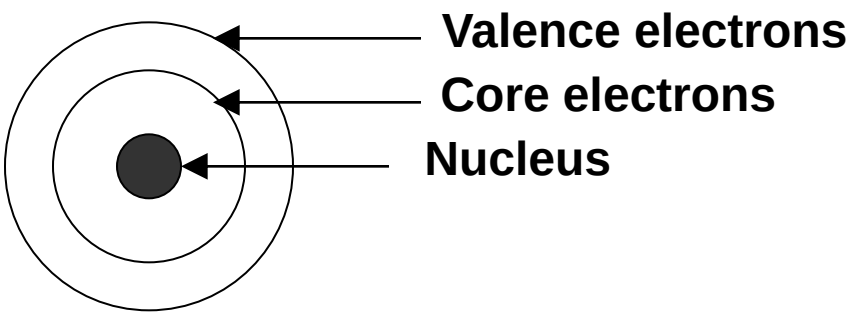
$$R = \frac{\rho L}{A} = \frac{L}{\sigma A}$$

$$J = \sigma F = qnv$$

$$v = \mu F$$

$$\boxed{\sigma = qn\frac{v}{F} = q\mu n}$$

Classical Model



"Free" valence electrons contribute to conductivity

Is this model accurate?

Electrons In Solids

Examine definition of conductivity

$$\boxed{\sigma = q\mu n}$$

Assuming μ is similar for differing materials (proportionality constant for velocity and electric field), compare σ for Al, C

$$n = 6.02\times10^{23}\,\frac{(\#elec/atom)(\text{density in } g/\text{cm}^3)}{\text{Atomic mass in } g/\text{mol}}\left(cm^{-3}\right)$$

<u>Aluminum</u>

3 valence electrons

$$density = 2.7\,g/\text{cm}^3$$

$$\text{Atomic mass} = 27\,g/mol$$

$$n = 1.8\times10^{23}cm^{-3}$$

<u>Carbon</u>

4 valence electrons

$$density = 3.52\,g/\text{cm}^3$$

$$\text{Atomic mass} = 12\,g/mol$$

$$n = 7.1\times10^{23}cm^{-3}$$

Does this make sense?

Electrons Contributing to Conduction

We are missing a key piece of the puzzle!

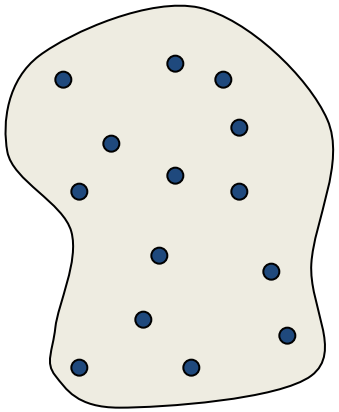
- **Start with atomic structure of material**
- **Determine how atomic structure affects electrons in the material**
- **Note that we will need to invoke principles of quantum mechanics (beyond the scope of this course!), we will simply provide outcomes**

Material Requirements

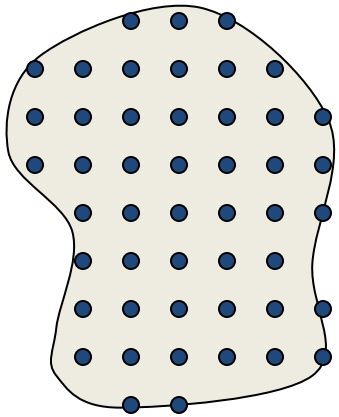
What can we use?

- Electrical conduction
- Range of conducting to insulating
- Solid state

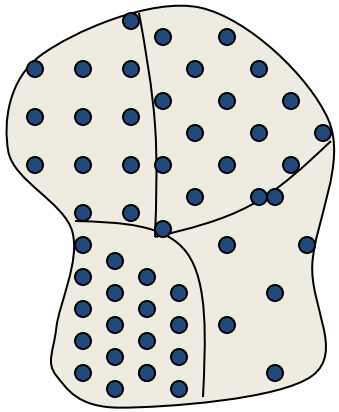
Types of solids



Amorphous



Crystalline



Polycrystalline

Common Semiconductors

PERIODIC CHART OF THE ELEMENTS

IA	IIA	IIIB	IVB	VB	VIB	VIIB	VIII			IB	IIB	IIIA	IVA	VA	VIA	VIIA	INERT GASES
1 H 1.00797																1 H 1.00797	2 He 4.0026
3 Li 6.939	4 Be 9.0122											5 B 10.811	6 C 12.0112	7 N 14.0067	8 O 15.9994	9 F 18.9984	10 Ne 20.183
11 Na 22.9898	12 Mg 24.312											13 Al 26.9815	14 Si 28.086	15 P 30.9738	16 S 32.064	17 Cl 35.453	18 Ar 39.948
19 K 39.102	20 Ca 40.08	21 Sc 44.956	22 Ti 47.90	23 V 50.942	24 Cr 51.996	25 Mn 54.9380	26 Fe 55.847	27 Co 58.9332	28 Ni 58.71	29 Cu 63.54	30 Zn 65.37	31 Ga 69.72	32 Ge 72.59	33 As 74.9216	34 Se 78.96	35 Br 79.909	36 Kr 83.80
37 Rb 85.47	38 Sr 87.62	39 Y 88.905	40 Zr 91.22	41 Nb 92.906	42 Mo 95.94	43 Tc (99)	44 Ru 101.07	45 Rh 102.905	46 Pd 106.4	47 Ag 107.870	48 Cd 112.40	49 In 114.82	50 Sn 118.69	51 Sb 121.75	52 Te 127.60	53 I 126.904	54 Xe 131.30
55 Cs 132.905	56 Ba 137.34	*57 La 138.91	72 Hf 178.49	73 Ta 180.948	74 W 183.85	75 Re 186.2	76 Os 190.2	77 Ir 192.2	78 Pt 195.09	79 Au 196.967	80 Hg 200.59	81 Tl 204.37	82 Pb 207.19	83 Bi 208.980	84 Po (210)	85 At (210)	86 Rn (222)
87 Fr (223)	88 Ra (226)	‡89 Ac (227)	104 Rf (261)	105 Db (262)	106 Sg (266)	107 Bh (262)	108 Hs (265)	109 Mt (266)	110 ? (271)	111 ? (272)	112 ? (277)						

Numbers in parenthesis are mass numbers of most stable or most common isotope.

Atomic weights corrected to conform to the 1963 values of the Commission on Atomic Weights.

The group designations used here are the former Chemical Abstract Service numbers.

* Lanthanide Series

58 Ce 140.12	59 Pr 140.907	60 Nd 144.24	61 Pm (147)	62 Sm 150.35	63 Eu 151.96	64 Gd 157.25	65 Tb 158.924	66 Dy 162.50	67 Ho 164.930	68 Er 167.26	69 Tm 168.934	70 Yb 173.04	71 Lu 174.97

‡ Actinide Series

90 Th 232.038	91 Pa (231)	92 U 238.03	93 Np (237)	94 Pu (242)	95 Am (243)	96 Cm (247)	97 Bk (247)	98 Cf (249)	99 Es (254)	100 Fm (253)	101 Md (256)	102 No (256)	103 Lr (257)

Crystal Structure

Lattice

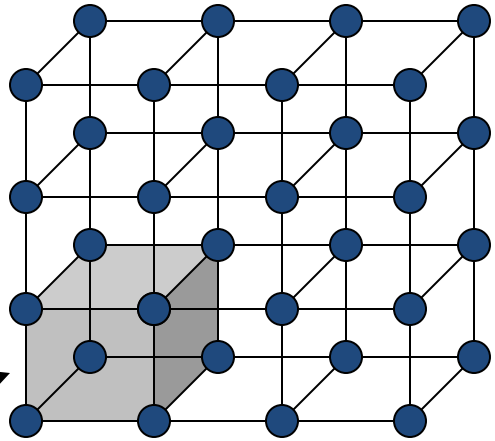
Periodic arrangement of atoms in a crystal

Unit cell

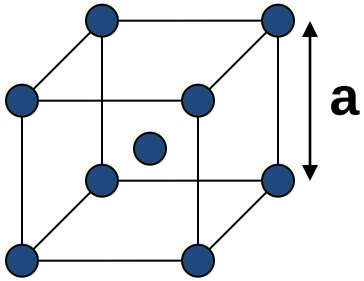
Small volume of crystal that may be used to reproduce the entire crystal

Primitive unit cell

Smallest unit cell that describes the crystal



Simple cubic

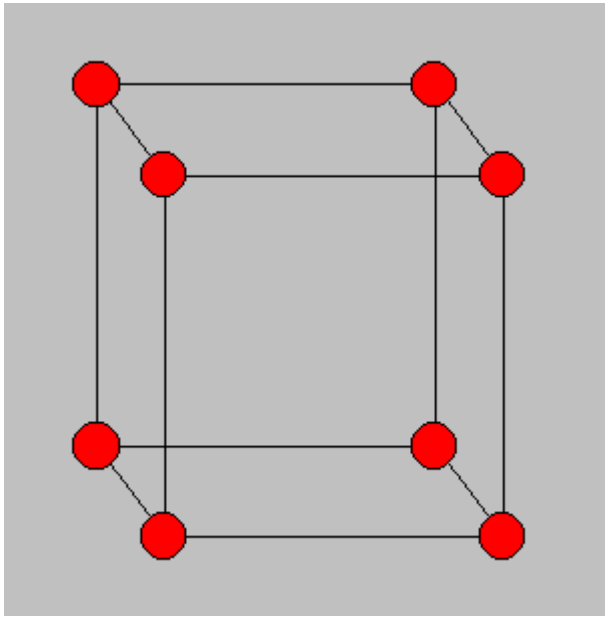


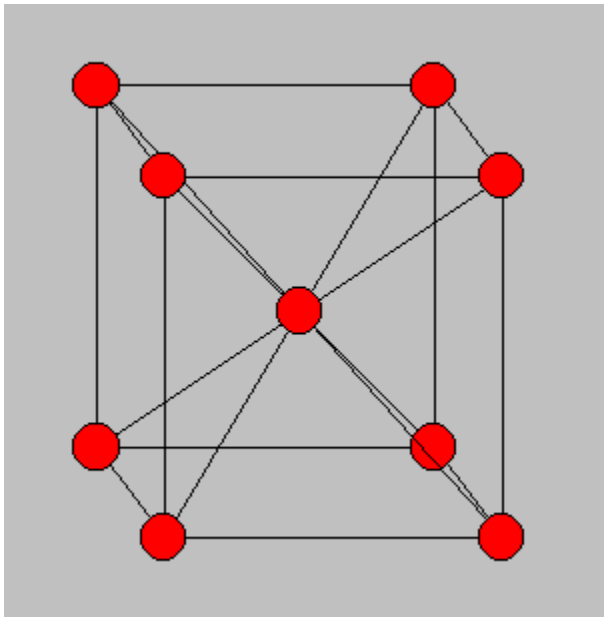
lattice constant

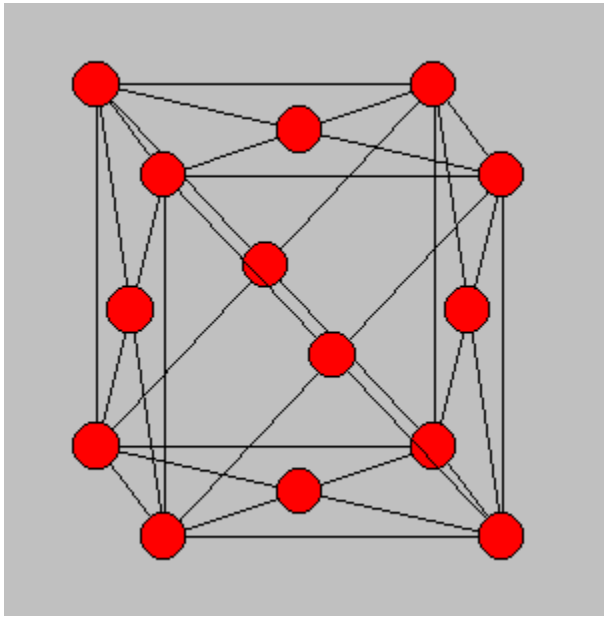
Body centered cubic (BCC)

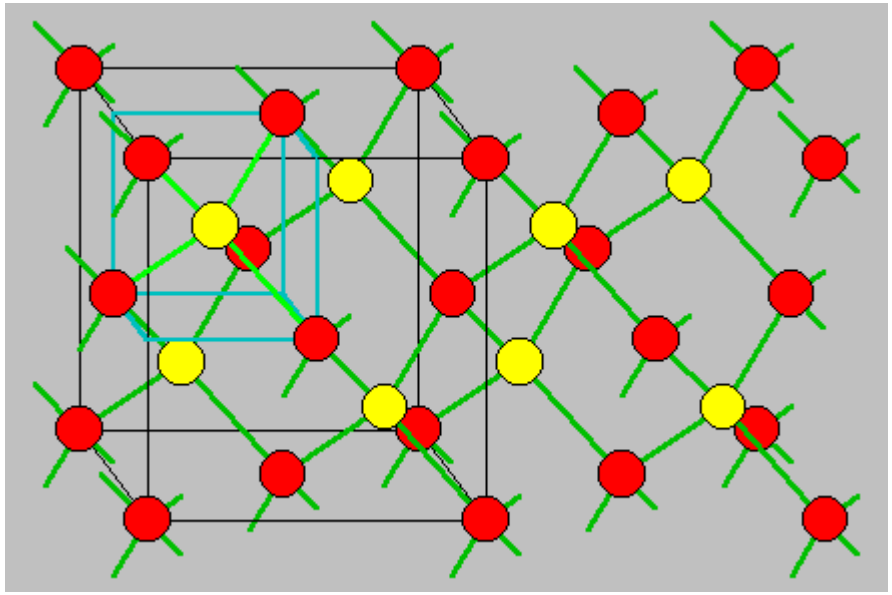
Lattice constant is a *material parameter*

Cubic Lattice Types





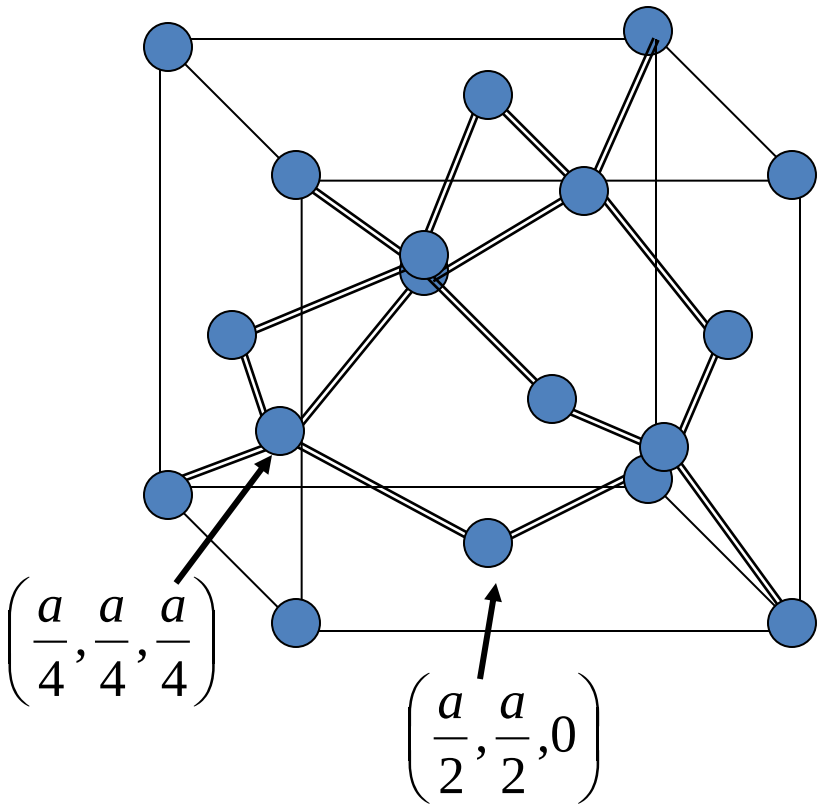




Semiconductor Crystal Structure

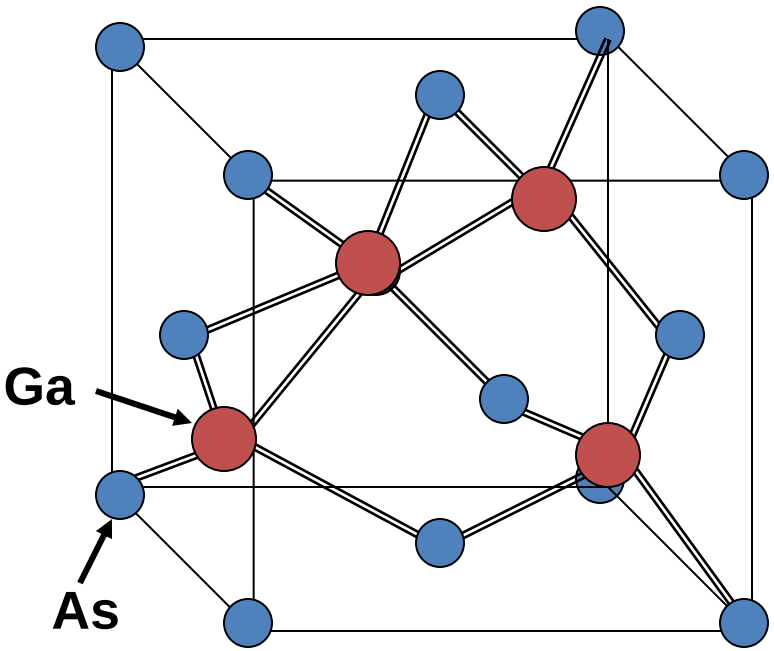
Diamond

(Si, Ge)

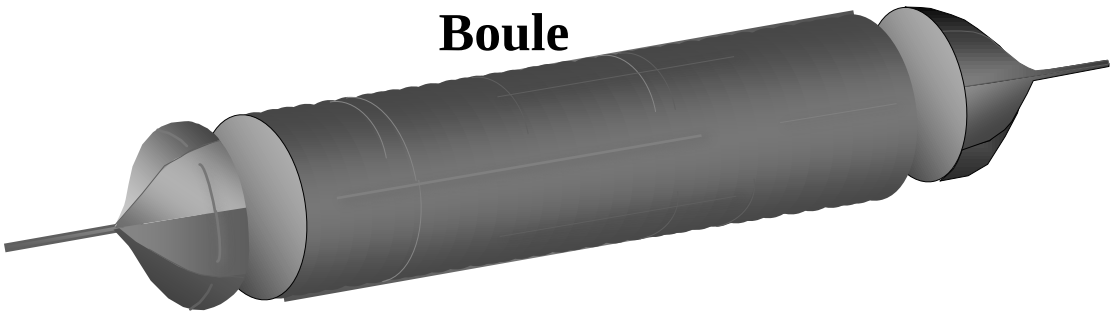


Zinc Blende

(GaAs, InP, AlSb, …)



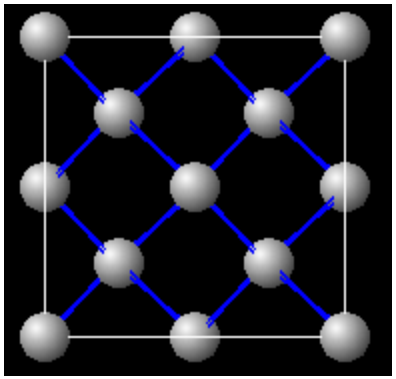
Semiconductor Wafers

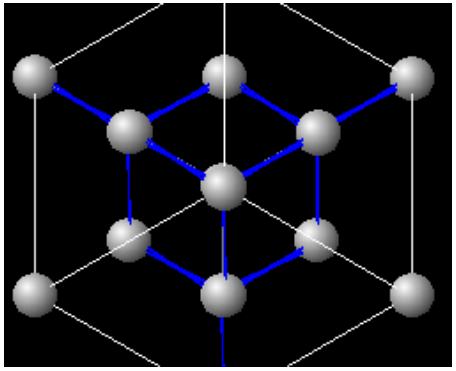


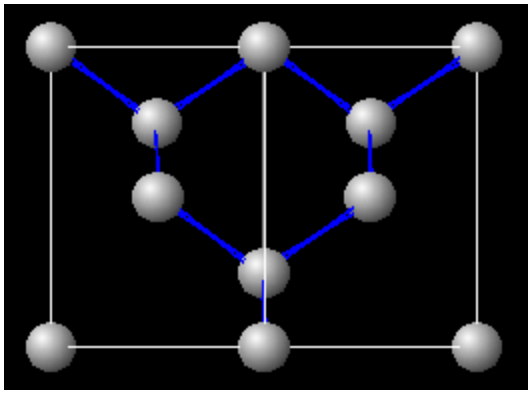
Semiconductor Wafers

- Atomic arrangement not symmetric in all directions
- Chemical and electronic properties will depend on atomic arrangement
- Need a method of specifying atomic arrangement or orientation (what surface are you growing on?)

Different crystalline faces of silicon

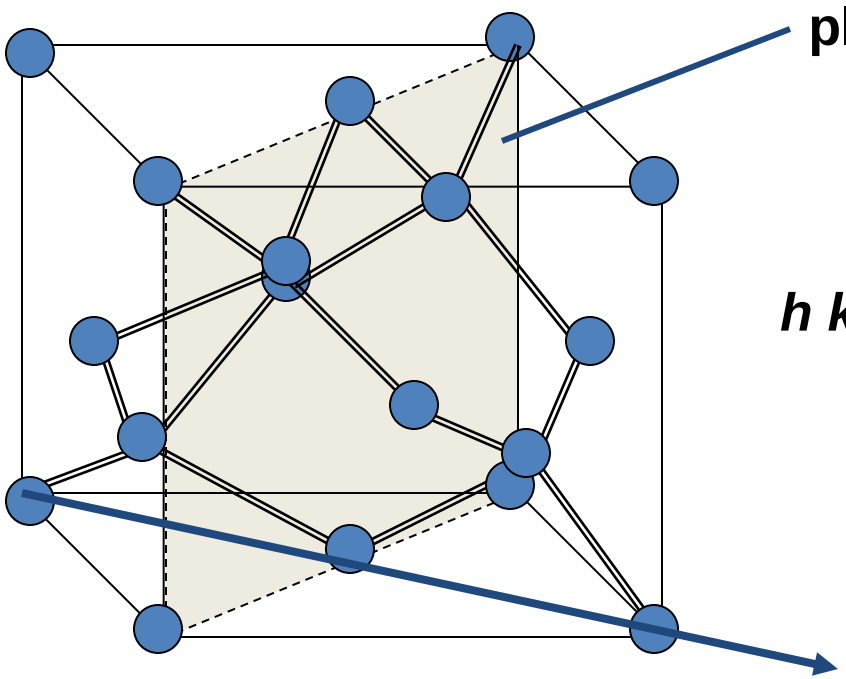




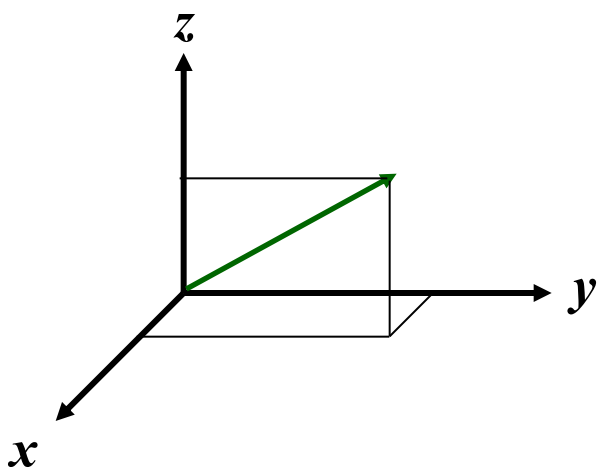


Miller Indices

Semiconductor devices fabricated on crystal surface – need method of describing crystalline direction/planes



Determining Miller Indices for Directions



1. **Decompose the vector into its components**

2. **Convert the components into the smallest possible whole number set**

Miller Indices

(*hkl*) Crystal plane

{*hkl*} Equivalent planes

[*hkl*] Crystal direction

<*hkl*> Equivalent directions

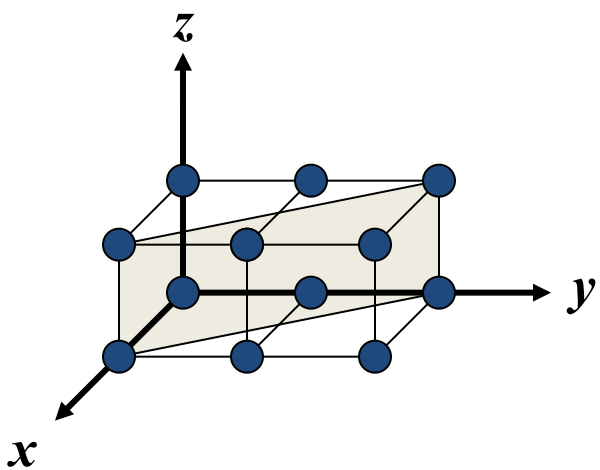
In a cubic lattice, the vector perpendicular to (h k l) plane is [h k l] direction

Determining Miller Indices

1. Find intercepts (as multiple of lattice constant)

2. Take reciprocal

3. Multiply by lowest common denominator



intercepts at (1, 2, ∞)

reciprocal (1, 1/2, 0)

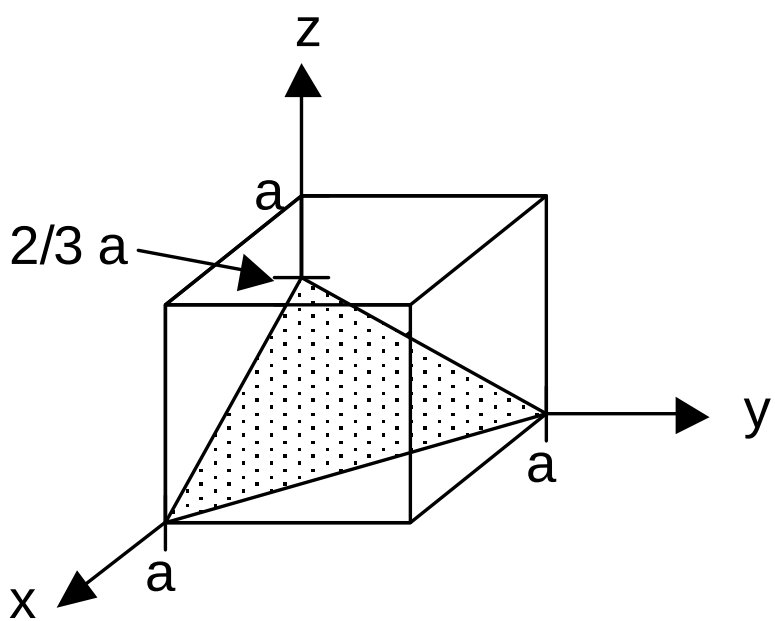
LCM (2, 1, 0)

(210) plane

Vector perpendicular to plane is [210] direction

Example: Miller Index

Determine the representation of the plane below



Example: Visualize Miller Plane

Draw the Miller Plane (212) and Miller Direction [110]