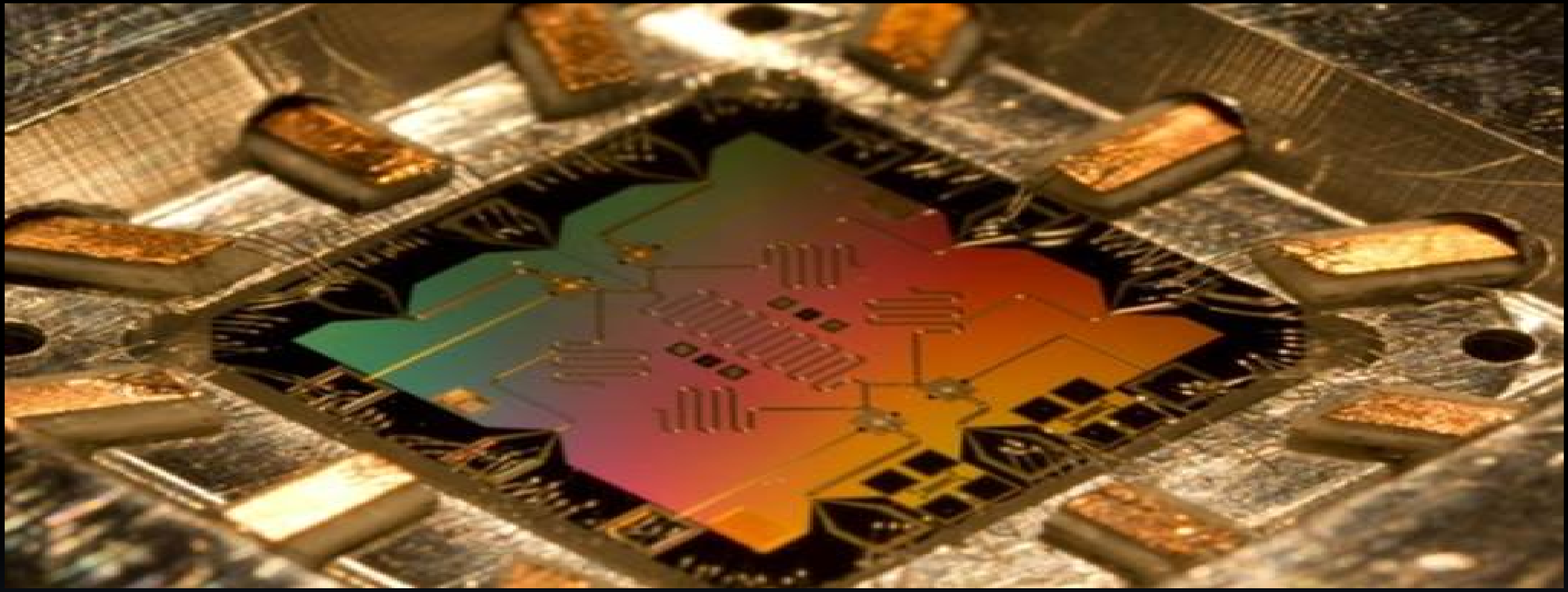
PHYSICAL ELECTRONICS(ECE3540)

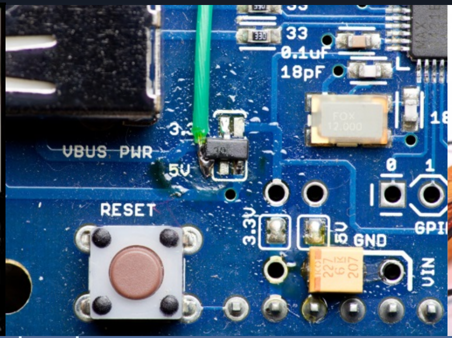


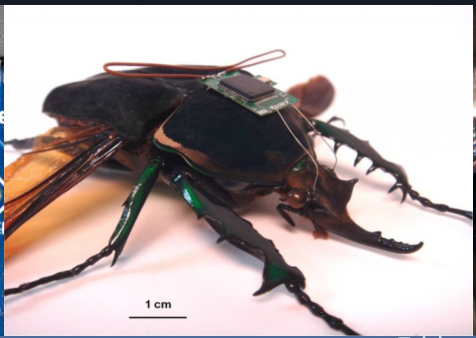
Brook Abegaz, Tennessee Technological University, Fall 2013

Chapter 1 – The Crystal Structure of Solids

- Physical Electronics:
  - Includes aspects of the physics of electron movement from an electrical engineering point of view.
  - Focuses on the electrical properties and characteristics of semi-conductor materials and devices starting from the physical composition or arrangement of atoms in a solid to the chemical composition which determines the chemical property of atoms.
  - Uses the principles of Quantum mechanics to explain property of electronic devices

- Application Areas of Physical Electronics
  - Electronic devices used in telecommunication systems, control systems, digital systems and power systems.
  - Measuring instruments and cathode ray tubes.
  - Image intensifiers used in astronomy.
  - Micro-electronic and Nano-electronic mechanical systems (MEMS and NEMS respectively).
  - Optoelectronics and Lasers used in medical equipment.



- Conductivity:
  - Different materials have different conductivity (commonly measured in mho/m or S/m) that ranges very widely from one material to another. (in ranges of 10^{30})
  - Comparison of Conductivity of materials
    - Conductivity of a ceramic = 10^{-22}S/m
    - Conductivity of a metal = 10^{8}S/m
    - Ratio of conductivity of a metal to that of a ceramic=10^{30}.
    - Ratio of radius of the earth to radius of an electron = 3,959 miles (6.371 x10^{6} m)/ 2.818 x 10^{-15}m = 2.3x10^{21}.

Electrical Resistivity and Conductivity of Materials

Material	Resistivity ρ (Ω*m) at 20 °C	Conductivity σ (S/m) at 20 °C
Silver	1.59×10^{-8}	6.30×10^{7}
Copper	1.68×10^{-8}	5.96×10^{7}
Gold	2.44×10^{-8}	4.10×10^{7}
GaAs	5×10^{-7} to 10×10^{-3}	5×10^{-8} to 10^{3}
Germanium	4.6×10^{-1}	2.17
Silicon	6.40×10^{2}	1.56×10^{-3}
Glass	10×10^{10} to 10×10^{14}	10^{-11} to 10^{-15}
Air	1.3×10^{16} to 3.3×10^{16}	3×10^{-15} to 8×10^{-15}
Fused Quartz (SiO2)	7.5×10^{17}	1.3×10^{-18}
Teflon $(C_2F_4)_n$	10×10^{22} to 10×10^{24}	10^{-25} to 10^{-23}

- Semiconductor Materials
  - A group of materials having conductivities between a metal and a non-metal.
  - Could refer to elemental semiconductors (group 4 elements) or compound semiconductors (a combination of group 3 and group 5 elements).
  - Elemental semiconductors = Si, Ge, C, Sn
  - Compound semiconductors = GaAs, GaP, AlP, AlAs
  - Ternary compound semiconductors = $Al_xGa_{1-x}As$

- Types of Solids
  - Amorphous = order only with in a few atomic dimensions.
  - Polycrystalline = a high degree of order over many dimensions.
  - Crystalline = a higher degree of order and geometric periodicity.

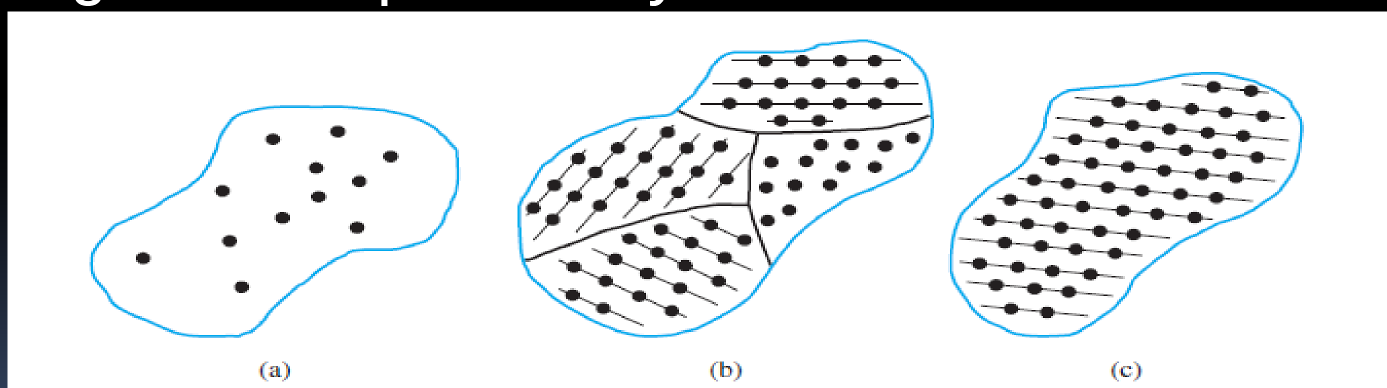


Fig. 1: Schematics of three general types of crystals, a) amorphous, b) polycrystalline, c) single crystalline

- <u>Space Lattice</u>
- Representation of a single crystal material having a regular geometric periodicity of atoms.
  - Lattice point = a dot representation of a particular atomic array which can be repeated over the structure using translation. Every lattice point 'p' can be found as: $p = ax + by + cz$ where a,b,c are integers.
  - Unit Cell = small volume of a crystal that can be used to reproduce the entire crystal.

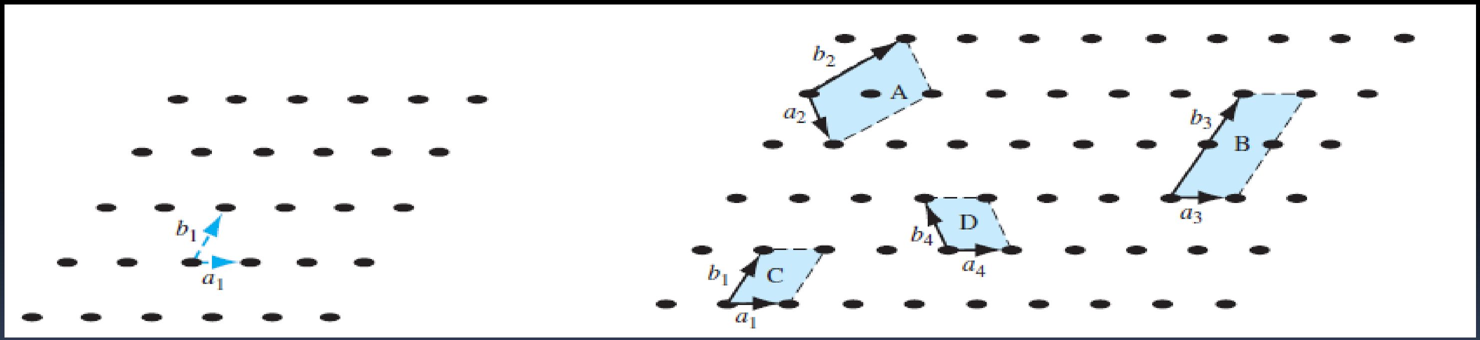


Fig. 2 Two-dimensional representation of a single-crystal lattice.
Fig. 3 Two-dimensional representation of a single-crystal lattice showing various possible unit cells.

- Basic Crystal Structures
  - Simple Cubic (SC) = has an atom located at each corner. ‘a’ = Lattice Constant of the cube.
  - Body Centered Cubic (BCC) = an SC with an additional atom at the center of the cube.
  - Face Centered Cubic (FCC) = an SC with additional atoms on each face of the cube.

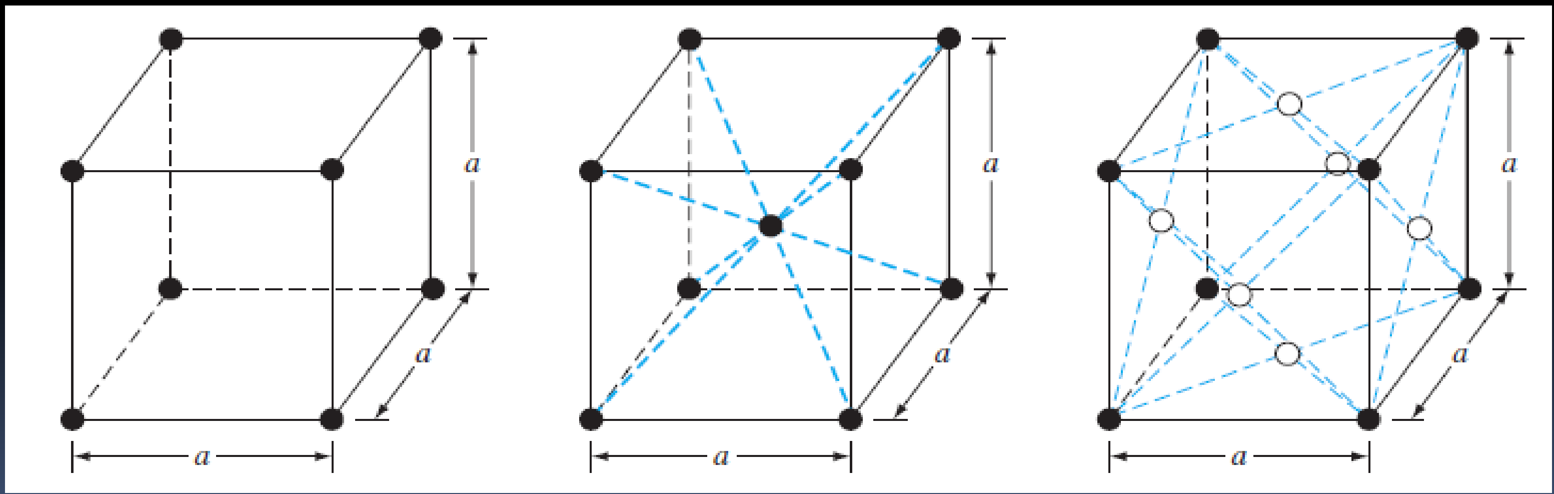


Fig. 4: Three lattice types, a) SC, b) BCC and c) FCC

- **Exercise**

1. Consider a single crystal material that is a body centered cubic with a lattice constant 'a' = 15Å (1Å = 1.0×10^{-10} m). Find the effective number of atoms per unit cell and the volume density of atoms.

- **Solution**

For a body centered cube:

1. Effective # of atoms /unit cell = (1/8) * 8 + 1 = 2.
2. Volume density = Effective # of atoms /unit cell

   of atoms volume of unit cell

   $= 2/(a^3) = 2/(15 \times 10^{-10})^3 = 5.926 \times 10^{26}$ atoms/m^3.

- <u>Exercise</u>

2. The lattice constant of a face-centered cubic lattice is 4.25Å. Determine:
   - The effective number of atoms per unit cell.
   - The volume density of atoms.

- <u>Solution</u>
  - Effective number of atoms per unit cell =

    $(1/8) * 8 + (1/2) * 6 = 1+3 = 4.$
  - Volume density = $4/(4.25\times10^{-10})^3 = 5.211\times10^{28}$ atoms/m^3.
  - Volume density = $4/(4.25\times10^{-8})^3 = 5.211\times10^{22}$ atoms/cm^3.

- Miller Indices
  - Surfaces or planes through a crystal can be described by considering the intercepts of the plane along the x, y and z axes of the lattice.
  - The surface density of atoms is important, for e.g., in determining how another material such as an insulator will "fit" on the surface of a semiconductor material.

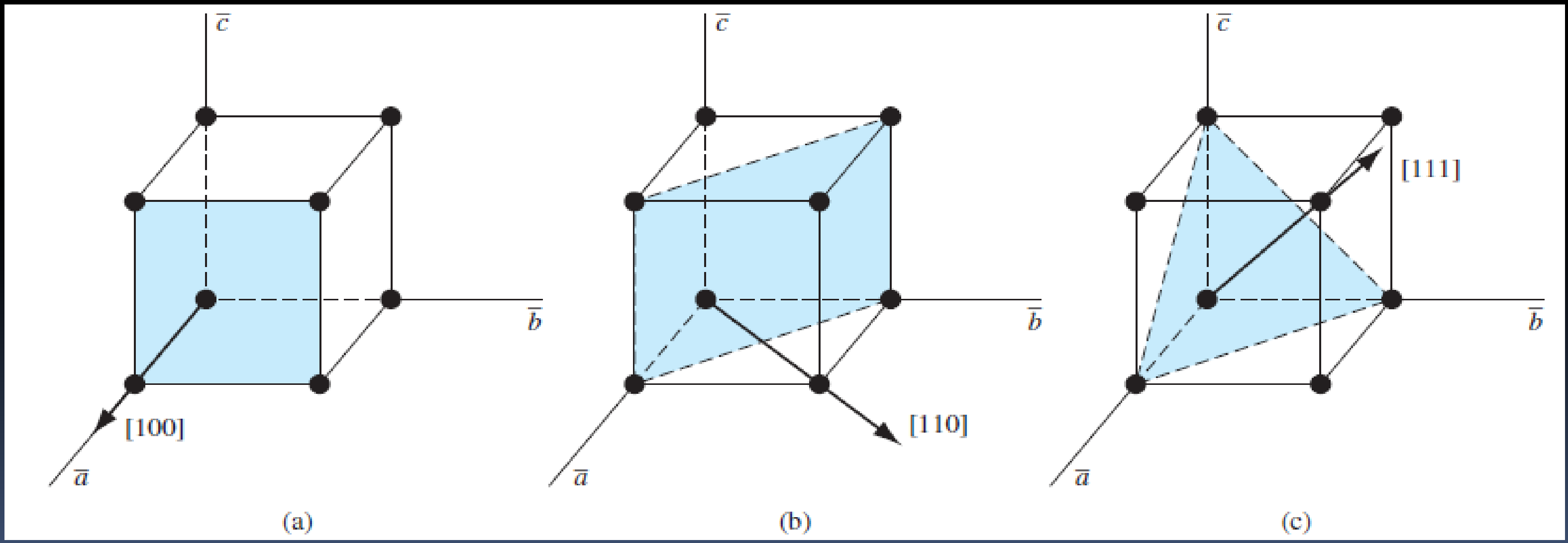


Fig. 5: lattice planes and directions: a) (100) plane, b) (110) plane and c) (111) plane.

- Diamond Structure
  - is the structure of Semiconductor elements in group IV including Silicon and Germanium.
  - is a body-centered cubic with four of the corner atoms missing.
  - Every atom has four nearest neighbors.

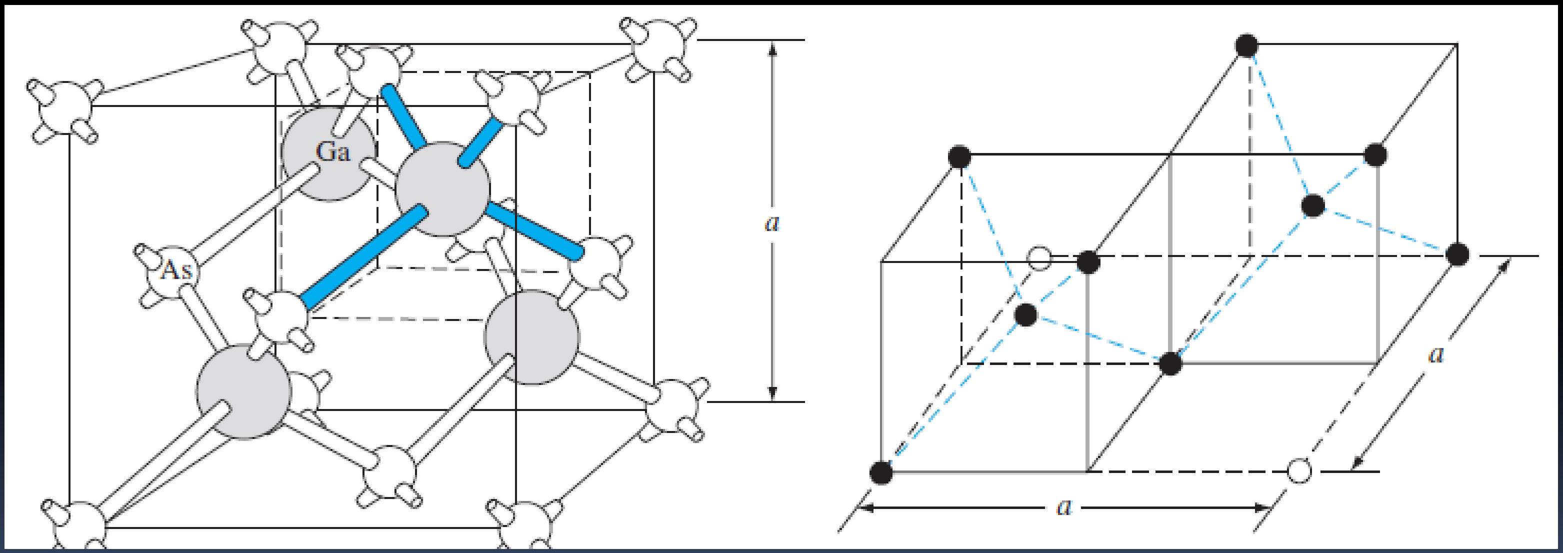
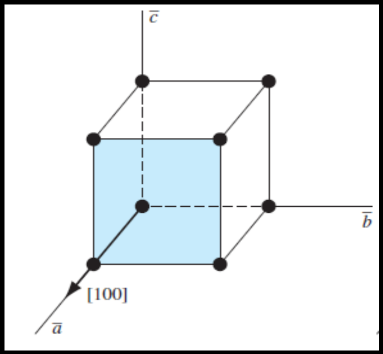


Fig. 6: Lattice Structure of GaAs.
Fig. 7: Bottom half portion of the diamond lattice.

- <u>Exercise</u>

3. The lattice constant of a face-centered-cubic structure is 4.25Å. Calculate the surface density of atoms for a) a (100) plane.



- <u>Solution</u>

a) For a face centered cube (100) plane:

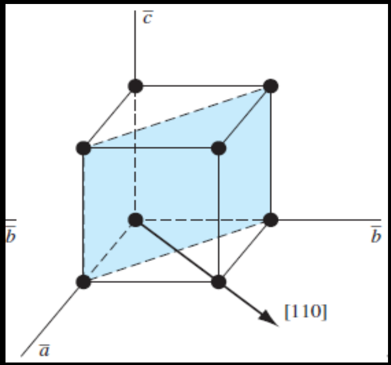
Surface Area = (4.25Å)(4.25Å) = $18.0625\times10^{-20}m^2$

Effective # of atoms = (1/4)*4+1 = 2.

Surface Density = Effective # of atoms/Surface Area = $2/18.0625\times10^{-20}m^2 = 1.1073\times10^{19}m^{-2}$.

- <u>Exercise</u>

3. The lattice constant of a face-centered-cubic structure is 4.25Å. Calculate the surface density of atoms for b) a (110) plane.



- <u>Solution</u>

b) For a face centered cube (110) plane:

Surface Area = (4.25Å)(***<u>Hypotenuse</u>***)

<u>Hypotenuse</u> **= [(**4.25Å)^2+ **(**4.25Å)^2]$^{1/2}$ =6.01Å

Surface Area = (4.25Å)(6.01Å) = 25.54x10^{-20}m^{-2}

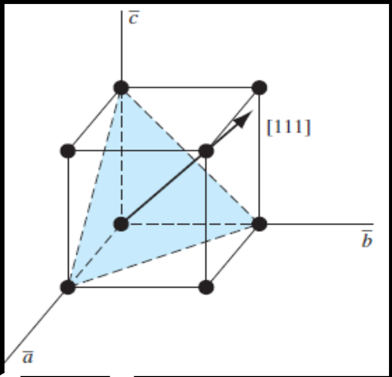
Surface Density = 2/(4.25Å)(6.01Å)(10^{-20}) = 7.8x10^{18}m^{-2}

- Take Home Exercise

1. The lattice constant of a face-centered-cubic structure is 4.25Å. Calculate the surface density of atoms for a (111) plane.

- Note:
- Take home exercises are given for you to practice what has been discussed in class. You don't have to submit your solution to a take home exercise. We will solve the take home exercise problems given in a class on the following class.
- On the other hand, those homework that count toward your final grades are given on separate sheets and have longer due dates to turn them in.
- Even if you are after the due date of a homework, you can still submit your homework to get partial credit for it.

Take Home Solution



- Effective # of Atoms = 1/6 * 3 + ½ * 3 = 2
- Surface area = ½ (***Hypotenuse***)(h)
- h =((0.5* ***Hypotenuse***)^2 + (4.25Å)^2)$^{0.5}$
- h = 5.205Å.
- Surface area = ½*6.01*5.205 = 15.64Å
- Surface density = 2 / 15.64Å = 1.278*10^{15} cm^{-2}

- Reading Assignment
- Text Book: Semiconductor Physics and Devices, Basic Principles, Donald A. Neamen
- Read the Prologue Part:

"Semiconductors and the Integrated Circuit"

- Discussion on that topic is on Friday, 8/30/13.

Semiconductors and the Integrated Circuit

- Integration refers to complex circuits with millions of devices can be fabricated on a single chip of semiconductor material in the order of $1cm^2$ with possibly more than 100 terminals.
- ICs could contain arithmetic, logic and memory functions on a single chip – such ICs are called *microprocessor*.
- Since devices can be fabricated close to one another, the time delay of signals is short.

IC Fabrication Steps

1. Thermal Oxidation = is the creation of native oxide of SiO_2 which is used as a Gate Insulator in MOSFETS and as an insulator known as Field Oxide between devices.

- Most other semiconductors do not form native oxides of sufficient quality to be used in device fabrication. (Why Si is preferred)

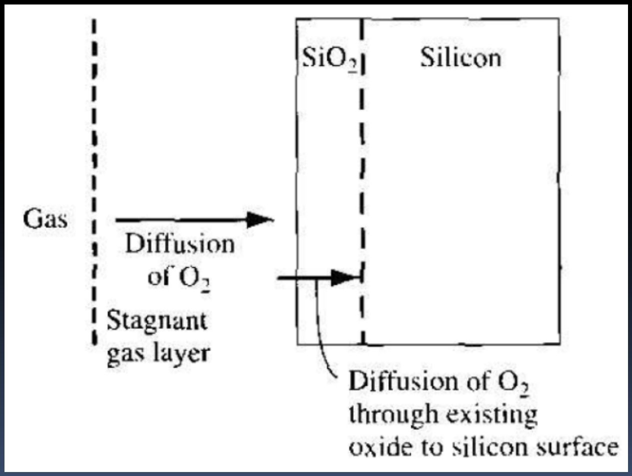


Fig. 8: Schematic of the Oxidation Process

IC Fabrication Steps

2. Photomasking or Photolithography

Photomask = physical representation of a device or its portion whose opaque region is made of UV absorbing material.

Photoresist = an organic polymer that undergoes a chemical change when exposed to UV.

- ✓ First, a photoresist is spread over the surface of the SC.
- ✓ Then, the photoresist is exposed to UV through the photomask.
- ✓ Finally, the photoresist is developed in a chemical solution where the developer removes unwanted portions of the photoresist to generate appropriate patters on the Silicon.

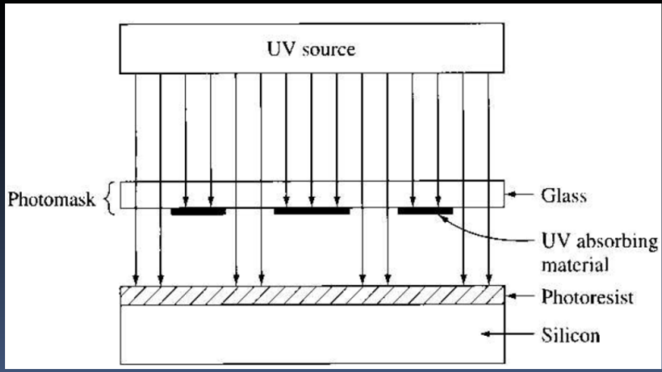


Fig. 9: Schematic showing the use of a Photo-mask

IC Fabrication Steps

3. Etching

After forming photoresist pattern, the Silicon portions uncovered by the photoresist can be etched.

Plasma etching uses an etch gas such as CFC and radio-frequency voltage between cathode and anode terminals where the Silicon wafer is placed on the cathode.

Positively charged ions in the plasma are accelerated toward the cathode and bombard the wafer normal to the surface.

IC Fabrication Steps

4. Diffusion

Process by which specific types of ‘impurity’ atoms are introduced into the Silicon material.

Important since dopting can change conductivity type of materials so that PN junction can be formed.

Dopant atoms include Boron and Phosphorus. They gradually diffuse into Silicon because of a density gradient inside a high T° (1100^0 C) furnace.

The final concentraiton of diffused atoms is Non-linear.

IC Fabrication Steps

5. Ion Implantation

An alternative to high temperature diffusion.

Accelerates a beam of dopant ions at high energy and towards the surface of a semiconductor.

Advantage: it is a low T^o process.

it has very well definition of layers.

Disadvantage: ion bombarding may cause damage.

IC Fabrication Steps

6. Metallization, Bonding and Packaging

- Connects semiconductor devices.

a) Vapor deposition technique: is used to deposit metal films.
b) Photolithography and Etching: are used to form actual interconnect lines.
c) Silicon Nitride: is deposited finally as a protective layer.

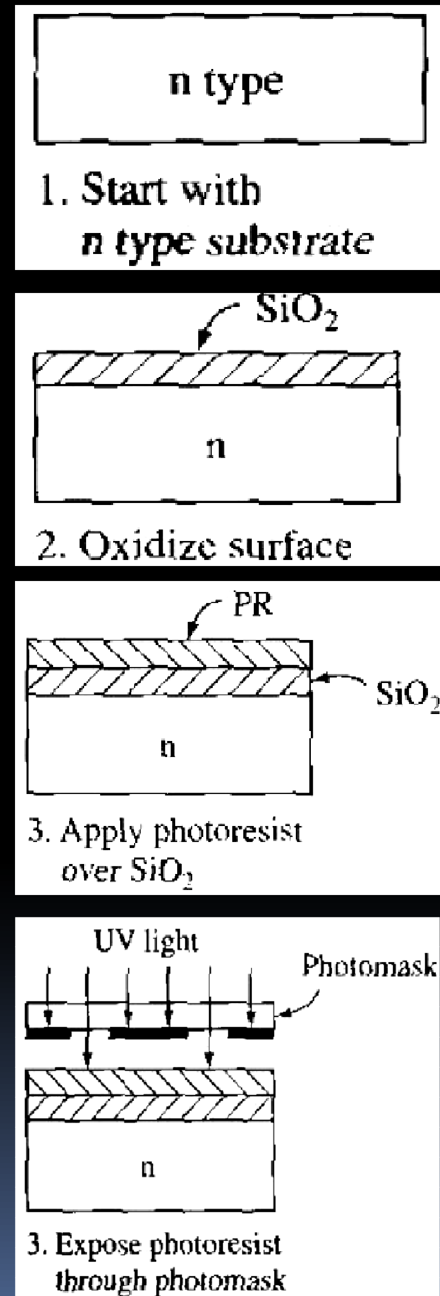
Basic Steps in PN Junction formation

1. Start with “n-type” substrate

2. Oxidize the surface.

3. a) Apply photoresist over SiO_2.

3. b) Expose photoresist through photomask.

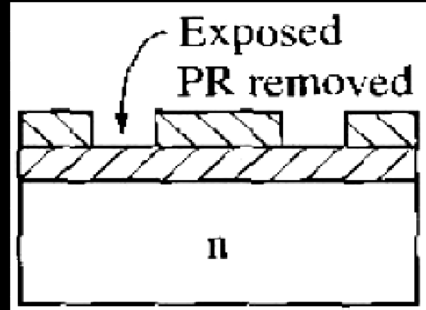


Basic Steps in PN Junction formation

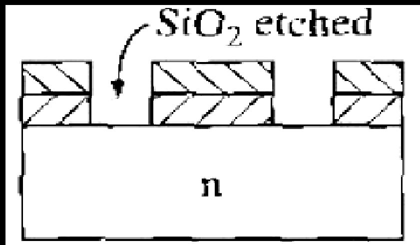
4. Remove exposed photoresist.

5. Etch exposed SiO_2.

6. Ion implant or diffuse Boron to Silicon.

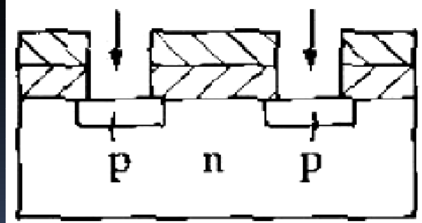


4. Remove exposed photoresist



5. Etch exposed SiO_2

Ion implant or diffuse p-regions

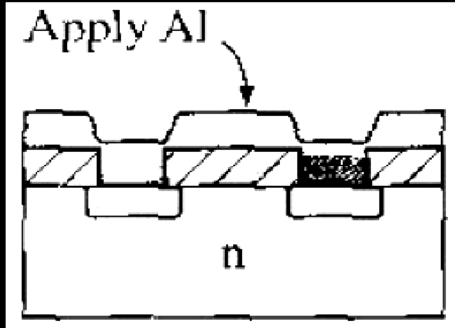


6. Ion implant or diffuse boron into silicon

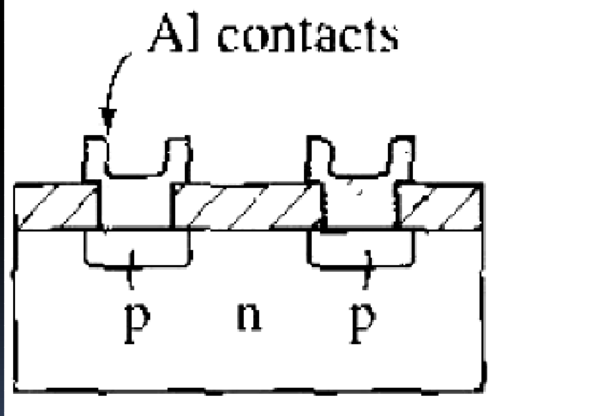
Basic Steps in PN Junction formation

7. Remove PR and splutter Al on surface.

8. Apply PR, photomask and etch to form Al contacts over ‘p’ regions.



7. Remove PR and sputter Al on surface



8. Apply PR, photomask, and etch to form Al contacts over p-regions

Chapter Take Home

- Text Book Problems 1.1, 1.7, 1.21, 1.15

Picture Credits

- Quantum Computer Picture

  Credit: Erick Lucero
- The Cisco Learning Network
  - https://learningnetwork.cisco.com/thread/46685
- Defense Advanced Research Projects Agency (DARPA): Hybrid Insect Micro Electromechanical Systems (HI-MEMS)
  - http://www.infiniteunknown.net
- LSO Medical Group
  - http://www.lsomedical.com/en/content/about-lso-medical