EE143 – Fall 2016
Microfabrication Technologies

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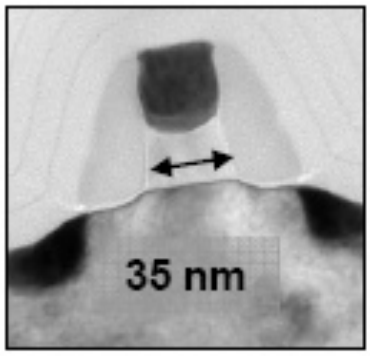
Evolution of Devices

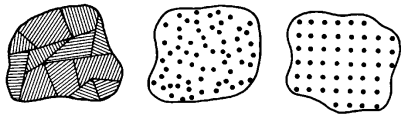
Yesterday's Transistor (1947)



Today's Transistor (2006)

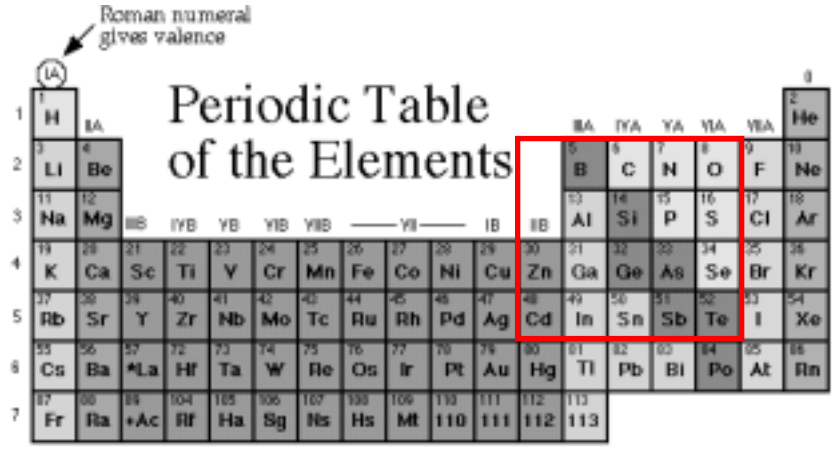
Why "Semiconductors"?

- **Conductors – e.g. Metals**
- **Insulators – e.g. Sand (SiO_2)**
- **Semiconductors**
  - **Conductivity between conductors and insulators**
  - **Generally crystalline in structure**
    - **In recent years, non-crystalline semiconductors have become commercially very important**



Polycrystalline amorphous crystalline

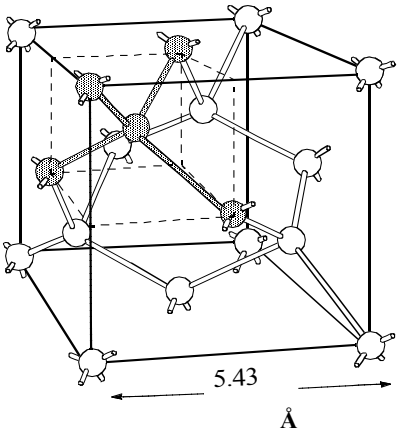
What are semiconductors?



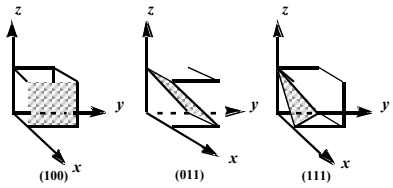
Elements: Si, Ge, C
Binary: GaAs, InSb, SiC, CdSe, etc.
Ternary+: AlGaAs, InGaAs, etc.

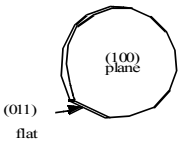
Silicon Crystal Structure

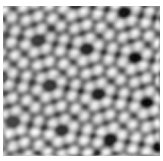
- Unit cell of silicon crystal is cubic.
- Each Si atom has 4 nearest neighbors.



Silicon Wafers and Crystal Planes



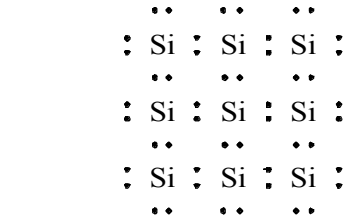




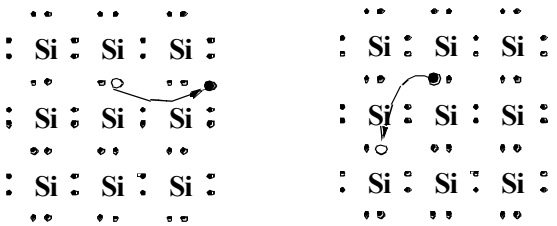
Si (111) plane

- 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.

Bond Model of Electrons and Holes (Intrinsic Si)



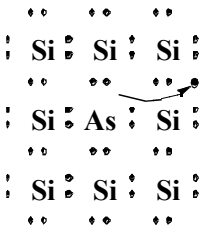
Simplified view of silicon crystal in a two-dimensional representation.



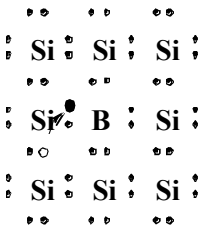
conduction

When an electron breaks loose and becomes a conduction electron, a "hole" is also created

Dopants in Silicon



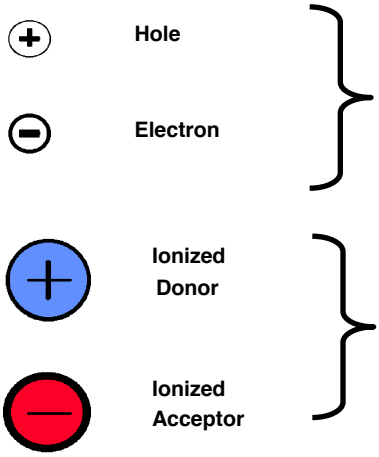
N-type Si



P-type Si

- As (Arsenic), a Group V element, introduces conduction electrons and creates N-type silicon, and is called a donor.
- B (Boron), a Group III element, introduces holes and creates P-type silicon, and is called an acceptor.
- Donors and acceptors are known as dopants.

Types of charges in semiconductors



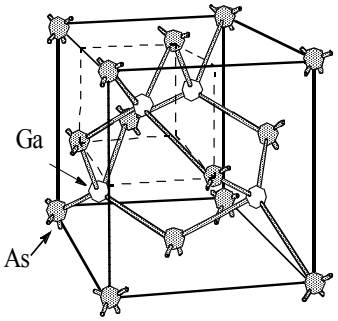
Mobile Charge Carriers
they contribute to current flow with electric field is applied.

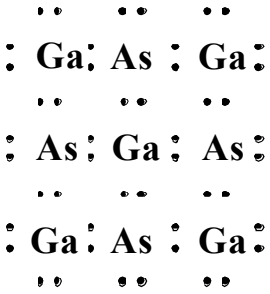
Immobile Charges
they DO NOT contribute to current flow with electric field is applied. However, they affect the local electric field

Doped Si and Charge

- **What is the net charge of your Si when it is electron and hole doped?**

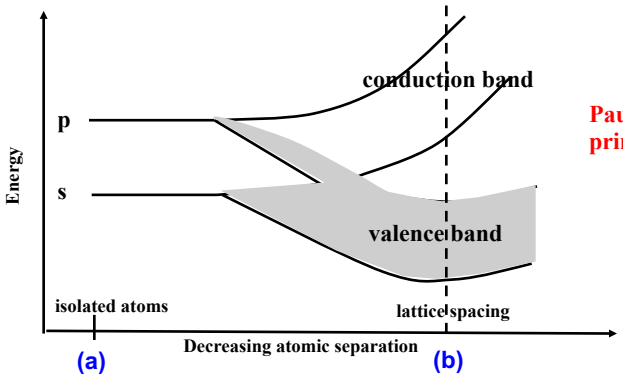
GaAs, III-V Compound Semiconductors, and Their Dopants





- GaAs has the same crystal structure as Si.
- GaAs, GaP, GaN are III-V compound semiconductors, important for optoelectronics.
- Which group of elements are candidates for donors? acceptors?

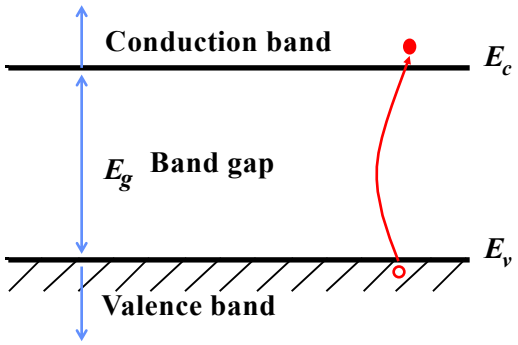
From Atoms to Crystals



Pauli exclusion principle

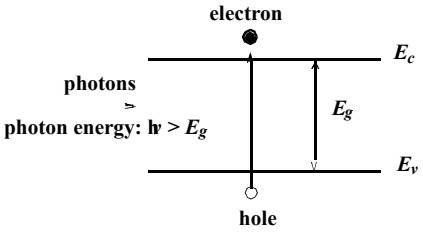
- Energy states of Si atom (a) expand into energy bands of Si crystal (b).
- The lower bands are filled and higher bands are empty in a semiconductor.
- The highest filled band is the *valence band.*
- The lowest empty band is the *conduction band*

Energy Band Diagram



- *Energy band diagram* shows the bottom edge of conduction band, E_c , and top edge of valence band, E_v .
- E_c and E_v are separated by the *band gap energy*, E_g .

Measuring the Band Gap Energy by Light Absorption

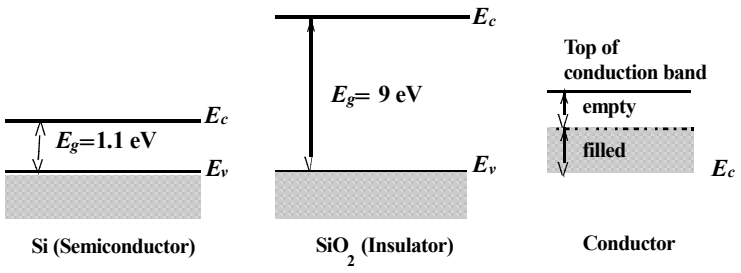


• E_g can be determined from the minimum energy ($h\nu$) of photons that are absorbed by the semiconductor.

Bandgap energies of selected semiconductors

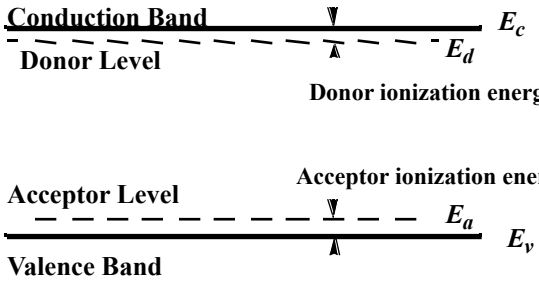
Material	PbTe	Ge	Si	GaAs	GaP	Diamond
E_g (eV)	0.31	0.67	1.12	1.42	2.25	6.0

Semiconductors, Insulators, and Conductors



- Totally filled bands and totally empty bands do not allow current flow.
  - Just as there is no motion of liquid in a totally filled or totally empty bottle.
- Metal conduction band is half-filled.
- Semiconductors have lower E_g's than insulators and can be doped

Donor and Acceptor Levels in the Band Model

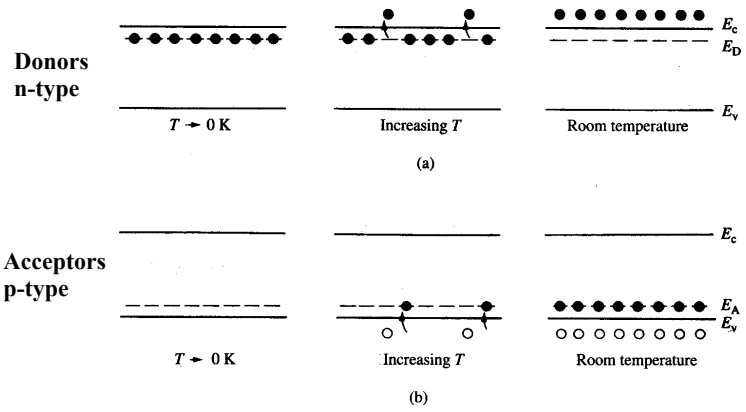


Ionization energy of selected donors and acceptors in silicon

	Donors			Acceptors		
Dopant	Sb	P	As	B	Al	In
Ionization energy, $E_c - E_d$ or $E_a - E_v$ (meV)	39	44	54	45	57	160

Hydrogen: $E_{ion} = \dfrac{m_0 q^4}{8\varepsilon_0^2 h^2} = 13.6$ eV

Dopants and Free Carriers



Dopant ionization energy ~50meV (very low).

General Effects of Doping on n and p

Charge neutrality: $n + N_a^- - p - N_d^+ = 0$

N_a^- : number of ionized acceptors /cm3

N_d^+ : number of ionized donors /cm3

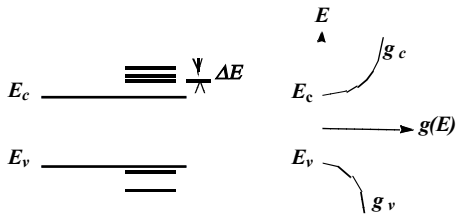
Assuming total ionization of acceptors and donors:

$$n + N_a - p - N_d = 0$$

N_a : number of acceptors /cm3

N_d : number of donors /cm3

Density of States



$$g_c(E) \quad \frac{\text{number of states in } E}{E \text{ volume}} \quad \frac{1}{\text{eV cm}^3}$$

$$g_c(E) \quad \frac{m_n^* \sqrt{2m_n^*(E - E_c)}}{^2\hbar^3}$$

$$g_v(E) \quad \frac{m_p^* \sqrt{2m_p^*(E_v - E)}}{^2\hbar^3}$$

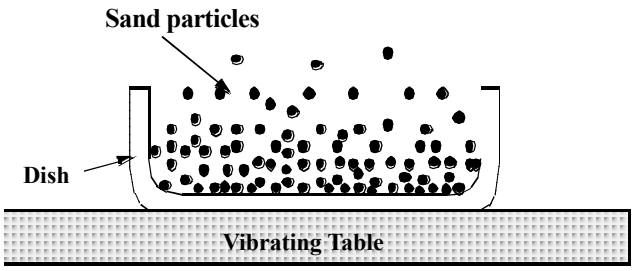
Thermal Equilibrium

- No external forces applied:
  - electric field = 0
  - magnetic field = 0
  - mechanical stress = 0
- Thermal agitation –> electrons and holes exchange energy with the crystal lattice and each other

  ⇒ Every energy state in the conduction and valence bands has a certain probability of being occupied by an electron

Thermal Equilibrium

An Analogy for Thermal Equilibrium



There is a certain probability for the electrons in the conduction band to occupy high-energy states under the agitation of thermal energy (vibrating atoms, etc.)

Fermi-Dirac Distribution

Fermi Function

Probability that an available state at energy E is occupied:

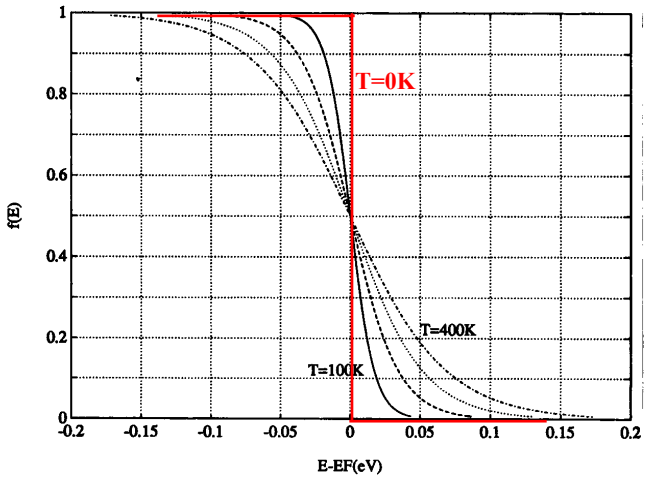
$$f(E) = \frac{1}{1 + e^{(E - E_F)/kT}}$$

E_F is called the ***Fermi energy*** or the ***Fermi level***

There is only one Fermi level in a system at equilibrium.

At $E=E_F$, $f(E)=1/2$

Effect of Temperature on f(E)



1-23

Question

- If f(E) is the probability of a state being occupied by an electron, what is the probability of a state being occupied by a hole?

1-24

Carrier Concentration at Equilibrium: Electrons

Equilibrium Carrier Concentrations

- Integrate $n(E)$ over all the energies in the conduction band to obtain n

$$n = \int_{E_c}^{\text{top of conduction band}} g_c(E) f(E) dE$$

- By using the Boltzmann approximation, and extending the integration limit to ∞, we obtain

$$n = N_c e^{-(E_c - E_F)/kT} \quad \text{where} \quad N_c = 2\left(\frac{2\pi m_n^* kT}{h^2}\right)^{3/2}$$

***N_c* is called the *effective density of states (of the conduction band)*.**

Carrier Concentration at Equilibrium: Holes

- Integrate $p(E)$ over all the energies in the valence band to obtain p

$$p = \int_{\text{bottom of valence band}}^{E_v} g_v(E)[1 - f(E)]dE$$

- By using the Boltzmann approximation, and extending the integration limit to -∞, we obtain

$$p = N_v e^{-(E_F - E_v)/kT} \quad \text{where} \quad N_v = 2\left(\frac{2\pi m_p^* kT}{h^2}\right)^{3/2}$$

N_v* is called the *effective density of states of the valence band.

Intrinsic Semiconductor

- **Extremely pure semiconductor sample containing an insignificant amount of impurity atoms.**

$$\mathbf{n = p = n_i}$$

E_f lies in the middle of the band gap

Material	Ge	Si	GaAs
E_g (eV)	0.67	1.12	1.42
n_i (1/cm^3)	2 x 10^{13}	1 x 10^{10}	2 x 10^6