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 (SiO₂)
- Semiconductors
  - Conductivity between conductors and insulators
  - Generally crystalline in structure
    - In recent years, non-crystalline semiconductors have become commercially very important

**Polycrystalline amorphous crystalline**

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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

- 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.

When an electron breaks loose and becomes a conduction electron, a “hole” is also created.

Dopants in Silicon

- 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

- **Hole**
- **Electron**
- **Ionized Donor**
- **Ionized Acceptor**

**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.

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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

- 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.

<table>
<thead>
<tr>
<th>Material</th>
<th>PbTe</th>
<th>Ge</th>
<th>Si</th>
<th>GaAs</th>
<th>GaP</th>
<th>Diamond</th>
</tr>
</thead>
<tbody>
<tr>
<td>$E_g$ (eV)</td>
<td>0.31</td>
<td>0.67</td>
<td>1.12</td>
<td>1.42</td>
<td>2.25</td>
<td>6.0</td>
</tr>
</tbody>
</table>
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

Conduction Band

Donor Level

Acceptor Level

Valence Band

Ionization energy of selected donors and acceptors in silicon

<table>
<thead>
<tr>
<th>Donor</th>
<th>Sb</th>
<th>P</th>
<th>As</th>
<th>B</th>
<th>Al</th>
<th>In</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ionization energy, $E_c - E_d$ or $E_v - E_a$ (meV)</td>
<td>39</td>
<td>44</td>
<td>54</td>
<td>45</td>
<td>57</td>
<td>160</td>
</tr>
</tbody>
</table>

Hydrogen: $E_{ion} = \frac{m_e q^4}{8 \hbar^2} = 13.6$ eV
Dopants and Free Carriers

Dopant ionization energy ~50meV (very low).

Donors
n-type

\[ T = 0 \text{ K} \]

Increasing \( T \)

Room temperature \( E_a \)

(a)

Acceptors
p-type

\[ T = 0 \text{ K} \]

Increasing \( T \)

Room temperature \( E_a \)

(b)

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

\[ n(E) = \frac{g_c(E)}{V} \]

\[ g_c(E) = \frac{1}{eV \text{ cm}^3} \]

\[ g_v(E) = m^* c_2 \left( \frac{2m^*}{\hbar^2} \right)^{1/2} \]

\[ g_c(E) = m^* c_2 \left( \frac{2m^*}{\hbar^2} \right)^{1/2} \]

Thermal Equilibrium

- No external forces applied:
  - electric field = 0
  - magnetic field = 0
  - mechanical stress = 0

- Thermal agitation \( \rightarrow \) electrons and holes exchange energy with the crystal lattice and each other

  \[ \Rightarrow \] 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 $f(E)$

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?
Carrier Concentration at Equilibrium: Electrons

Equilibrium Carrier Concentrations

- Integrate $n(E)$ over all the energies in the conduction band to obtain $n$
  
  $$n = \int_{E_{c}}^{E_{c,\text{top}}} g_{c}(E) f(E) dE$$

- By using the Boltzmann approximation, and extending the integration limit to $\infty$, we obtain
  
  $$n = n_{c} e^{-(E_{F} - E_{c})/kT}$$
  
  where $n_{c} = 2 \left( \frac{2\pi m^{*} kT}{\hbar^{2}} \right)^{3/2}$

  $n_{c}$ 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 $p$
  
  $$p = \int_{E_{v}}^{E_{v,\text{bottom}}} g_{v}(E) \left[1 - f(E)\right] dE$$

- By using the Boltzmann approximation, and extending the integration limit to $-\infty$, we obtain
  
  $$p = n_{v} e^{-(E_{F} - E_{v})/kT}$$
  
  where $n_{v} = 2 \left( \frac{2\pi m^{*} kT}{\hbar^{2}} \right)^{3/2}$

  $n_{v}$ is called the effective density of states of the valence band.
Intrinsic Semiconductor

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

\[ n = p = n_i \]

\[ E_f \] lies in the middle of the band gap

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<td>1.42</td>
</tr>
<tr>
<td>( n_i ) (1/cm(^3))</td>
<td>( 2 \times 10^{13} )</td>
<td>( 1 \times 10^{10} )</td>
<td>( 2 \times 10^{6} )</td>
</tr>
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