ECE 225
Lecture 2
Semiconductor Physics Review

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Outline

• Band Model
• Metal, Insulator and Semiconductor
• Electron / Hole Concentration
• Extrinsic Semiconductors
• P-N Junction
• MOS
• MOSFET

Please Review Lecture 5, ECE 122A, Fall 2014
Band Model of Solids

- Electron Energy Level

\[ E_n = \frac{-Z^2 m_0 q^4}{8 \varepsilon_0^2 h^2 n^2} \]
Band Model of Solids

Pauli Exclusion Principle (PEP)

The splitting of the discrete states into two states in consistent with the Pauli exclusion principle.
Band Model of Solids

- The allowed/forbidden energy band
Band Model of Solids

- Silicon: The 14 electrons are placed into the following 3 energy levels and 5 orbitals: $1s^2 \ 2s^2 \ 2p^6 \ 3s^2 \ 3p^2$
- The splitting of the 3s and 3p states of Si into the allowed and forbidden bands
Semiconductors/Metals/Insulators
Metals, Semiconductors and Insulators

- **Conduction** happens if one band is *neither empty nor full*

- Consider N sodium atoms
  - Total number of available states = $2N$
  - $1s^2 \ 2s^2 \ 2p^6 \ 3s^1$
  - N conduction electrons

- metallic
Metals, Semiconductors and Insulators

- Insulator

- Examples:
  - SiO2
  - AlN
Metals, Semiconductors and Insulators

- **insulators vs. semiconductors?**
  - Si with $E_G=1.12$ eV is a semiconductor
  - SiO$_2$ with $E_G \approx 5$ eV is an insulator

- Impurities in semiconductors are almost fully ionized at room temperatures

  *Ref.: Charles Kittel, ‘Introduction to Solid State Physics’, 7th edition*
Metals, Semiconductors and Insulators

- Two types of charged particles exist in a semiconductor
  - Electron
  - Hole

\[ T=0K \quad T>0 \]
Electron Concentration (n) in a Bulk Semiconductor

- **two concepts**
  - Density of States (DOS)
  - Fermi-Dirac Occupation Function

- **DOS:**
  - **Definition:** \( D(E) \, dE = \# \text{ of “allowed” energy states between } E \text{ and } E+dE \text{ per unit volume} \)
  - **Expressed in** \( \text{cm}^{-3} \)
Electron Concentration in a Semiconductor

- Fermi-Dirac Occupation Function

\[ f_D(E) = \frac{1}{1 + e^{\frac{-(E_F - E)}{k_B T}}} \]

- \( f_D(E) = 0.5 \) at \( E = E_F \) (\( E_F \) is the Fermi level…)

- \( f_D(E) = \) probability of occupation of a state of energy \( E \), given that such a state exists.

- Probability of a hole in a state of energy \( E \) is \((1 - f_D(E))\) (Why?)
Fermi-Dirac Function $f(E)$:

- At higher temperatures, $(E-E_F) \gg kT$
- Fermi-Dirac (FD) distribution function reduces to the Boltzmann (BZ) distribution function: $f(E) = \exp\left(-\frac{(E-E_F)}{kT}\right)$
Electron and Hole Concentrations

\[ n = \int_{E_C}^{\infty} D(E) f(E) dE \]

- Integrating:
  \[ n_0 = N_C e^{\frac{(E_F - E_C)}{k_B T}} \]

- Analogous expression for hole concentration:
  - (A hole is a vacant state in a band)
  
  \[ p_0 = N_V e^{\frac{(E_V - E_F)}{k_B T}} \]

\( N_C \) and \( N_V \) are called the "effective density of states"...why?
Electron and Hole Concentrations

- Exercise: calculate $n_0$ for intrinsic (undoped, pure) Si at 300K
  - $N_c = 3.2 \times 10^{19}$ cm$^{-3}$
  - $E_i - E_V = 0.5506$ eV
  - $E_g = 1.11$ eV

- Result: $n_0 = 1.45 \times 10^{10}$ cm$^{-3} = p_o$
Extrinsic Semiconductors

- To increase conductivity, *doping* adds impurities to silicon crystal

- Two types of impurities:
  - *donors*
  - *Acceptors*
  - Impurities are ionized when they donate or accept an electron
N-Type Semiconductors

- **N-Type**: Large concentration of electrons in conduction band
- **Created by donor impurities**
  - One extra electron than Silicon
  - Silicon: periodic table column IV
  - Donors: periodic table column V
    - Phosphorus (P)
    - Arsenic (As)
    - Antimony (Sb)
- **Doping concentration**: \( N_D \) (atoms/cm\(^3\))
N-Type Semiconductors (2)

- Donor impurities create “donor level” in energy band diagram
P-Type Semiconductors

- **P-Type**: Large concentration of holes in valence band
- **Created by acceptor impurities**
  - Acceptors: one fewer electron than Silicon
  - Silicon: periodic table column IV
  - Acceptors: periodic table column III
    - Boron (B)
    - Aluminum (Al)
    - Gallium (Ga)
- **Doping concentration**: $N_A$
P-Type Semiconductors (2)

- Acceptor impurities create “acceptor level” in energy band diagram

![Energy band diagrams with acceptor levels at different temperatures](image)
Extrinsic Energy Band Diagram

- Effect of doping on Fermi level $E_F$
  - N-Type: Fermi level moves up
  - P-Type: Fermi level moves down

$$q \phi_F = E_F - E_i$$

$\phi_F$: V
$q \phi_F$: eV
Extrinsic Semiconductor (Summary)

Electron affinity: energy to move electron from conduction band to free space

Work function: energy to move electron from Fermi level to free space
Electron Currents

- **Two types of current** in semiconductors
  - **Drift current**: Electron motion due to electric field
  - **Diffusion current**: Electron motion due to differences in carrier concentration

- Semiconductors rely on interaction between these two currents!

- Current density \( J \) is always used rather than actual current value: \( A/cm^2 \)

- **Actual current** \( I = J \cdot A \)
Drift Current

- With no electric field, there is no net motion of electrons, but each electron moves randomly....why?

- With electric field, there is net force on each electron, causing acceleration

- Acceleration causes collisions, which balance electric field

- Force on electron: \( F_x = -qE_x \)

- Average net velocity: \( \langle v_x \rangle = -\frac{q\tilde{t}}{m^*_n} E_x \)
Drift Current (2)

Given average velocity, find current density:

\[ J_x = \frac{nq^2 \bar{v}}{m_n} E_x \]

Define \( \mu_n = \text{electron mobility} \): ease with which electrons drift in a material

\[ \mu_n = \frac{q\bar{v}}{m_n} \]

\[ J_x = qn\mu_n E_x \]

Hint: estimate the charge crossing an area \( A \) in time \( dt \): \( nq\bar{v}A dt \)

\( J_x = \text{A/cm}^2 \)

\( n = \text{electrons/cm}^3 \)

\( \mu = \text{cm}^2/\text{V-s} \)
Drift Current (3)

Therefore current density is proportional to electric field (Ohm’s Law):

\[ J_x = qn \mu_n E_x \]

\[ \sigma = qn \mu_n \]

\[ J_x = \sigma E_x \]

\[ \sigma \text{ is the conductivity of the material} \]

\[ \sigma = 1/\rho, \text{ where } \rho \text{= resistivity} \]

or \( V = I.R \)

Since, \( J = I/A = E/\rho \)

And \( E = V/L \)
Drift Current Example

- Find the approximate electron current for intrinsic silicon
  - Size = 1 cm$^3$
  - Voltage applied: 1V

- $\mu_n = 600 \text{ cm}^2/\text{V} \cdot \text{s}$
- $q = 1.6 \times 10^{19} \text{ C}$
Diffusion Current

- Diffusion is due to electron or hole concentration gradient
  - Concentration gradient = $d_n/d_x$ or $d_p/d_x$
- Flux density $\phi_n$, $\phi_p$ is rate of electron or hole flow, per unit area
  $$\phi_n = -D_n \frac{dn}{dx} \quad \phi_p = -D_p \frac{dp}{dx}$$
- $D_n$, $D_p$ is diffusion coefficient
  $$J_n = qD_n \frac{dn}{dx} \quad J_p = -qD_p \frac{dp}{dx}$$
Total Current: Electrons

- **Drift:**
  - Electrons drift opposite to the electric field.
  - Drift current is in the same direction as the electric field.

- **Diffusion:**
  - Electrons diffuse in the direction of decreasing concentration.
  - Diffusion current is in opposite direction to decreasing concentration.

\[
J_n(x) = q\mu_n n(x)E(x) + qD_n \frac{dn(x)}{dx}
\]

- Drift
- Diffusion
Total Current: Holes

- **Drift:**
  - Holes drift with the electric field
  - Drift current is in the same direction as the electric field

- **Diffusion:**
  - Holes diffuse in the direction of decreasing concentration
  - Diffusion current is in the same direction as decreasing concentration

\[
J_p(x) = q\mu_p p(x)E(x) - qD_p \frac{dp(x)}{dx}
\]

- Drift
- Diffusion
Equilibrium

- At equilibrium, no current flows
- Any diffusion current must be balanced by an equal drift current, and vice-versa.
- For example (for electrons):
  \[ q\mu_n n(x)E(x) = -qD_n \frac{dn(x)}{dx} \]

- Equilibrium Fermi level must be flat:
  \[ \frac{dE_F}{dx} = 0 \]
P/N Junctions

- put two types of semiconductors together

- Large concentration gradient at junction
P/N Junctions (2)

- Immobile ions are left behind
- Electric field forms, from N to P
- E-field causes drift in opposite direction as diffusion
- Equilibrium No current flows
Depletion region forms around junction

“Depleted” of any mobile charges (holes or electrons)

Charge in depletion region due to fixed ions

Electric field causes a potential difference across junction: known as built-in voltage $V_0$
At thermal equilibrium, no net current flow

- When drift + diffusion currents = 0, \( \frac{dE_f}{dx} = 0 \)
- Bands must bend so that Fermi level is constant

\( V_0 = \) built-in voltage
The Diode

Cross-section of pn-junction in an IC process

One-dimensional representation

diode symbol

Mostly occurring as parasitic element in Digital ICs
Bias Effects on PN Junction

**Equilibrium**

- Smaller E field
- Smaller depletion W

**Forward bias**

- Larger E field
- Larger depletion W

**Reverse bias**

- Lower potential barrier
- h^+ diffusion

- Higher potential barrier
- e^- diffusion
MOS Structure

- **MOS**: Metal-oxide-semiconductor
  - Gate: metal (or polysilicon)
  - Oxide: silicon dioxide, grown on substrate
- **MOS capacitor**: two-terminal MOS structure

![MOS Structure Diagram]

- Gate terminal
- Metal gate (Al)
- Oxide (SiO$_2$)
- Si substrate
- Body or substrate terminal
MOS Energy Band Diagram

- **Work function** $(q\Phi_M, q\Phi_S)$: energy required to take electron from Fermi level to free space
- **Electron affinity** is the energy required to move an electron from conduction band to free space $(E_0) = q\chi_S$
- **Work function** difference between Al and Si = 0.8V

![MOS Energy Band Diagram](image-url)
MOS Energy Band Diagram

- Bands must bend for Fermi levels to line up
- Amount of bending is equal to work function difference: \( q\Phi_M - q\Phi_S \)
- Fermi levels equalized by transfer of –ve charge from materials with higher \( E_F \) (smaller work functions) across interfaces to materials with lower \( E_F \)
- Part of voltage drop occurs across oxide, rest occurs next to O-S interface

\[ \Phi_F = \text{Fermi potential (difference between } E_F \text{ and } E_i \text{ in bulk)} \]
\[ \Phi_S = \text{surface potential} \]
MOS Capacitor Operation

- Assume p-type substrate
- Three regions of operation
  - Accumulation ($V_G < 0$)
  - Depletion ($V_G > 0$ but small)
  - Inversion ($V_G >> 0$)
Accumulation

- **Negative voltage on gate**: attracts holes in substrate towards oxide
- Holes “accumulate” on Si surface (surface is more strongly p-type)
- Electrons pushed deeper into substrate

![Diagram of accumulation process]

\[ V_G < 0 \]
\[ V_B = 0 \]

\[ E_{Fm}, E_{C}, E_{i}, E_{Fp}, E_{V} \]
Depletion

- Positive voltage on gate: repels holes in substrate
  - Holes leave behind negatively charged acceptor ions
- Depletion region forms: devoid of carriers
  - Electric field directed from gate to substrate
- Bands bend downwards near surface
  - Surface becomes less strongly p-type ($E_F$ close to $E_i$)

\[ V_G > 0 \]
\[ V_B = 0 \]

![Diagram showing depletion region and band bending](image.png)
Inversion

- Increase voltage on gate, bands bend more
- Additional minority carriers (electrons) attracted from substrate to surface
  - Forms “inversion layer” of electrons
- Surface becomes n-type

P-type Si substrate

\[ V_G \gg 0 \]

\[ V_B = 0 \]

\[ E_{ox} \]

\[ qV_G \]

\[ E_{Fm} \]

\[ E_C \]

\[ E_i \]

\[ E_{Fp} \]

\[ E_V \]
Inversion

Definition of inversion

- Point at which density of electrons on surface = density of holes in bulk
- Surface potential is same as $\phi_F$, but different sign

Remember:

$q\phi_F = E_F - E_i$

$q\phi_s = -q\phi_F$
MOS Capacitor (Review)

(a) $V_g < 0$

(b) $0 < V_g < V_t$

(c) $V_g > V_t$

FIG 2.2 MOS structure demonstrating (a) accumulation, (b) depletion, and (c) inversion