ESE370: Circuit-Level Modeling, Design, and Optimization for Digital Systems

Day 9: September 17, 2014
MOS Model

You are Here

• Previously: simple models
  – Comfortable with basic functions and circuits
• This week and next (4 lectures)
  – Detail semiconductor, MOSFET phenomenology
  → Don’t Blink!
• Rest of terms
  – Implications

Today

• MOS Structure
• Basic Idea
• Semiconductor Physics
  – Metals, insulators
  – Silicon lattice
  – Band Gaps
  – Doping

MOS

• Metal Oxide Semiconductor

Oblique Side Top

Capacitor

• Charge distribution and field?

Metal – gate
Oxide – insulator separating gate from channel
  – Ideally: no conduction from gate to channel
Semiconductor – between source and drain
See why gate input capacitive?
Idea

- Semiconductor – can behave as metal or insulator
- Voltage on gate creates an electrical field
- Field pulls (repels) charge from channel
  - Causing semiconductor to switch conduction
  - Hence “Field-Effect” Transistor

Source/Drain Contacts

- Contacts: Conductors → metallic
  - Connect to metal wires that connect transistors

Fabrication

- Start with Silicon wafer
- Dope
- Grow Oxide (SiO₂)
- Deposit Metal
- Mask/Etch to define where features go

Dimensions

- Channel Length (L)
- Channel Width (W)
- Oxide Thickness (T_{ox})
  - Process named by minimum length
    - 22nm → L=22nm

Conduction

- Metal – conducts
- Insulator – does not conduct
- Semiconductor – can act as either
Why metal conduct?

- Electrons move
- Must be able to "remove" electron from atom or molecule

Conduction

Atomic States

- Quantized Energy Levels
- Must have enough energy to change level (state)

Thermal Energy

- Except at absolute 0
  - There is always free energy
  - Causes electrons to hop around
    - ....when enough energy to change states
  - Energy gap between states determines energy required

Silicon Atom

- How many valence electrons?
Silicon

- 4 valence electrons
  - Inner shells filled
  - Only outer shells contribute to chemical interactions

Silicon-Silicon Bonding

- Can form covalent bonds with 4 other silicon atoms

Silicon Lattice

- Forms into crystal lattice

http://www.webelements.com/silicon/crystal_structure.html

Outer Orbital?

- What happens to outer shell in Silicon lattice?

Energy?

- What does this say about energy to move electron?
**State View**

Energy

Valance Band – all states filled

**State View**

Energy

Conduction Band – all states empty

Valance Band – all states filled

**Band Gap and Conduction**

Insulator

\[ E_v \]

8 ev

\[ E_c \]

Metal

\[ E_v \]

\[ E_c \]

OR

Semiconductor

\[ E_v \]

1.1 ev

\[ E_c \]

**Doping**

- Add impurities to Silicon Lattice
  - Replace a Si atom at a lattice site with another

- E.g. add a Group 15 element
  - E.g. P (Phosphorus)
  - How many valence electrons?

**Doping with P**

- Add impurities to Silicon Lattice
  - Replace a Si atom at a lattice site with another

- E.g. add a Group 15 element
  - E.g. P (Phosphorus)
  - How many valence electrons?
Doping with P

- End up with extra electrons
  - Donor electrons
- Not tightly bound to atom
  - Low energy to displace
  - Easy for these electrons to move

Doped Band Gaps

- Addition of donor electrons makes more metallic
  - Easier to conduct

Localized

- Electron is localized
- Won’t go far if no low energy states nearby
- Increase doping concentration
  - Fraction of P’s to Si’s
  - Decreases energy to conduct

Electron Conduction

Capacitor Charge

- Remember capacitor charge
**MOS Field?**

- What does “capacitor” field do to the doped semiconductor channel?

- **Vgs=0**
  - No field
  - - -
  
  - **Vgs>0**
  - Conducts
  - - -

**MOS Field Effect**

- Charge on capacitor
  - Attract or repel charge in channel
  - Change the donors in the channel
  - Modulates conduction
  - Positive
    - Attracts carriers
    - Enables conduction
  - Negative?
    - Repel carriers
    - Disable conduction

**Group 13**

- What happens if we replace Si atoms with group 13 atom instead?
  - E.g. B (Boron)
  - Valance band electrons?

**Doping with B**

- End up with electron vacancies -- Holes
  - Acceptor electron sites
  - Easy for electrons to shift into these sites
    - Low energy to displace
    - Easy for the electrons to move
    - Movement of an electron best viewed as movement of hole

**Hole Conduction**

**Doped Band Gaps**

- Addition of acceptor sites makes more metallic
  - Easier to conduct

\[ E_v = 0.045 \text{eV} \]

\[ E_A = 1.1 \text{eV} \]
**Field Effect?**

- Effect of positive field on Acceptor-doped Silicon?
- Effect of negative field on Acceptor-doped Silicon?

**MOSFETs**

- Donor doping
  - Excess electrons
  - Negative or N-type material
  - NFET
- Acceptor doping
  - Excess holes
  - Positive or P-type material
  - PFET

**MOSFET**

- Semiconductor can act like metal or insulator
- Use field to modulate conduction state of semiconductor

**Admin**

- HW 3 due tomorrow
- New Ketterer combo on Piazza
- Friday: back here for lecture
  - MOS Transistor Basics
- HW4 is out