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

Lee 6: September 14, 2015
MOS Model

You are Here: Transistor Edition
- Previously: simple models (0 and 1st order)
  - Comfortable with basic functions and circuits
- This week and next (4 lectures)
  - Detailed semiconductor discussion
  - MOSFET phenomenology
  - Don’t Blink!
- Rest of term
  - Implications of the MOS device

Today
- MOS Structure
- Basic Fabrication
- Semiconductor Physics
  - Metals, insulators
  - Silicon lattice
  - Band gaps
  - Doping
  - Field Effects

MOS
- Metal Oxide Semiconductor

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

Capacitor
- Charge distribution and field?
- How much charge on plates?
Idea

- Semiconductor – can behave as metal or insulator
- Voltage on gate induces an electrical field
- Induced field attracts (repels) charge in semiconductor to form a channel
  - Semiconductor can be switched between conducting and not conducting
  - 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 ($\text{SiO}_2$)
- Deposit Metal
- Mask/Etch to define where features go

Dimensions

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

Conduction

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

Conduction
- Electrons move
- Must be able to “remove” electron from atom or molecule

Atomic States
- Quantized Energy Levels (bands)
  - Valence and Conduction Bands
- 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 there is 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

Silicon Ingot

1 impurity atom per 10 billion silicon atoms

Silicon Lattice

- Cartoon two-dimensional view

Outer Orbital?

- What happens to outer shell in Silicon lattice?
Energy?

- What does this say about energy to move electron?

Energy State View

Valance Band – all states filled

Energy State View

Conduction Band – all states empty

Energy State View

Valance Band – all states filled

Band Gap and Conduction

- Insulator: \( E_v \), \( 8\text{ev} \) to \( E_c \)
- Metal: \( E_v \) to \( E_c \)
- OR
- Semiconductor: \( E_v \) to \( 1.1\text{ev} \) to \( E_c \)

Doping

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

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?

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

Electron is localized
- Won’t go far if no low energy states nearby
- Increasing doping concentration
  - Ratio of P atoms to Si atoms
  - Decreases energy to conduct
Electron Conduction

Capacitor Charge

- Remember capacitor charge

MOS Field?

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

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MOS Field Effect
- Charge on capacitor
  - Attract or repel charges to form channel
  - Modulates conduction
  - Positive
    - Attracts carriers
    - Enables conduction
  - Negative
    - Repels carriers
    - Disable conduction

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

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

- Effect of positive field on Acceptor-doped Silicon?

\[ V_{gs} = 0 \]

No field

\[ + + + + \]

\[ V_{op} > 0 \]

\[ + + + + \]

= No conduction

Field Effect?

- Effect of negative field on Acceptor-doped Silicon?

\[ V_{gs} = 0 \]

No field

\[ + + + + \]

\[ V_{op} < 0 \]

\[ + + + + \]

= Conduction

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