Diodes: Rectifiers and Clamp Circuits

OUTLINE

• Half-wave Rectifier
• Clamps and Voltage Doublers using Capacitors (the most challenging circuits in EE40)
• (EE 105 Small Signal Model)

Reading
Hambley 10.5-10.8

Power Conversion Circuits

• Converting AC to DC
• Potential applications: Charging a battery

\[ V_I = V_m \sin(\omega t) \]

\[ V_o \]
Rectifier Equivalent circuit

$V > 0.6V$, diode = short circuit
$\Rightarrow V_o = V_1 - 0.6$

$V < 0.6V$, diode = open circuit
$\Rightarrow V_o = 0$

Half-wave Rectifier Circuits

- Adding a capacitor: what does it do?
Half-Wave Rectifier

Level Shift Circuit

Once the capacitor is charged by the negative most voltage the rest of the signal is shifted up by that amount.
Voltage Doubler Circuit

The final output is the peak to peak voltage of the input.

Device Isolation using pn Junctions

No current flows if voltages are applied between n-type regions, because two pn junctions are “back-to-back”

=> n-type regions isolated in p-type substrate and vice versa
Why are pn Junctions Important for ICs?

• The basic building block in digital ICs is the MOS transistor, whose structure contains reverse-biased diodes.
  – pn junctions are important for electrical isolation of transistors located next to each other at the surface of a Si wafer.
  – The junction capacitance of these diodes can limit the performance (operating speed) of digital circuits.

We can build large circuits consisting of many transistors without worrying about current flow between devices. The p-n junctions isolate the transistors because there is always at least one reverse-biased p-n junction in every potential current path.
Modern Field Effect Transistor (FET)

- An electric field is applied normal to the surface of the semiconductor (by applying a voltage to an overlying electrode), to modulate the conductance of the semiconductor
  - Modulate drift current flowing between 2 contacts ("source" and "drain") by varying the voltage on the "gate" electrode
  - Metal-oxide-semiconductor (MOS) FET

MOSFET

- NMOS: N-channel Metal Oxide Semiconductor
  - L = channel length
  - W = channel width

- A GATE electrode is placed above (electrically insulated from) the silicon surface, and is used to control the resistance between the SOURCE and DRAIN regions
Without a gate voltage applied, no current can flow between the source and drain regions.

Above a certain gate-to-source voltage (threshold voltage $V_T$), a conducting layer of mobile electrons is formed at the Si surface beneath the oxide. These electrons can carry current between the source and drain.

**N-channel MOSFET**

- For current to flow, $V_{GS} > V_T$
- Enhancement mode: $V_T > 0$
- Depletion mode: $V_T < 0$
  - Transistor is ON when $V_G=0V$

**N-channel vs. P-channel MOSFETs**

- For current to flow, $V_{GS} < V_T$
- Enhancement mode: $V_T < 0$
- Depletion mode: $V_T > 0$
  - Transistor is ON when $V_G=0V$

(*"n+" denotes very heavily doped n-type material; "+p" denotes very heavily doped p-type material)
**NMOSFET $I_G$ vs. $V_{GS}$ Characteristic**

Consider the current $I_G$ (flowing into G) versus $V_{GS}$:

The gate is insulated from the semiconductor, so there is no significant gate current.


**NMOSFET $I_D$ vs. $V_{DS}$ Characteristics**

Next consider $I_D$ (flowing into D) versus $V_{DS}$, as $V_{GS}$ is varied:

Above threshold ($V_{GS} > V_T$): 
"inversion layer" of electrons appears, so conduction between S and D is possible

Below "threshold" ($V_{GS} < V_T$): 
no charge $\rightarrow$ no conduction
The MOSFET as a Controlled Resistor

- The MOSFET behaves as a resistor when $V_{DS}$ is low:
  - Drain current $I_D$ increases linearly with $V_{DS}$
  - Resistance $R_{DS}$ between SOURCE & DRAIN depends on $V_{GS}$
    - $R_{DS}$ is lowered as $V_{GS}$ increases above $V_T$

NMOSFET Example:

- $I_D$ is reduced by the voltage drop along the channel
- $I_D$ is reduced when carriers reach the velocity limit

MOSFET Current Saturation

1. $I_D$ is reduced by the voltage drop along the channel
2. $I_D$ is reduced when carriers reach the velocity limit