Lecture 5: Diodes and Transistors

Diodes:

- What do we use diodes for?
  - protect circuits by limiting the voltage (clipping and clamping)
  - turn AC into DC (voltage rectifier)
  - voltage multipliers (e.g. double input voltage)
  - non-linear mixing of two voltages (e.g. amplitude modulation)

Diodes (and transistors) are non-linear device: $V \neq IR$!

Diode conducts when $V_{\text{anode}} > V_{\text{cathode}}$

K.K. Gan

L5: Diodes and Transistors
◆ Diode is forward biased when $V_{\text{anode}} > V_{\text{cathode}}$.
   ■ Diode conducts current strongly
   ■ Voltage drop across diode is (almost) independent of diode current
   ■ Effective resistance (impedance) of diode is small

◆ Diode is reverse biased when $V_{\text{anode}} < V_{\text{cathode}}$.
   ■ Diode conducts current very weakly (typically < $\mu$A)
   ■ Diode current is (almost) independent of voltage, until breakdown
   ■ Effective resistance (impedance) of diode is very large

◆ Current-voltage relationship for a diode:
\[
I = I_s (e^{eV/kT} - 1)
\]
   ■ “diode”, “rectifier”, or “Ebers-Moll” equation
   ■ $I_s =$ reverse saturation current (typically < $\mu$A)
   ■ $k =$ Boltzmann's constant, $e =$ electron charge, $T =$ temperature
   ■ At room temperature, $kT/e = 25.3$ mV,
   \[
   I = I_s e^{eV/kT} \quad \text{if } V > 0 \\
   I = -I_s \quad \text{if } V < 0.
   \]

◆ Effective resistance of forward biased diode ($V > 0$):
\[
dV/dI = (kT/e)/I \approx 25 \, \Omega/I, \ I \text{ in mA}
\]
What's a diode made out of?
- Semiconductors!
- The energy levels of a semiconductor can be modified a material (e.g. silicon or germanium) that is normally an insulator will conduct electricity.
- Energy level structure of a semiconductor is complicated, requires quantum mechanical treatment.

<table>
<thead>
<tr>
<th>Material</th>
<th>Example</th>
<th>Resistivity ($\Omega$-cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductor</td>
<td>Copper</td>
<td>$1.56 \times 10^{-6}$</td>
</tr>
<tr>
<td>Semiconductor</td>
<td>Silicon</td>
<td>$10^3-10^6$</td>
</tr>
<tr>
<td>Insulator</td>
<td>Ceramics</td>
<td>$10^{11}-10^{14}$</td>
</tr>
</tbody>
</table>
How do we turn a semiconductor into a conductor?

*Dope it!*

- Doping is a process where impurities are added to the semiconductor to lower its resistivity.
- Silicon has 4 electrons in its valence level.
- We add atoms with 3 or 5 valence shell electrons to a piece of silicon.
  - Phosphorous, Arsenic, Antimony have 5 valence electrons
  - Boron, Aluminum, Indium have 3 valence electrons

**N** type silicon:
- Adding atoms which have 5 valence electrons makes the silicon more negative.
- The majority carriers are the excess electrons.

**P** type silicon
- Adding atoms which have 3 valence electrons makes the silicon more positive.
- The majority carriers are “holes”.
  - A hole is the lack of an electron in the valence shell.
How do we make a diode?
- Put a piece of N type silicon next to a piece of P type silicon.

Unbiased diode

Forward biased diode

Reversed biased diode

Very small leakage current

Very large leakage current

K.K. Gan
- diode characteristics
  - reverse voltage and current
  - peak current and voltage
  - capacitance
  - recovery time
  - sensitivity to temperature

- types of diodes
  - junction diode (ordinary type)
  - light emitting (LED)
    - "direct band gap" material: both holes and electrons have the same momentum
      - electron falls into a lower energy level when it meets a hole
      - energy is released in the form of a photon (light)
  - photodiodes (absorbs light, gives current)
  - Schottky (high speed switch, low turn on voltage, Al. on Silicon)
  - zener (special junction diode, use reversed biased)
  - tunnel ($I$ vs. $V$ slightly different than jd's, negative resistance!)
  - veractor (junction capacitance varies with voltage)
Examples of Diode Circuits

Simplest Circuit: What's voltage drop across diode?

In diode circuits we still use Kirchhoff's law:

\[ V_{DD} = V_D + IR \]

\[ I = \frac{V_{DD}}{R} - \frac{V_D}{R} \]

For this circuit \( I \) vs. \( V_D \) is a straight line with the following limits:

\[ V_D = 0 \quad \Rightarrow \quad I = \frac{V_{DD}}{R} \]

\[ V_D = V_{DD} \quad \Rightarrow \quad I = 0 \]

- The straight line (load line) is all possible \((V_D, I)\) for the circuit.
- The diode curve is all possible \((V_D, I)\) for the diode.
- The place where these two lines intersect gives the actual voltage and current for this circuit.
• Diode Protection (clipping and clamping)
  ✷ The following circuit will get rid of the negative part of the input wave.
  ✷ When the diode is negative biased, no current can flow in the resistor, so $V_{out} = 0$. 

\[ V_{out} = 0. \]
For more protection consider the following "clipping" circuit: for silicon $V_d \approx 0.6-0.7$ V

- If $V_a > V_{d1} + V_1$, then diode 1 conducts so $V_{out} \leq V_{d1} + V_1$.
- If $V_a < -V_{d2} - V_2$, then diode 2 conducts so $V_{out} \geq -V_{d2} - V_2$.
- If we assume $V_{d1} = V_{d2} \approx 0.7$ V and $V_1 = 0.5$, $V_2 = 0.25$ V,
  - for $V_{in} > 1.2$ V, d1 conducts
  - for $V_{in} < -0.95$ V, d2 conducts
Turning AC into DC (rectifier circuits)

- Consider the following circuit with 4 diodes: full wave rectifier.

  - In the positive part of $V_{in}$, diodes 2 and 3 conduct.
  - In negative part of the cycle, diodes 1 and 4 conduct.
  - This circuit has lots of ripple.
    - We can reduce ripple by putting a capacitor across the load resistor.
    - Pick $RC$ time constant such that: $RC > 1/(60 \text{ Hz}) = 16.6 \text{ msec}$.
      - example: $R = 100 \, \Omega$ and $C = 100 \, \mu\text{F}$ to reduce ripple
Transistors:
- Transistors are the heart of modern electronics (replaced vacuum tubes)
  - voltage and current amplifier circuits
  - low power and small size, can pack millions of transistors in mm² (chips in cell phones/laptops)
- In this class we will only consider bipolar transistors.
  - Bipolar transistors have 3 leads: emitter, base, collector
  - Bipolar transistors are two diodes back to back and come in two forms:

```
NPN
base
I_B
---
emitter
Positive Current Flow

P
N
unci
Emitter
Collector
```

```
PNP
base
I_B
---
emitter
Positive Current Flow

P
N
unci
Emitter
Collector
```

Arrow is always on the emitter and is in the direction of positive current flow.

- N material has excess negative charge (electrons).
- P material has excess positive charge (holes).
Some **simple** rules for getting transistors to work

1. For NPN (PNP) collector must be more positive (negative) in voltage than emitter.

2. Base-emitter and base-collector are like diodes:

   ![Diode Diagram](image)

   - For silicon transistors, $V_{BE} \approx 0.6-0.7\, \text{V}$ when transistor is **on**.

3. The currents in the base ($I_B$), collector ($I_C$) and emitter ($I_E$) are related as follows:
   - always: $I_B + I_C = I_E$
   - rough rule: $I_C \approx I_E$, and the base current is very small ($\approx 0.01\, I_C$)
   - Better approximation uses 2 related constants, $\alpha$ and $\beta$.
     - $I_C = \beta I_B$
     - $\beta$ is called the current gain, typically 20-200
     - $I_C = \alpha I_E$
     - $\alpha$ typically 0.99
   - Still better approximation:
     - uses 4 (hybrid) parameters to describe transistor performance ($\beta = h_{fe}$)
     - when all else fails, resort to the data sheets!

4. Common sense: must not exceed the power rating, current rating etc. or else the transistor dies.
Transistor Amplifiers

- Transistor has 3 legs, one of them is usually grounded.
- Classify amplifiers by what is common (grounded).

### Properties of Amplifiers

<table>
<thead>
<tr>
<th></th>
<th>Common Emitter</th>
<th>Common Base</th>
<th>Common Collector (emitter follower)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vbias</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vin</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Vout</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th></th>
<th>C E</th>
<th>C B</th>
<th>C C</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power gain</td>
<td>Y</td>
<td>Y</td>
<td>Y</td>
</tr>
<tr>
<td>Voltage gain</td>
<td>Y</td>
<td>Y</td>
<td>N</td>
</tr>
<tr>
<td>Current gain</td>
<td>N</td>
<td>Y</td>
<td></td>
</tr>
<tr>
<td>Input impedance</td>
<td>≈ 3.5 kΩ</td>
<td>≈ 30 Ω</td>
<td>≈ 500 kΩ</td>
</tr>
<tr>
<td>Output impedance</td>
<td>≈ 200 kΩ</td>
<td>≈ 3 MΩ</td>
<td>≈ 35 Ω</td>
</tr>
<tr>
<td>Output voltage phase change</td>
<td>180°</td>
<td>none</td>
<td>none</td>
</tr>
</tbody>
</table>
- **Biasing Transistors**
  - For an amplifier to work properly it must be biased on all the time, not just when a signal is present.
  - “On” means current is flowing through the transistor (therefore $V_{BE} \approx 0.6-0.7$ V).
  - We usually use a DC circuit ($R_1$ and $R_2$ in the circuit below) to achieve the biasing.

- **Calculating the operating (DC or quiescent) point of a Common Emitter Amplifier:**
  - We want to determine the operating (quiescent) point of the circuit.
  - This is a fancy way of saying what's $V_B$, $V_E$, $V_C$, $V_{CE}$, $I_C$, $I_B$, $I_E$ when the transistor is on, but $V_{in} = 0$.
  - The capacitors $C_1$ and $C_2$ are decoupling capacitors, they block DC voltages.
  - $C_3$ is a bypass capacitor that provides the AC ground (common).
Crude Method for determining operating point when no spec sheets are available.

a. Remember $I_B = I_C/\beta$ and $\beta \approx 100$ (typical value).
   ☞ we can neglect the current into the base since it’s much smaller than $I_C$ or $I_E$.

b. If transistor is “working” then $V_{BE} \approx 0.6-0.7$ V (silicon transistor).

c. Determine $V_B$ using $R_1$ and $R_2$ as a voltage divider
   \[
   V_B = 15 \, \text{V} \frac{R_2}{R_1 + R_2} = 3.6 \, \text{V}
   \]

d. Find $V_E$ using $V_B - V_E = 0.6 \, \text{V} \Rightarrow V_E = 3 \, \text{V}$.

e. $I_E = V_E/R_4 = 3\, \text{V}/12 \, \text{k}\Omega = 2.5 \, \text{mA}$.

f. Use the approximation $I_C = I_E \Rightarrow I_C = 2.5 \, \text{mA}$.

g. $V_C = 15 \, \text{V} - I_C R_3 = 15 - 2.5 \, \text{mA} \times 2.5 \, \text{k}\Omega = 8.75 \, \text{V}$.

h. $V_{CE} = 8.75 - 3 = 5.75 \, \text{V}$.
   ☞ The voltages at every point in the circuit are now determined!!!
Spec Sheet or Load line method

- Much more accurate than previous method.
- Load line is set of all possible values of \( I_C \) vs. \( V_{CE} \) for the circuit in hand.
- Assume same circuit as previous page and we know \( R_3 \) and \( R_4 \).
- If we neglect the base current, then
  \[
  15 = I_C(R_3 + R_4) + V_{CE}
  \]
  \[
  I_C = \frac{15}{R_3 + R_4} - \frac{V_{CE}}{R_3 + R_4}
  \]
- The above is a straight line in \((I_C, V_{CE})\) space.
- This line is the load line.
- Assume \( R_3 + R_4 = 3.75 \, \text{k}\Omega \), then we can plot the load line from the two limits:
  \( I_C = 0, \, V_{CE} = 15 \, \text{V} \) and \( V_{CE} = 0, \, I_C = 15 \, \text{V}/3.75 \, \text{k}\Omega = 4 \, \text{mA} \)

Spec. Sheet of 2N3904 transistor:
\( I_C \) vs. \( V_{CE} \) for various \( I_B \)
We want the operating point to be in the linear region of the transistor

- we want the output to be a linear representation of the input.

- Pick the operating point such that for reasonable changes in $V_{CE}$, $I_C$
  - the circuit stays out of the non-linear region and has $I_C > 0$.
  - $I_C$ must be $> 0$ or transistor won’t conduct current in the “correct” direction!
  - If circuit is in nonlinear region then $V_{out}$ is a distorted version of $V_{in}$.
  - If circuit is in region where $I_C = 0$ then $V_{out}$ is “clipped”.

- If we pick $I_C = 2.5$ mA as operating point
  - $V_{CE} > 0.5$ is the linear region.
  - Usually pick $I_C$ to be in the middle of the linear region.
  - amp will respond the same way to symmetric (around operating point) output voltage swings.

- If $I_C = 2.5$ mA and $I_B = 10-11$ $\mu$A
  - $V_{CE} = 5-6$ V

- Can now choose the values for resistors ($R_1, R_2$) to give the above voltages and currents.
Current Gain Calculation from Spec Sheet

- We define current gain as:
  \[ G = \frac{\Delta I_{out}}{\Delta I_{in}} \]
  - This quantity is often called \( \beta \).
  - In our example \( I_B \) is the input and \( I_C \) is the output.
- If we are in the linear region (\( V_{CE} > 0.5 \text{ V} \)) and the base current changes from 5 to 10 \( \mu \text{A} \)
  - the collector current (\( I_C \)) changes from \( \sim 1.1 \) to 2.2 mA.
  - \[ G = \frac{(2.2 - 1.1 \text{ mA})}{(10 - 5 \text{ } \mu \text{A})} \approx 200 \]
- Like almost all transistor parameters, the exact current gain depends on many parameters:
  - frequency of input voltage
  - \( V_{CE} \)
  - \( I_C \)
  - \( I_B \)