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 $V_{anode} > V_{cathode}$
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,
  \[ I = I_s e^{39V} \quad \text{if } V > 0 \]
  \[ I = -I_s \quad \text{if } V < 0. \]

Effective resistance of forward biased diode ($V > 0$):
\[ \frac{dV}{dI} = \frac{kT}{e} / I \approx 25 \, \Omega / I, \quad I \text{ in mA} \]
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 (Ω-cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Conductor</td>
<td>Copper</td>
<td>1.56x10^{-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>

![Diagram of energy bands and Fermi level](image-url)
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
  - Depletion zone

- Forward biased diode
  - Very small depletion zone
  - Forward Current
  - Barrier due to depletion region very small
  - Large current can flow

- Reversed biased diode
  - Very large depletion zone
  - Barrier due to depletion region very large
  - Small leakage current

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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)
- photodiodes (absorbs light, gives current)
- Schottky (high speed switch, low turn on voltage, Al. on Silicon)
- tunnel ($I$ vs. $V$ slightly different than jd's, negative resistance!)
- veractor (junction capacitance varies with voltage)
- zener (special junction diode, use reversed biased)
Examples of Diode Circuits

- Simplest Circuit: What's voltage drop across diode?

In diode circuits we still use Kirchhoff’s law:

\[
V_{\text{in}} = V_d + I_d R
\]

\[
I_d = \frac{V_{\text{in}}}{R} - \frac{V_d}{R}
\]

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

\[
V_d = 0 \quad \Rightarrow \quad I_d = \frac{V_{\text{in}}}{R} = 10 \text{ mA}
\]

\[
V_d = 1 \text{ V} \quad \Rightarrow \quad I_d = 0
\]

- 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 $V_{out} = 0$. 
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 thousands of transistors in mm^2 (computers)
- 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

<table>
<thead>
<tr>
<th>Emitter</th>
<th>Base</th>
<th>Collector</th>
</tr>
</thead>
<tbody>
<tr>
<td>N</td>
<td>P</td>
<td>N</td>
</tr>
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</table>

PNP

<table>
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<th>Emitter</th>
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<tbody>
<tr>
<td>P</td>
<td>N</td>
<td>P</td>
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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]

   - For silicon transistors, $V_{BE} \approx 0.6-0.7\ V$ 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.

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L5: Diodes and Transistors
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>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>Y</td>
<td>N</td>
<td>Y</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 $V_{BE} \approx 0.6-0.7 \text{ V}$).
  ♦ 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).
The 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. $V_C = 15 \text{ V} - I_C \cdot R_3 = 15 - 2.5 \text{ mA} \times 2.5 \text{ k}\Omega = 8.75 \text{ V}$.

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 $R_3 + R_4 = 3.75 \, k\Omega$, then we can plot the load line from the two limits:
    \[
    I_C = 0, \quad V_{CE} = 15 \, V \quad \text{and} \quad V_{CE} = 0, \quad I_C = \frac{15}{3.75 \, k\Omega} = 4 \, mA
    \]

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 \( I_B = 10-11 \) µA
- \( V_{CE} = 5-6 \) 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:
  \[ G = \frac{\Delta I_{\text{out}}}{\Delta I_{\text{in}}} \]
  - 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 (\( V_{\text{CE}} > 0.5 \text{ V} \)) and the base current changes from 5 to 10 \( \mu \text{A} \)
  - the collector current (\( I_C \)) changes from ~1.1 to 2.2 mA.
  - \[ G = \frac{2.2 \text{ mA} - 1.1 \text{ mA}}{10 \text{ \mu A} - 5 \text{ \mu A}} \approx 200 \]
- Like almost all transistor parameters, the exact current gain depends on many parameters:
  - frequency of input voltage
  - \( V_{\text{CE}} \)
  - \( I_C \)
  - \( I_B \)