Lecture 5: Diodes and Transistors

Invention of transistor and birth of modern electronics

John Bardeen, William Shockley and Walter Brattain at Bell Labs, 1948.

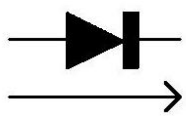
Vacuum tube

1st transistor

Transistor size now: 5 nm

Diodes:

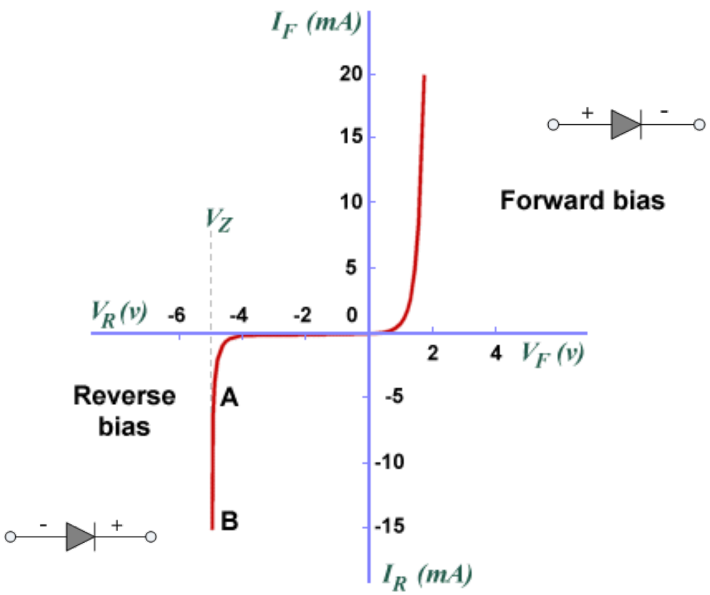
- What do we use diodes for?
  - protect circuits by limiting the voltage (clipping and clamping)
  - turn AC into DC (voltage rectifier)
  - voltage multipliers (e.g. double input voltage)
  - non-linear mixing of two voltages (e.g. amplitude modulation)

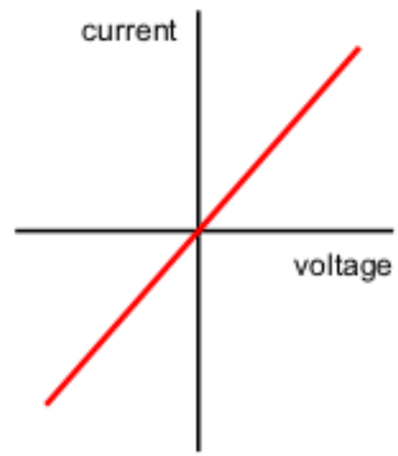
anode  cathode

Positive current flow

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

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





- Diode is forward biased when $V_{anode} > V_{cathode}$.
  - 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 $V_{anode} < V_{cathode}$.
  - Diode conducts current very weakly (typically < μA)
  - 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 < μA)
  - k = Boltzmann's constant, e = electron charge, T = temperature
  - At room temperature, $kT/e = 25.3$ mV,

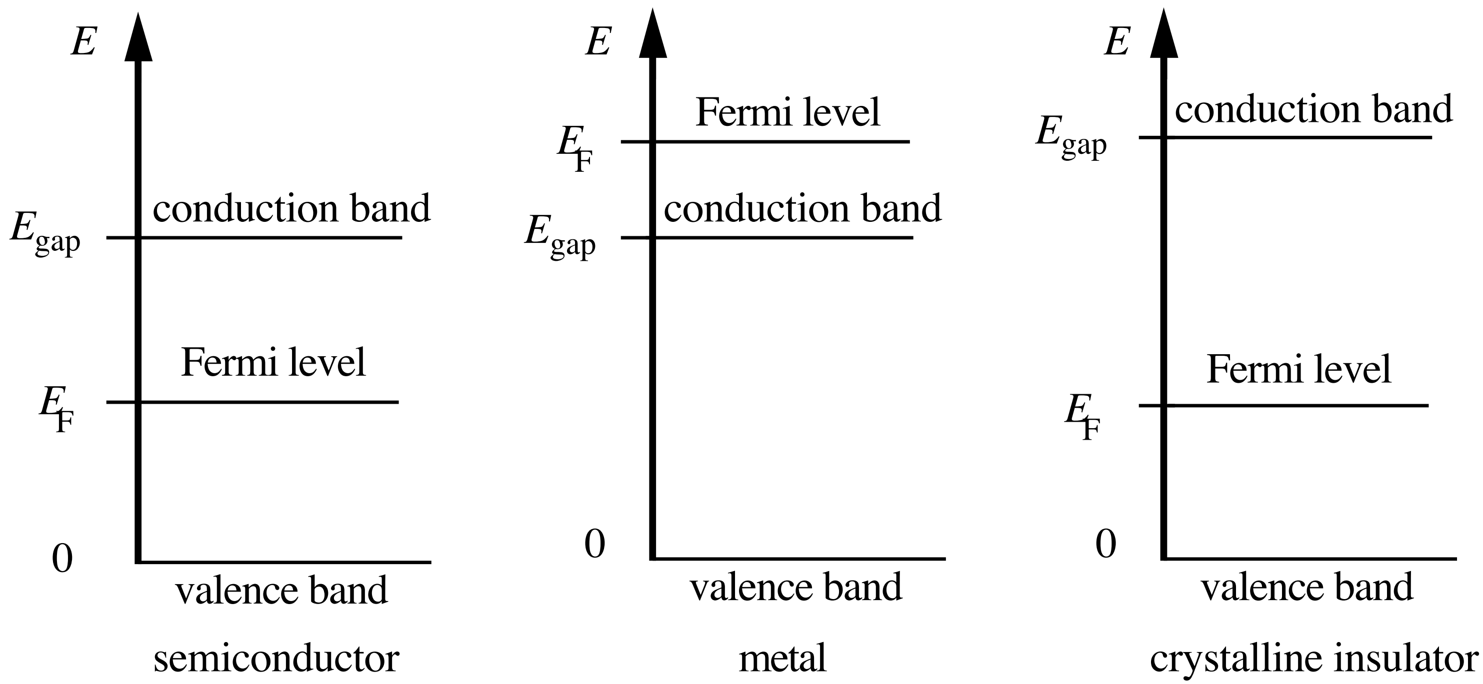
    $I = I_s e^{39V}$ if $V > 0$

    $I = -I_s$ if $V < 0$.

- Effective resistance of forward biased diode ($V > 0$):

  $dV/dI = (kT/e)/I \approx 25\ \Omega/I$, I 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.

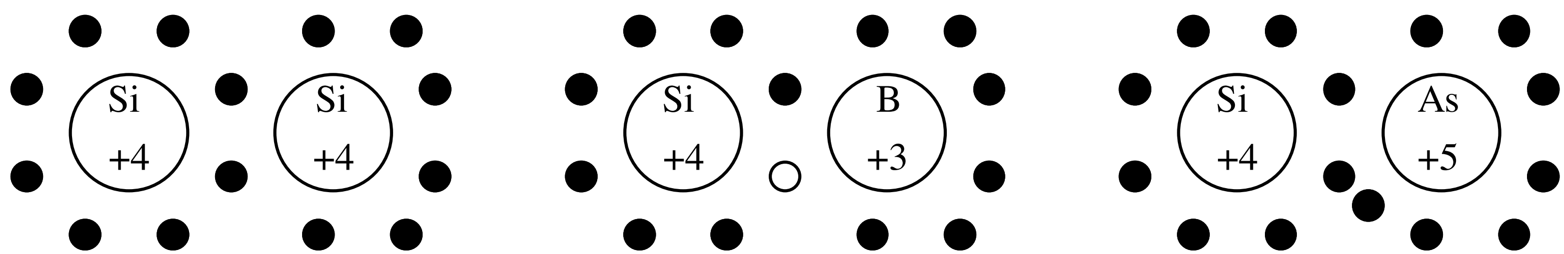


Material	Example	Resistivity (Ω-cm)
Conductor	Copper	1.56×10^{-6}
Semiconductor	Silicon	10^{3}-10^{6}
Insulator	Ceramics	10^{11}-10^{14}

- 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.

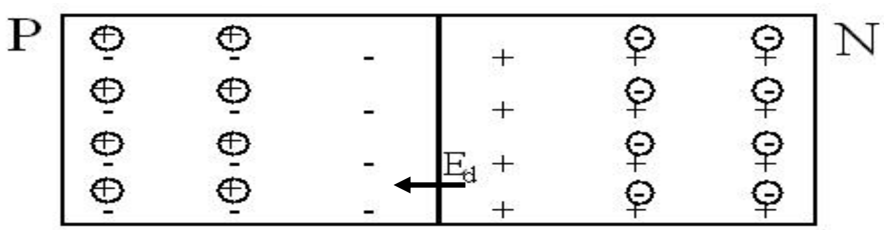
- **P** type silicon
  - Adding atoms which have 3 valence electrons makes the silicon more positive.
  - The majority carriers are "holes".
    - A hole is the lack of an electron in the valence shell.



Normal Silicon   P Type Silicon   N Type Silicon

- 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



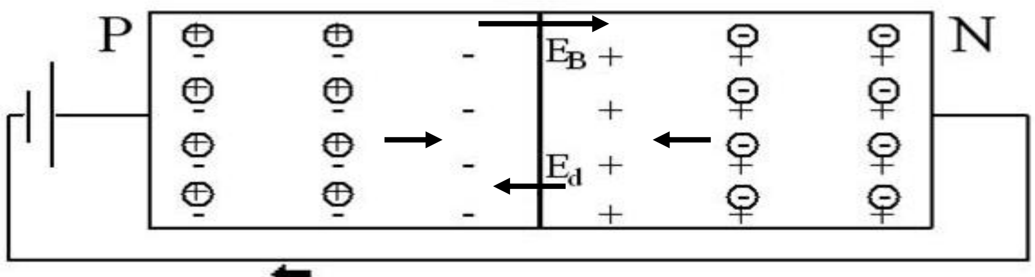
Silicon + Boron   Silicon + Arsenic

Very small leakage current

⊖ mobile electron
⊕ mobile hole
\- fixed ionized acceptor atom
\+ fixed ionized doner atom

- Forward biased diode

Very small depletion zone

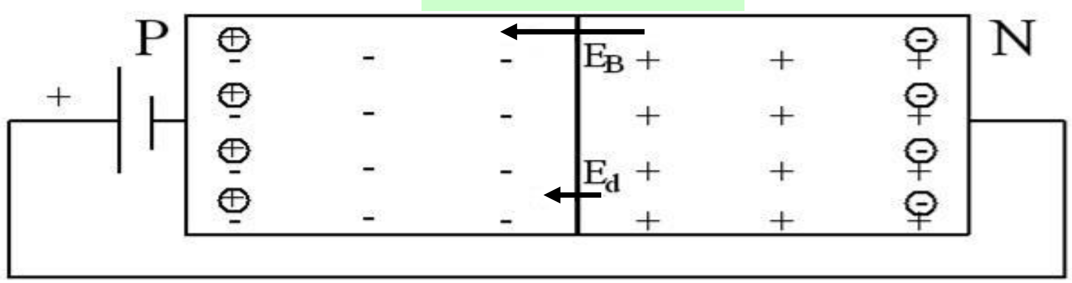


Forward Current

Barrier due to depletion region very small
➔ large current can flow

- Reversed biased diode

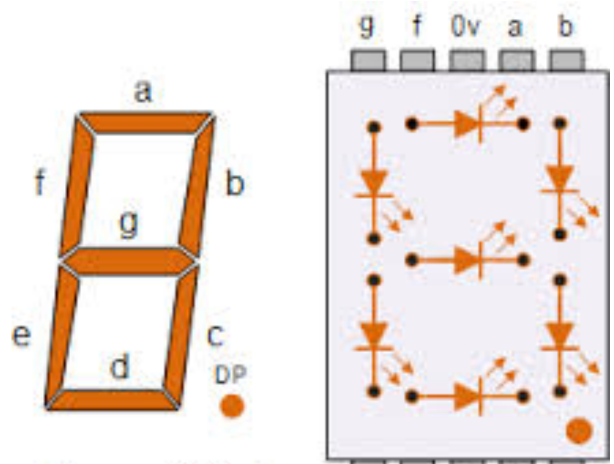
Very large depletion zone



Barrier due to depletion region very large
➔ small leakage current

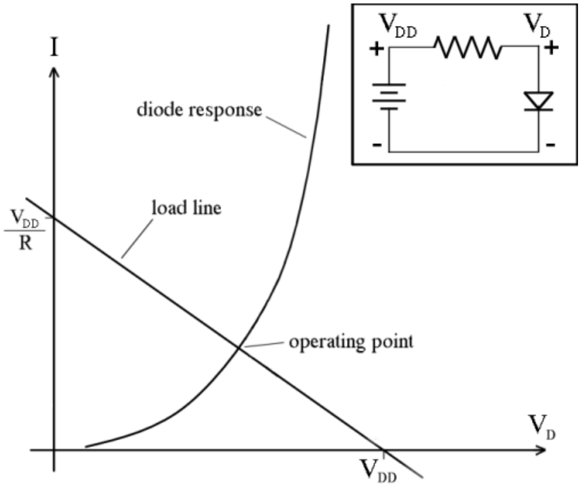
- diode characteristics
  - reverse voltage and current
  - peak current and voltage
  - capacitance
  - recovery time
  - sensitivity to temperature

- 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)



Common Cathode Display

- Examples of Diode Circuits
  - Simplest Circuit: What's voltage drop across diode?



  - In diode circuits we still use Kirchhoff' s law:

$$V_{DD} = V_D + IR$$

$$I = V_{DD}/R - V_D/R$$

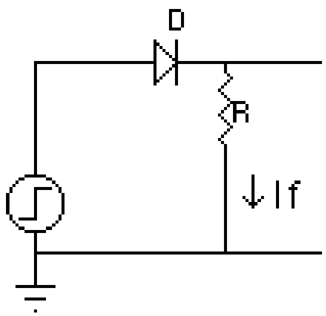
  - For this circuit I vs. V_D is a straight line with the following limits:

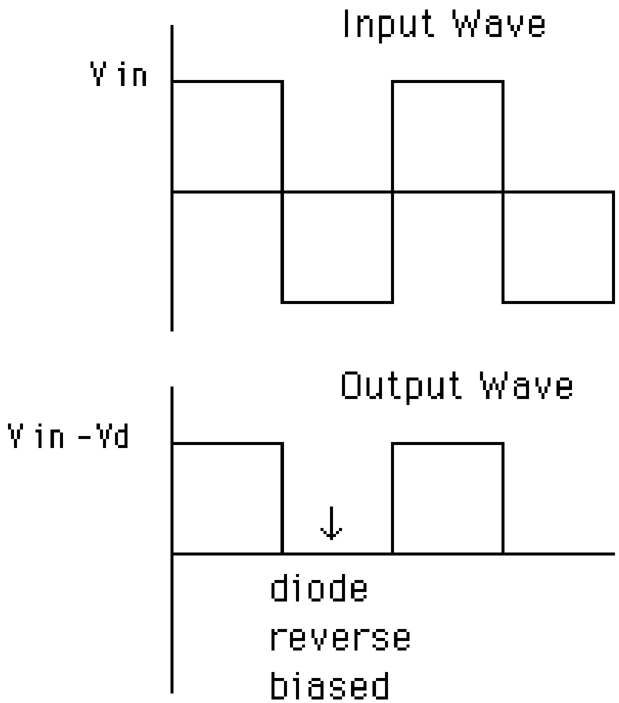
$$V_D = 0 \quad \Rightarrow \quad I = V_{DD} / R$$

$$V_D = V_{DD} \quad \Rightarrow \quad I = 0$$

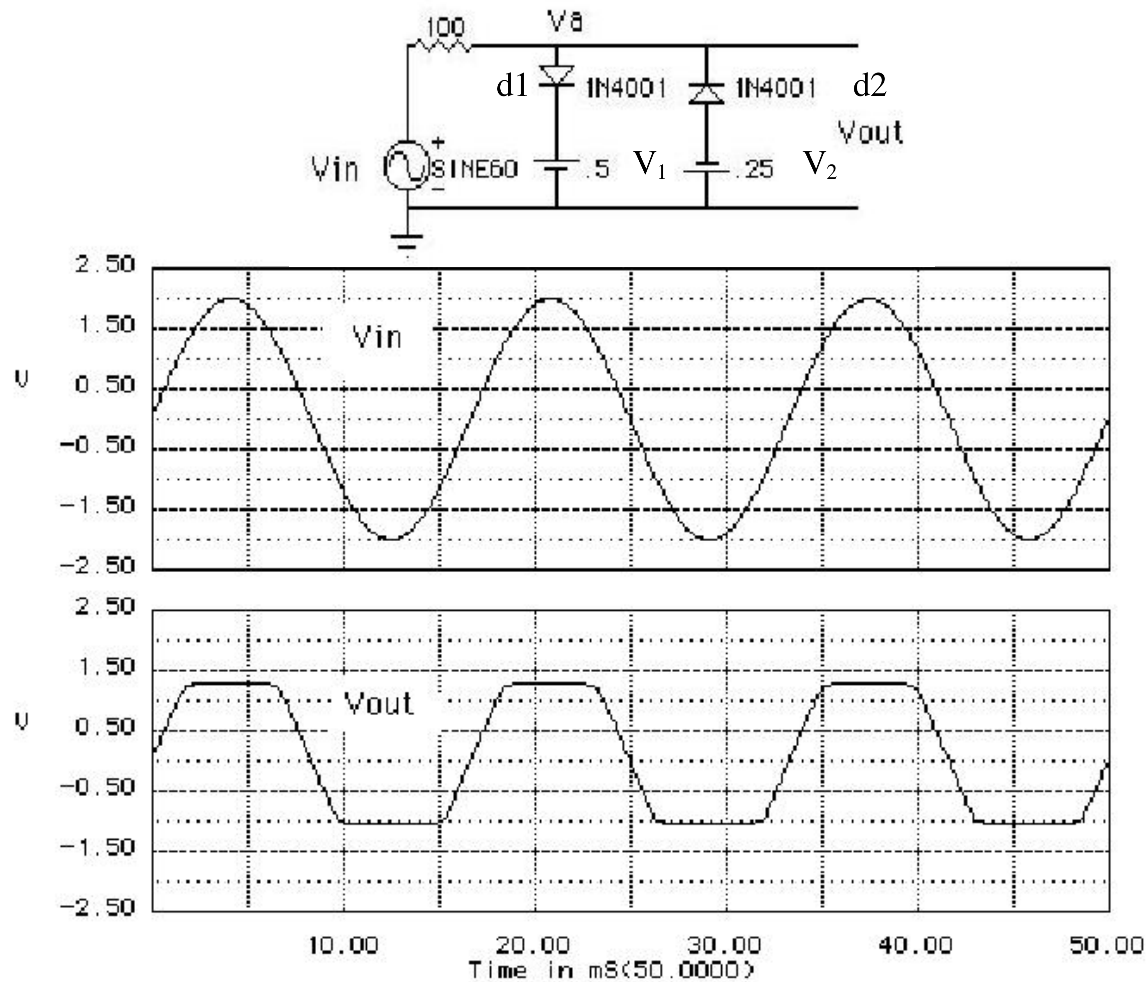
    - The straight line (load line) is all possible (V_D, I) for the **circuit**.
    - The diode curve is all possible (V_D, I) for the **diode**.
    - The place where these two lines intersect gives the actual voltage and current for this circuit.

- 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 $V_{out} = 0$.



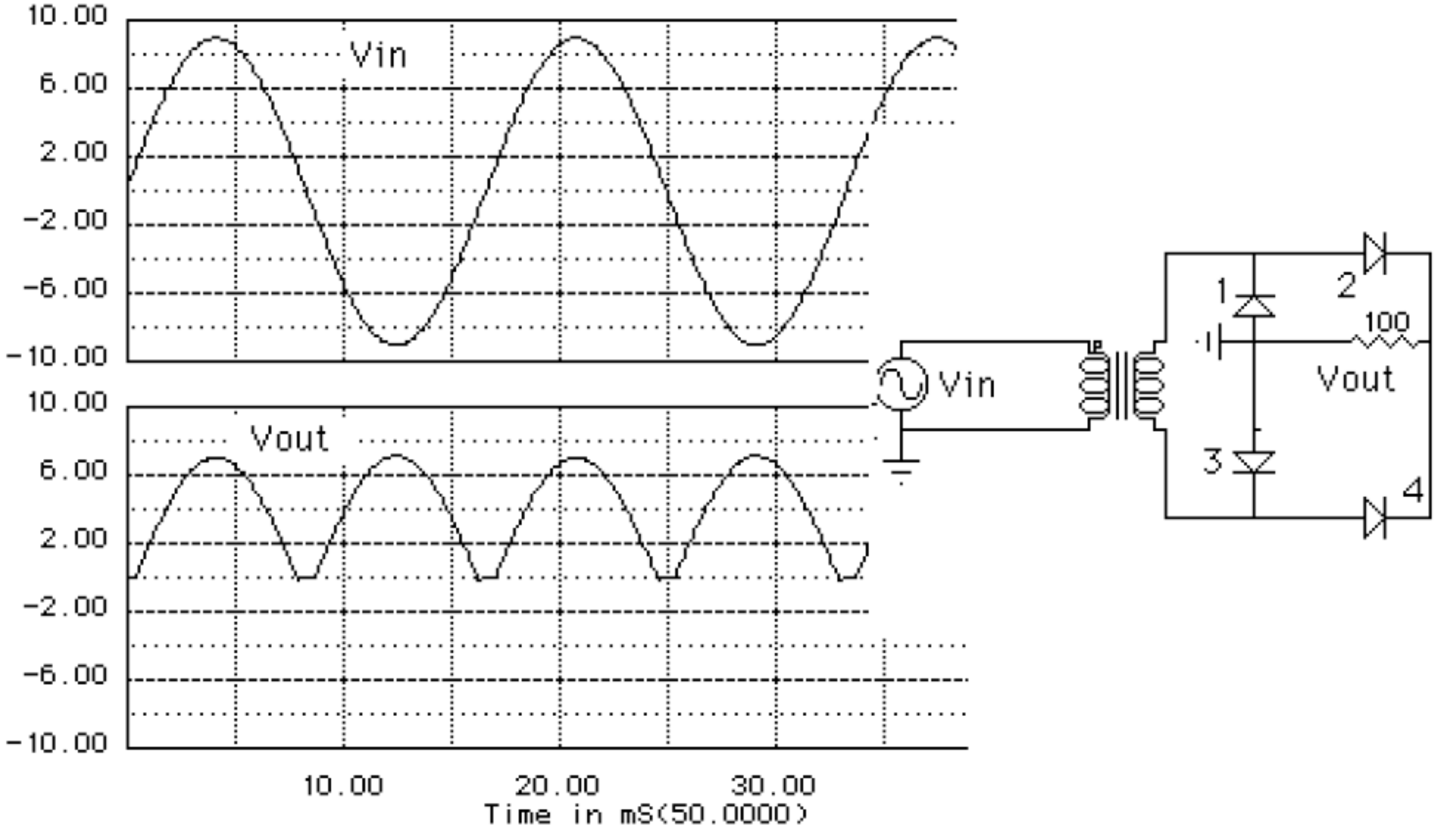


- For more protection consider the following "clipping" circuit: for silicon $V_d \approx 0.6\text{-}0.7$ V

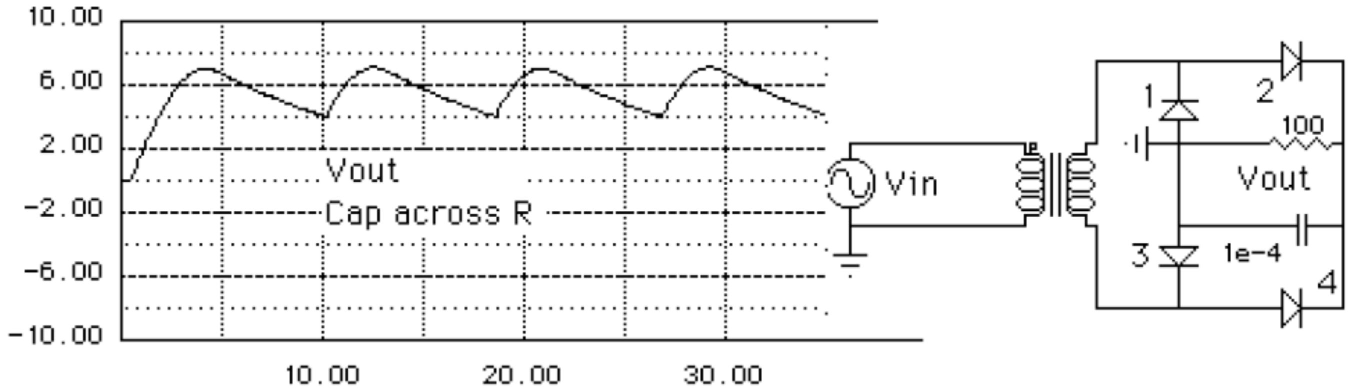


- If $V_a > V_{d1} + V_1$, then diode 1 conducts so $V_{out} \le V_{d1} + V_1$.
- If $V_a < -V_{d2} - V_2$, then diode 2 conducts so $V_{out} \ge -V_{d2} - V_2$.
- If we assume $V_{d1} = V_{d2} \approx 0.7$ V and $V_1 = 0.5$, $V_2 = 0.25$ V,
  - for $V_{in} > 1.2$ V, d1 conducts
  - for $V_{in} < -0.95$ V, d2 conducts

- Turning AC into DC (rectifier circuits)
  - Consider the following circuit with 4 diodes: full wave rectifier.

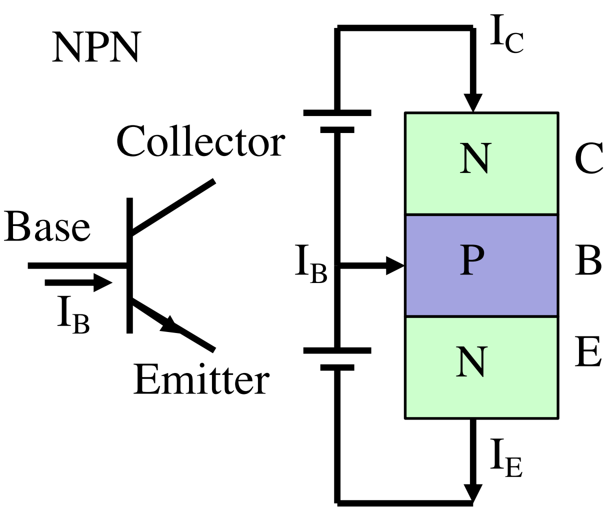


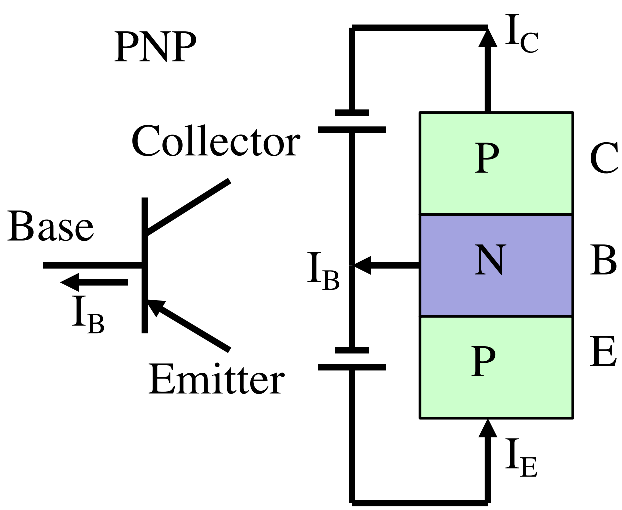
  - In the positive part of V_{in}, diodes 2 and 3 conduct.
  - In negative part of the cycle, diodes 1 and 4 conduct.
  - This circuit has lots of ripple.
    - We can reduce ripple by putting a capacitor across the load resistor.
    - Pick RC time constant such that: $RC > 1/(60\text{ Hz}) = 16.6$ msec.
      - 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 mm^2 (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:





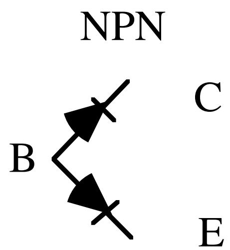
Arrow is always on the emitter and is in the direction of positive current flow

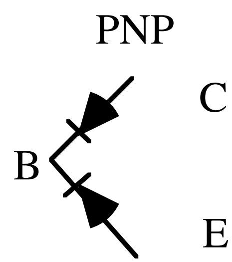
- N material has excess negative charge (electrons).
- P material has excess positive charge (holes).

- 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:



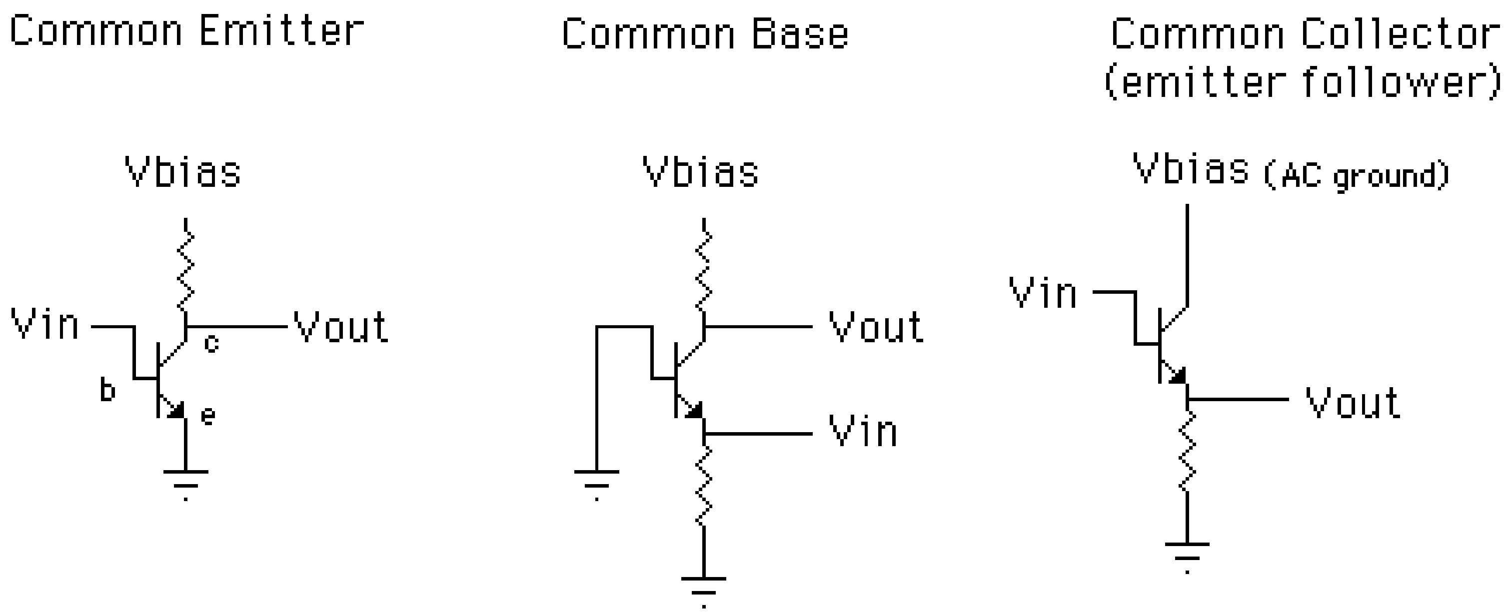


⇨ For silicon transistors, $V_{BE} \approx$ **0.6-0.7 V** when transistor is **on**.

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, α and β.
     - $I_C = \beta I_B$
       - β is called the current gain, typically 20-200
     - $I_C = \alpha I_E$
       - α 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*).

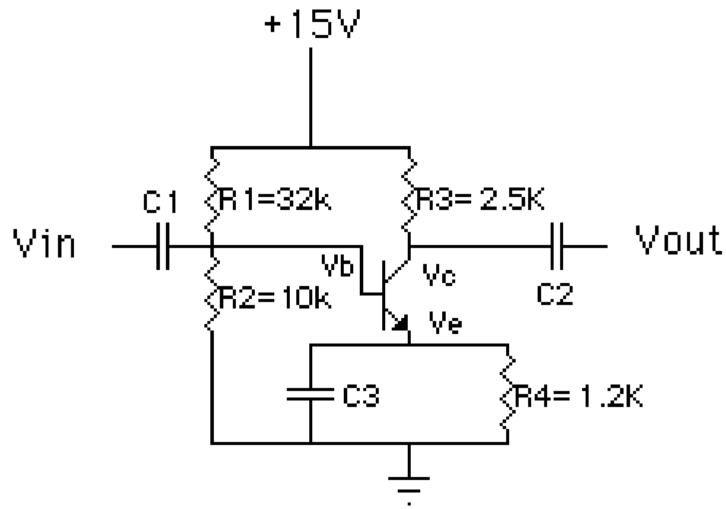


Properties of Amplifiers

	C E	C B	C C
Power gain	Y	Y	Y
Voltage gain	Y	Y	N
Current gain	Y	N	Y
Input impedance	≈ 3.5 kΩ	≈ 30 Ω	≈ 500 kΩ
Output impedance	≈ 200 kΩ	≈ 3 MΩ	≈ 35 Ω
Output voltage phase change	180^0	none	none

- 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 $V_{BE} \approx 0.6\text{-}0.7$ 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:



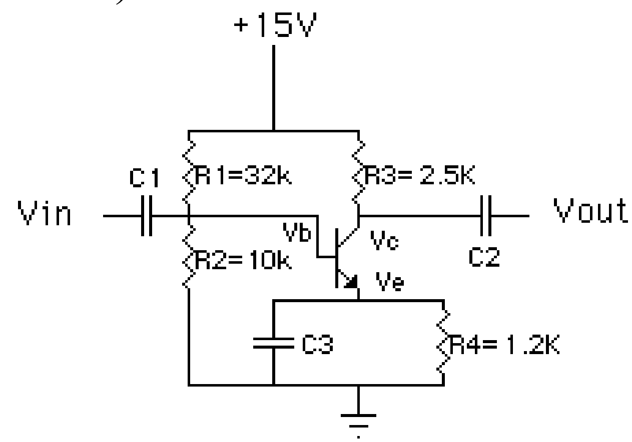
Common Emitter Amp

  - 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 $V_{BE} \approx 0.6\text{-}0.7$ 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 $V_B - V_E = 0.6$ V $\Rightarrow V_E = 3$ V.
  e. $I_E = V_E / R_4 = 3\text{V}/1.2\text{ k}\Omega = 2.5$ mA.
  f. Use the approximation $I_C = I_E \Rightarrow I_C = 2.5$ mA.
  g. $V_C = 15\text{ V} - I_C R_3 = 15 - 2.5\text{ mA} \times 2.5\text{ k}\Omega = 8.75$ V.
  h. $V_{CE} = 8.75 - 3 = 5.75$ V.
     ⇨ The voltages at every point in the circuit are now determined!!!



Common Emitter Amp

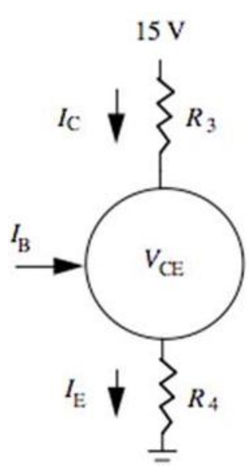
- **Spec Sheet or Load line method**
  - ⇨ Much more accurate than previous method.
  - ◆ Load line is set of all possible values of I_C vs. V_{CE} for the circuit in hand.
  - ◆ Assume same circuit as previous page and we know R_3 and R_4.
  - ◆ If we neglect the base current, then

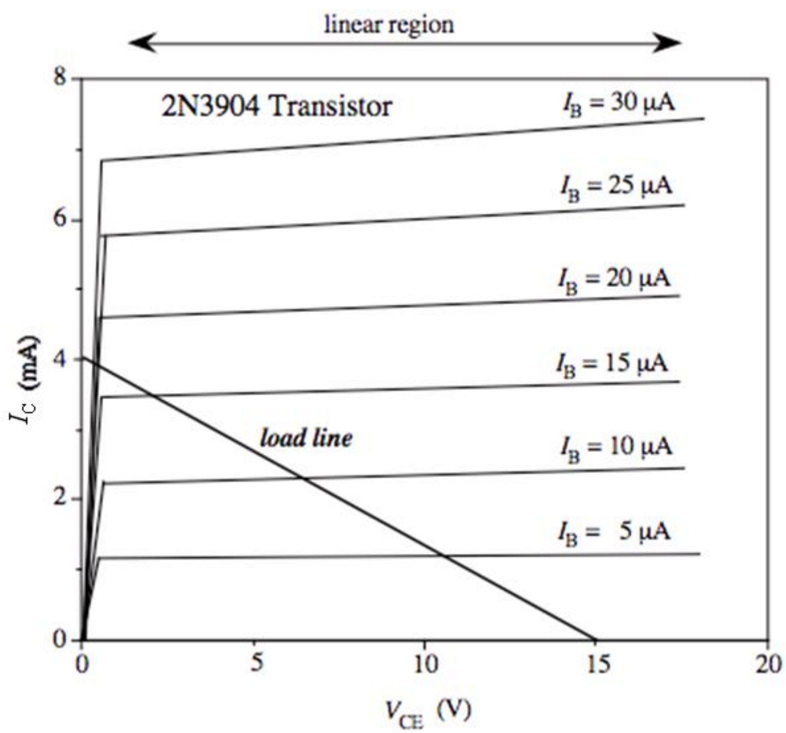
$$15 = I_C(R_3 + R_4) + V_{CE}$$

$$I_C = 15/(R_3 + R_4) - V_{CE}/(R_3 + R_4)$$

  - ◆ 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:

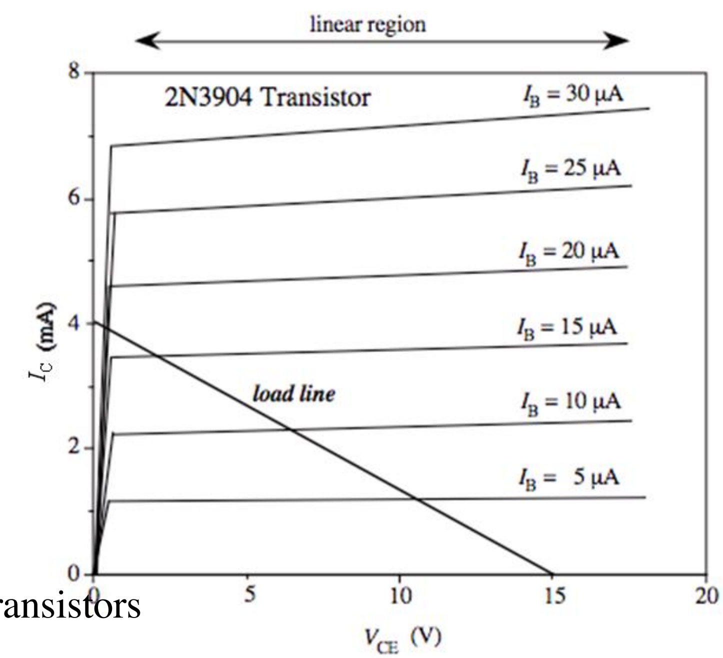
$$I_C = 0,\ \ V_{CE} = 15\ \text{V} \quad \text{and} \quad V_{CE} = 0,\ I_C = 15\ \text{V}/3.75\ \text{k}\Omega = 4\ \text{mA}$$





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 $I_B = 10\text{-}11\ \mu A$
  - ⇨ $V_{CE} = 5\text{-}6$ 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:

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