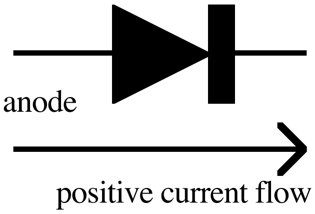
Diodes and Transistors

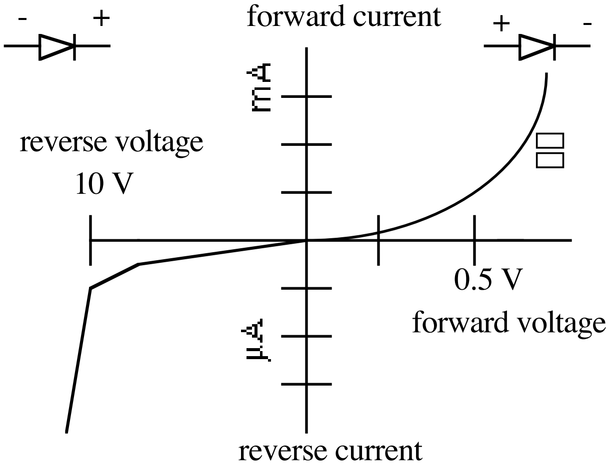
Diodes

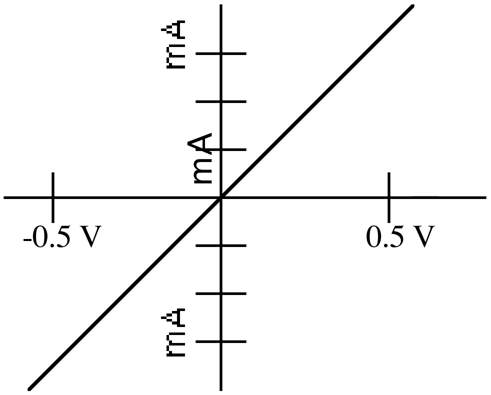
- What do we use diodes for?
    - protect circuits by limiting the voltage (clipping and clamping)
    - turn AC into DC (voltage rectifier)
    - voltage multipliers (e.g. double input voltage)
    - non-linear mixing of two voltages (e.g. amplitude modulation)
- Symbol for Diode:



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

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





Diode is <u>forward</u> 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 <u>reverse</u> biased when $V_{\text{anode}} < V_{\text{cathode}}$.

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 can be expressed as:

$$I = I_s(e^{eV/kT} - 1)$$

known as: "diode", "rectifier", or "Ebers-Moll" equation

I_s = reverse saturation current (typically < μA)

k = Boltzmann's constant, e = electron charge, T = temperature

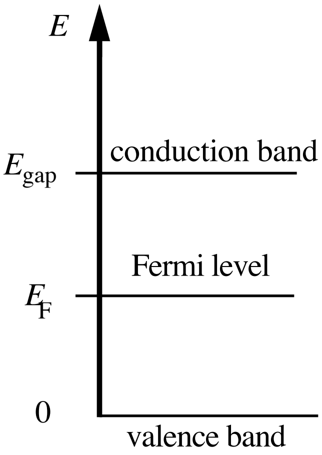
At room temperature, $kT/e = 25.3$ mV,

$I = I_s e^{39V}$ if $V > 0$ and $I = -I_s$ if $V < 0$.

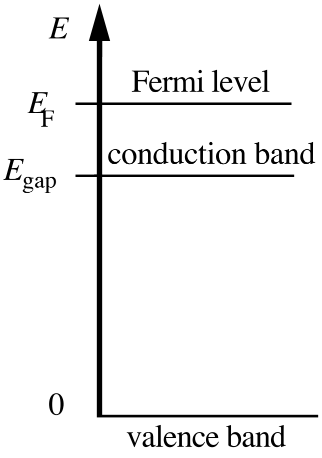
Effective resistance of forward biased diode ($V > 0$) diode: $dV/dI = (kT/e)/I \approx 25\ \Omega / I$, I in mA

- What's a diode made out of? Semiconductors!

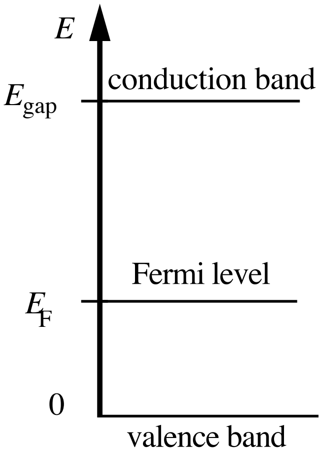
The energy levels of a semiconductor can be modified so that a material (e.g. silicon or germanium) that is normally an insulator will conduct electricity. Energy level structure of a semiconductor is quit complicated, requires a quantum mechanical treatment.



semiconductor



metal



crystalline insulator

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 which have a different number of valence shell electrons

    3 or 5 to a piece of silicon.

      Phosphorous, Arsenic, Antimony have 5 valence electrons

      Boron, Aluminum, Indium have 3 valence electrons

- **N** type silicon:

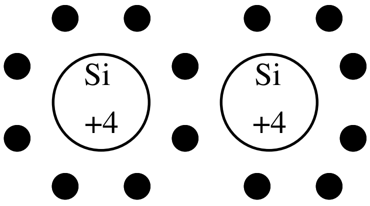
  Adding atoms which have 5 valence electrons makes the silicon more negative.

  The majority carriers are the excess electrons.

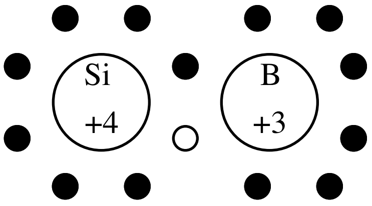
- **P** type silicon

  Adding atoms which have 3 valence electrons makes the silicon more positive.

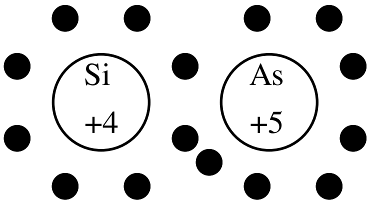
  The majority carriers are "holes". A hole is the lack of an electron in the valence shell.



Normal Silicon



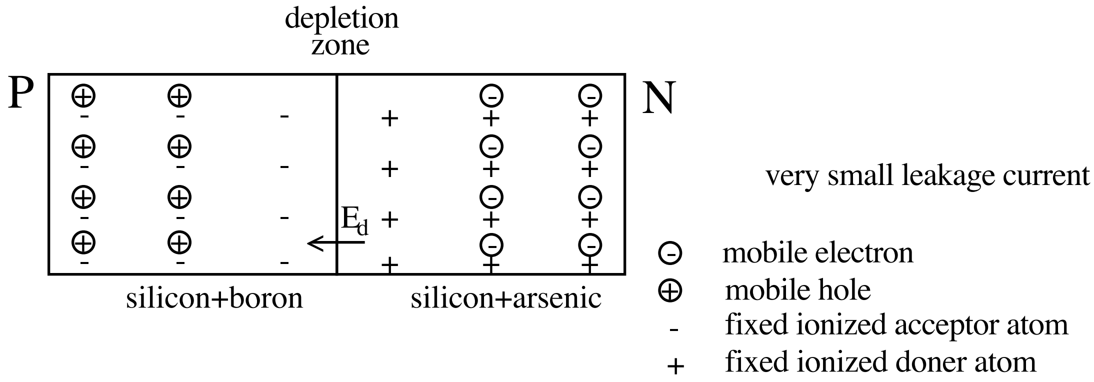
P Type Silicon



N Type Silicon

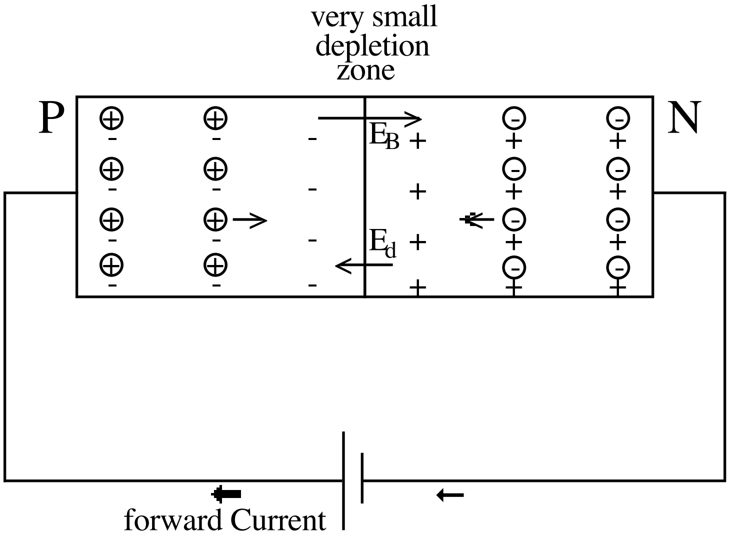
- How do we make a diode?
  Put a piece of N type silicon next to a piece of P type silicon.

- Unbiased diode



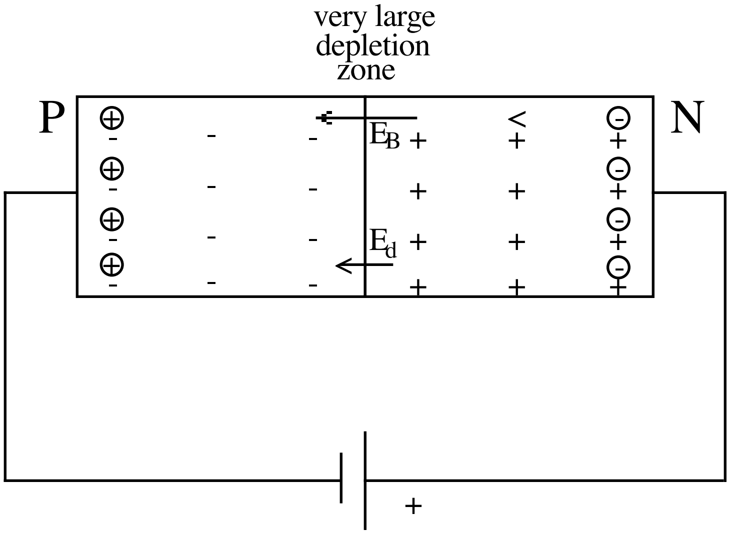
very small leakage current

- Forward biased diode



barrier due to depletion
region very small
large current can flow

- Reversed biased diode



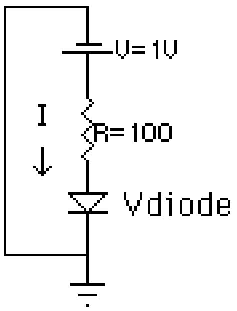
barrier due to depletion
region very large
small leakage current

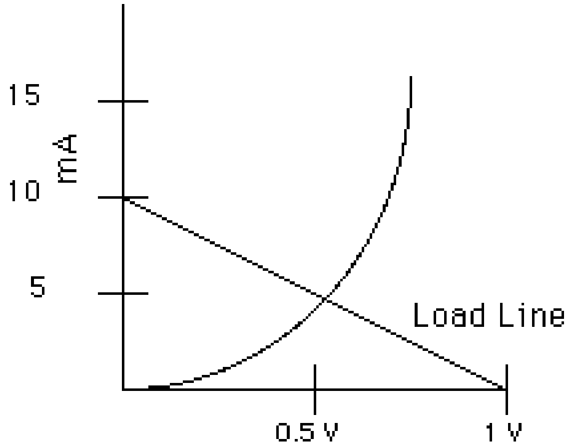
- diode characteristics
  - reverse voltage and current
  - peak current and voltage
  - capacitance
  - recovery time
  - sensitivity to temperature

- types of diodes
  - junction diode (ordinary type)
  - light emitting (LED)
  - 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 cap. varies with voltage)
  - zener (special junction diode, use reversed biased)

<u>Examples of Diode Circuits</u>

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





In diode circuits we still use Kirchhoff’s law:

$$V_{\mathrm{in}} = V_{\mathrm{d}} + I_{\mathrm{d}} R$$

$$I_{\mathrm{d}} = V_{\mathrm{in}} / R - V_{\mathrm{d}} / R$$

For this circuit I_{d} vs. V_{d} is a straight line with the following limits:

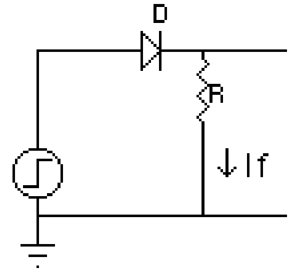
$$V_{\mathrm{d}} = 0 \quad \Rightarrow \quad I_{\mathrm{d}} = V_{\mathrm{in}} / R = 10 \text{ mA}$$

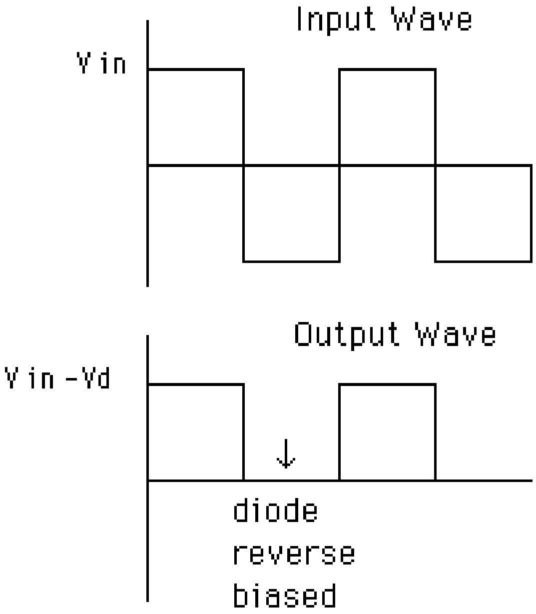
$$V_{\mathrm{d}} = 1 \text{ V} \quad \Rightarrow \quad I_{\mathrm{d}} = 0$$

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 us the actual voltage and current for <u>this</u> circuit.

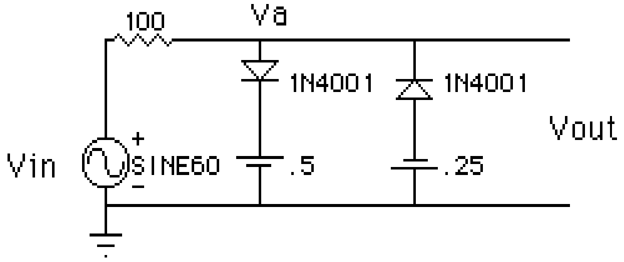
- Diode Protection (clipping and clamping)

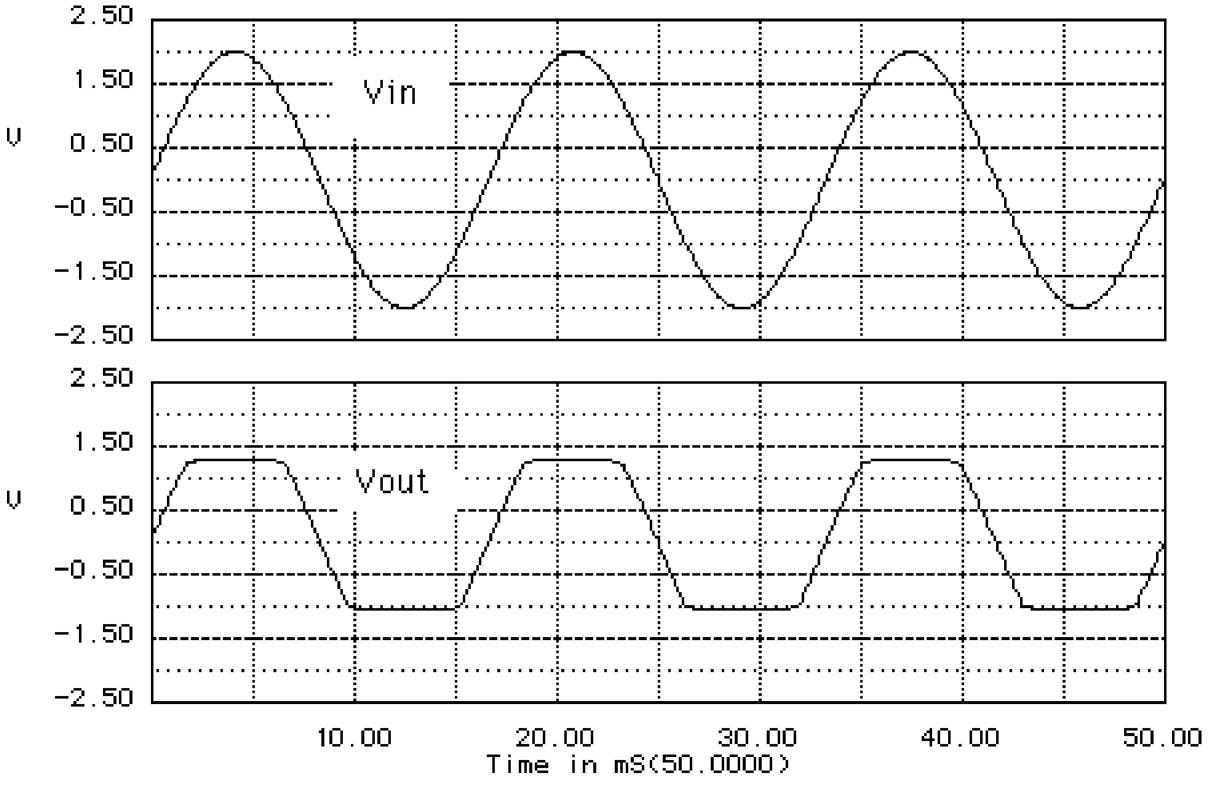
  The following circuit will get rid of the negative part of the input wave.
  When the diode is negative biased, no current can flow in the *R*, so $V_{out} = 0$.





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

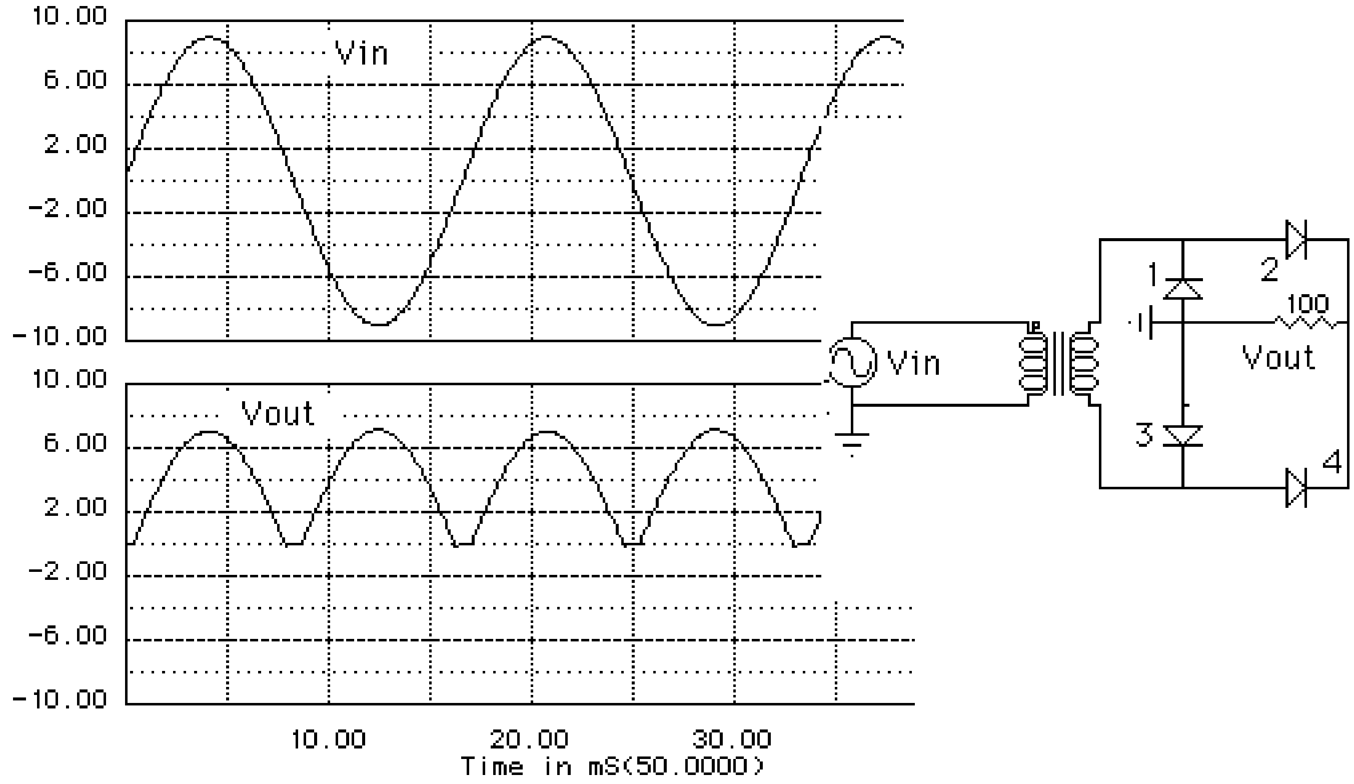


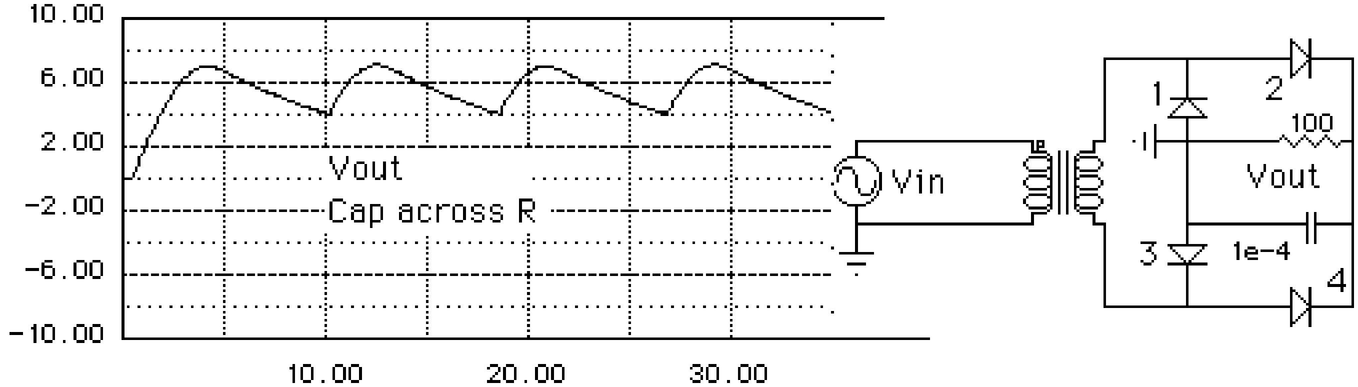


If $V_a > V_{d1} + V_1$, then diode 1 conducts so $V_{out} \approx V_a$.
If $V_a < -V_{d2} - V_2$, then diode 2 conducts so $V_{out} \geq V_a$.
If we assume $V_{d1} = V_{d2} \approx 0.7$ V and $V_1 = 0.5$, $V_2 = 0.25$ V,
then for $V_{in} > 1.2$ V, D1 conducts and $V_{in} < -0.95$ V, D2 conducts.

- Turning AC into DC (rectifier circuits)

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





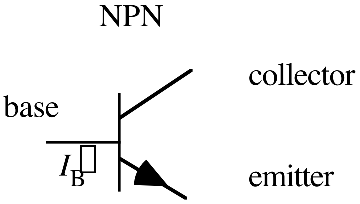
In the positive part of V_{in}, diodes 2 and 3 conduct. In negative part of the cycle, diodes 1 and 4 conduct.

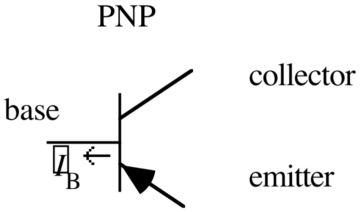
This circuit has lots of ripple. We can reduce ripple by putting a capacitor across the load resistor (see third plot).
Pick RC time constant such that: $RC > 1/(60\text{ Hz}) = 16.6$ msec.
(example has $R = 100\ \Omega$ and $C = 100\ \mu$F to show diminished ripple)

Transistors

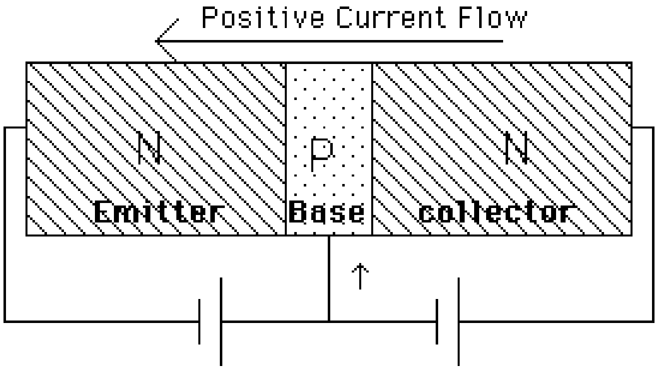
- Transistors are the heart of modern electronics (replaced vacuum tubes)
  - voltage and current amplifier circuits
  - high frequency switching (computers)
  - impedance matching
  - low power
  - small size, can pack thousands of transistors in mm^2

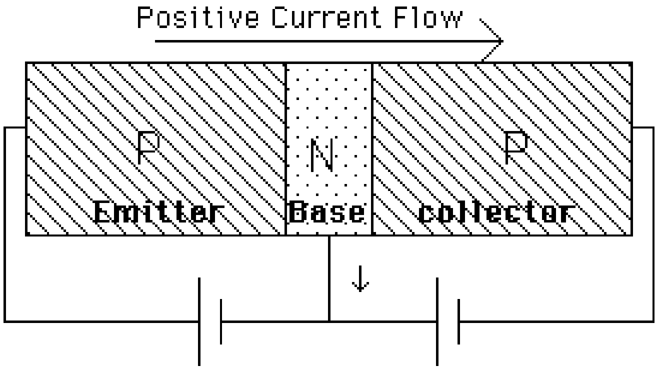
- In this class we will only consider *bipolar* transistors.
  - Bipolar transistors have 3 leads:
    - emitter, base, collector
  - Bipolar transistors are two diodes back to back and come in two forms:





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

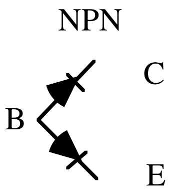


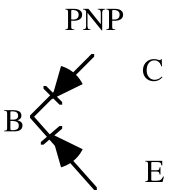


N material has excess negative charge (electrons).
P material has excess positive material (holes).

- Some <u>simple</u> 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} ≈ **0.6-0.7 V** when transistor is <u>on</u>.

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, β and α.

$I_C = \beta I_B$ β is called the current gain, typically 20-200

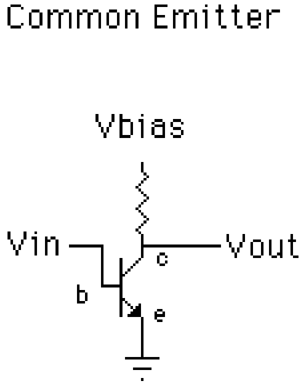
$I_C = \alpha I_E$ α typically 0.99

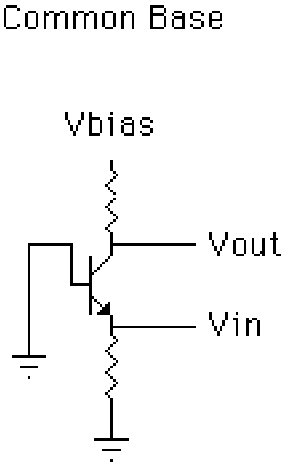
Still better approximation uses 4 (hybrid parameters) numbers to describe transistor performance ($\beta = h_{fe}$) when all else fails, resort to the data sheets!

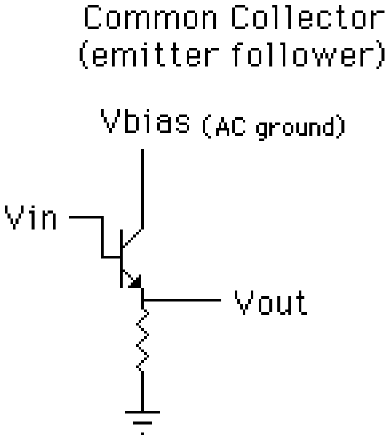
4) Common sense: must not exceed the power rating, current rating etc. or else the transistor dies.

•Transistor Amplifiers

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







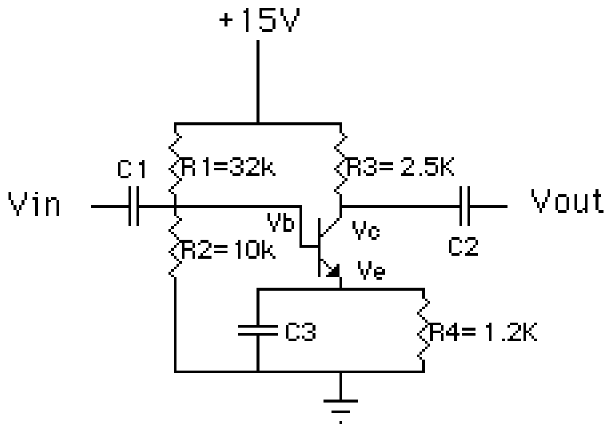
Properties of Amplifiers

	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 if we have a "working" circuit like the one below.



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.
It 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). Thus we can neglect the current into the base since its 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, $V_E = 3$ V here.
e) Find I_E using $I_E = V_E / R_4 = 3\text{ V} / 1.2\text{ k}\Omega = 2.5\text{ mA}$.
f) Use the approximation $I_C = I_E$ so $I_C = 2.5$ mA also.
g) Find V_C. $V_C = 15\text{ V} - I_C R_3 = 15 - 2.5\text{ mA} \times 2.5\text{ k}\Omega = 8.75\text{ V}$.
h) V_{CE} is now determined $V_{CE} = 8.75 - 3 = 5.75$ 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

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

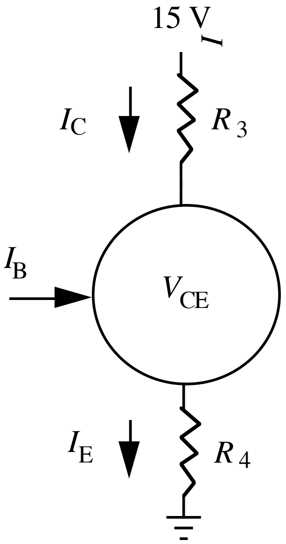
$$I_C = 15/(R_3 + R_4) - V_{CE}/(R_3 + R_4)$$

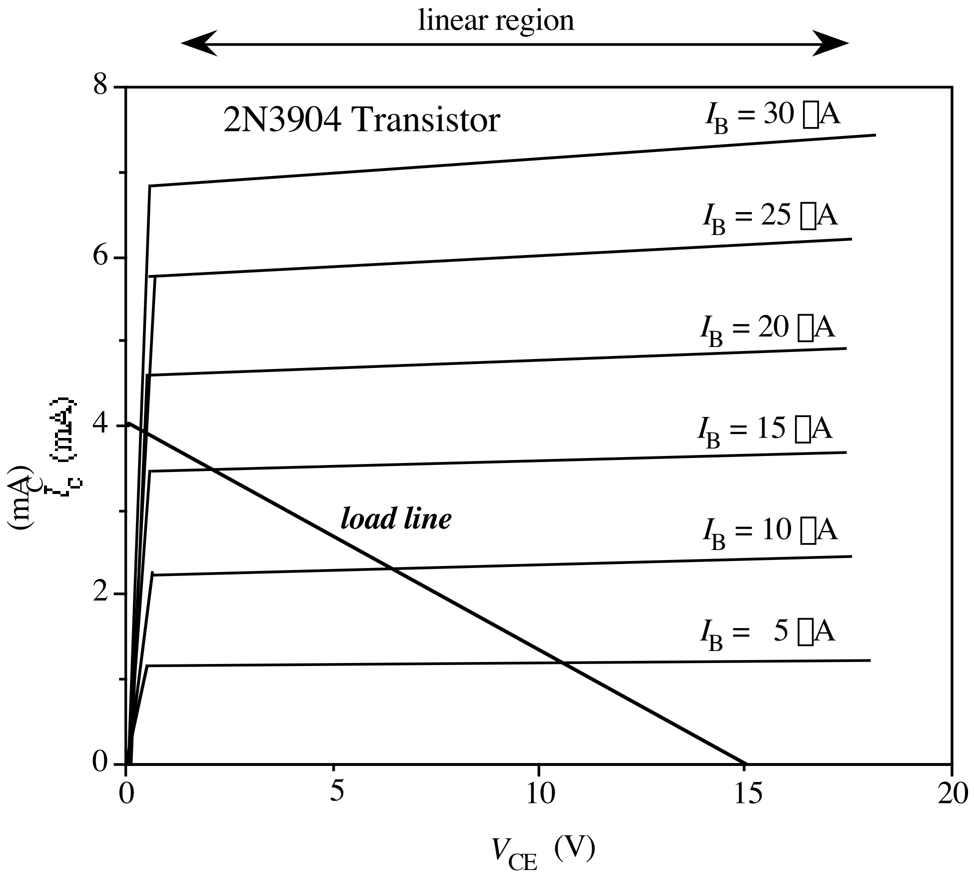
The above is a straight line in (I_C, V_{CE}) space. This line is the load line.

Plot on it spec sheet (Below is I_C vs. V_{CE} for various I_B for a 2N3904 transistor).

Assume $R_3 + R_4 = 3.75\ \mathrm{k\Omega}$, then we can plot the load line from the two limits:

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





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).

You 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 then from spec sheet the range
$V_{CE} < 0.5$ is in the non-linear region!
$V_{CE} > 0.5$ V is in the linear region! Looks ok as long as $I_C > 0$.

Usually pick I_C to be in the middle of the linear region. This way the amp will respond the same way to symmetric (around the operating point) output voltage swings.

If $I_C = 2.5$ mA and $I_B = 10$-11 μA, then from above spec sheet for 2N3904 transistor $V_{CE} = 5$-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

From the above spec sheet we can also calculate the current gain of the amplifier.
We define current gain as:

$$G = \Delta I_{\text{out}} / \Delta I_{\text{in}} \text{ (often this quantity is called } \beta\text{).}$$

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 then the collector current (I_C) changes from (approx.) 1.1 mA to 2.2 mA. Thus the current gain is:

$$G = (2.2 - 1.1 \text{ mA})/(10 - 5\ \mu\text{A}) \approx 200$$

Note: Like almost all transistor parameters, the exact current gain depends on many parameters:
frequency of input voltage
V_{CE}
I_C
I_B