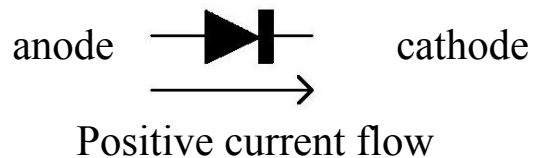


## Lecture 5: Diodes and Transistors

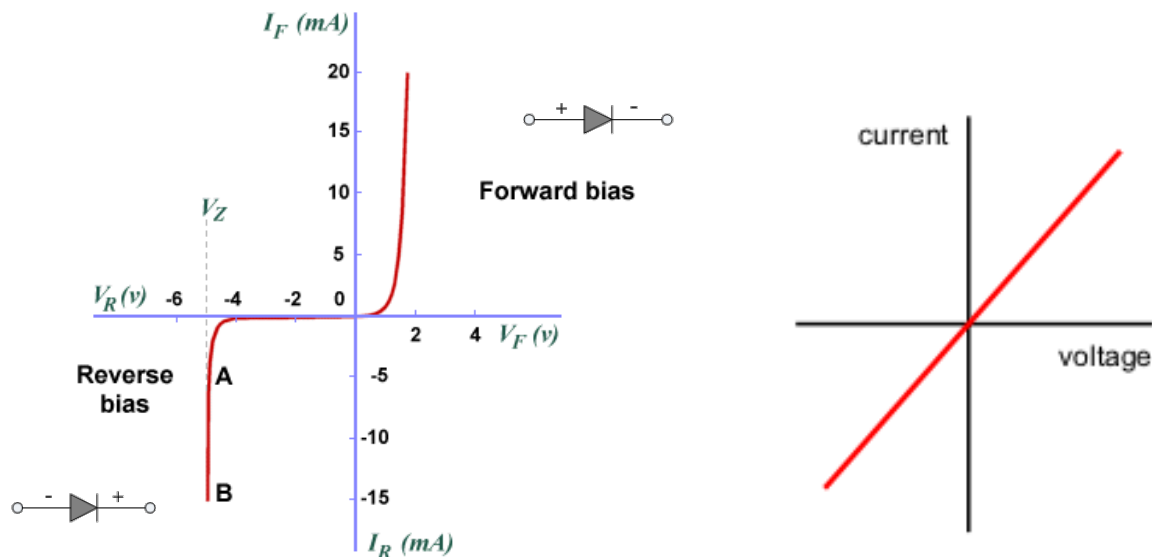
### Diodes:

- 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)



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

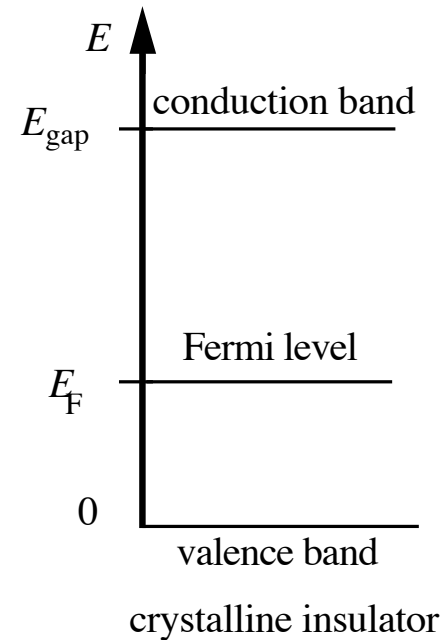
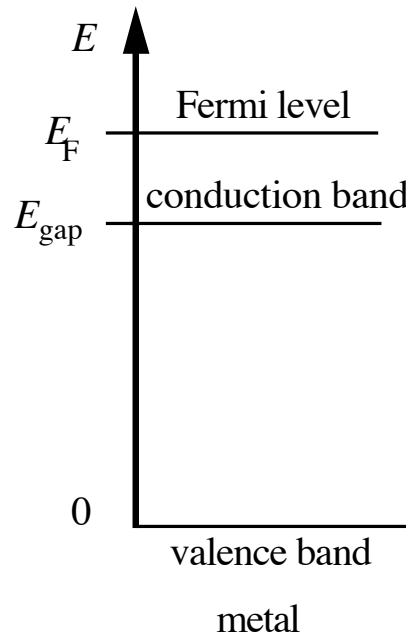
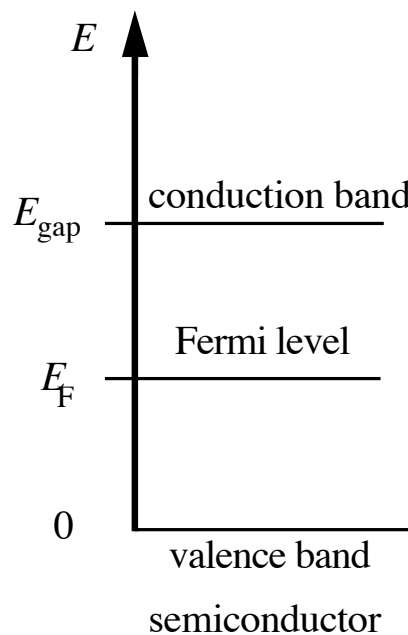
- Diodes (and transistors) are non-linear device:  $V \neq IR$ !



- ◆ 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  $< \mu\text{A}$ )
  - 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  $< \mu\text{A}$ )
  - $k$  = Boltzmann's constant,  $e$  = electron charge,  $T$  = temperature
  - At room temperature,  $kT/e = 25.3 \text{ mV}$ ,
 
$$I = I_s e^{39V} \quad \text{if } V > 0$$

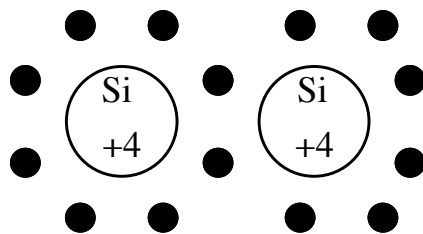
$$I = -I_s \quad \text{if } V < 0.$$
  
- ◆ Effective resistance of forward biased diode ( $V > 0$ ):
 
$$dV/dI = (kT/e)/I \approx 25 \text{ } \Omega/I, \text{ } I \text{ in mA}$$

- 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.

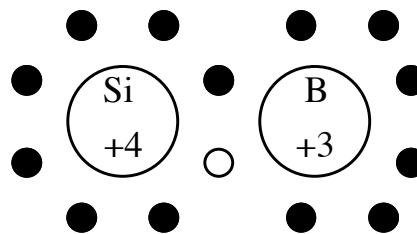


<b>Material</b>	<b>Example</b>	<b>Resistivity (<math>\Omega\text{-cm}</math>)</b>
Conductor	Copper	$1.56 \times 10^{-6}$
Semiconductor	Silicon	$10^3\text{-}10^6$
Insulator	Ceramics	$10^{11}\text{-}10^{14}$

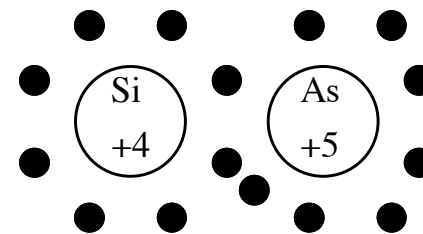
- How do we turn a semiconductor into a conductor?
  - ◆ *Dope it!*
  - ◆ Doping is a process where impurities are added to the semiconductor to lower its resistivity
  - ◆ Silicon has 4 electrons in its valence level
  - ◆ We add atoms with 3 or 5 valence shell electrons to a piece of silicon.
    - 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



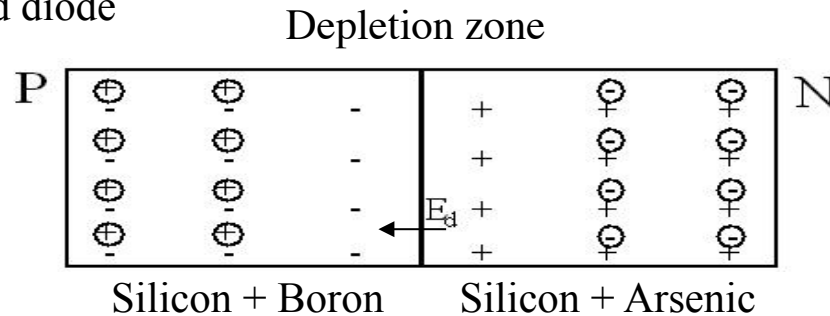
P Type Silicon



N Type Silicon

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

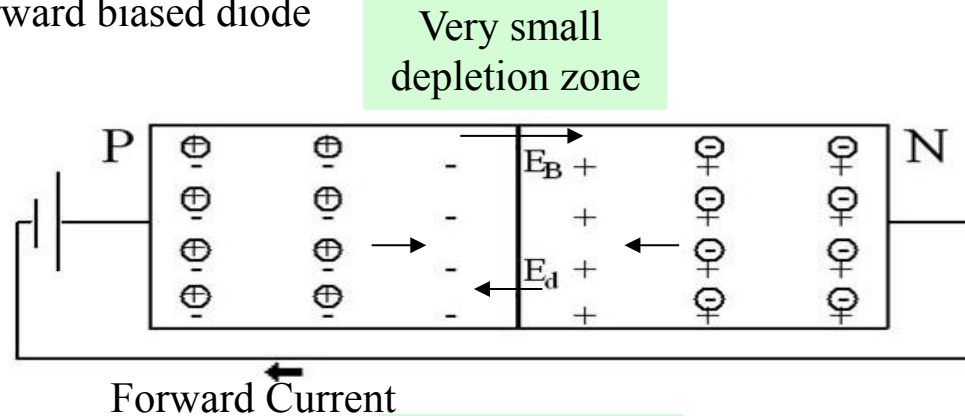
- Unbiased diode



Very small leakage current

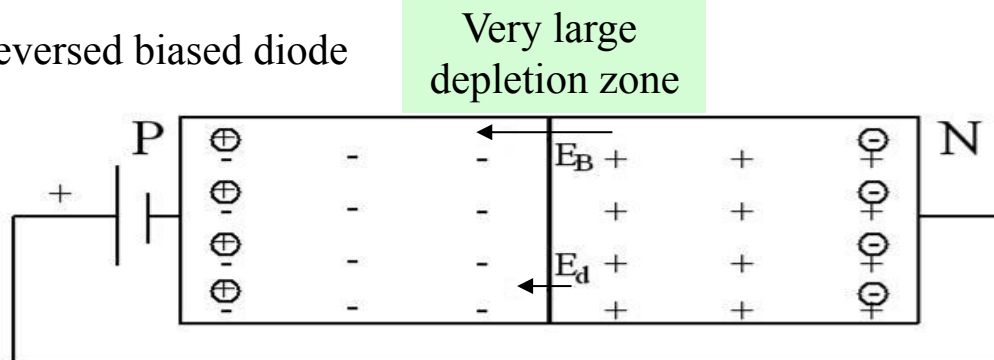
- $\ominus$  mobile electron
- $\oplus$  mobile hole
- fixed ionized acceptor atom
- + fixed ionized doner atom

- Forward biased diode



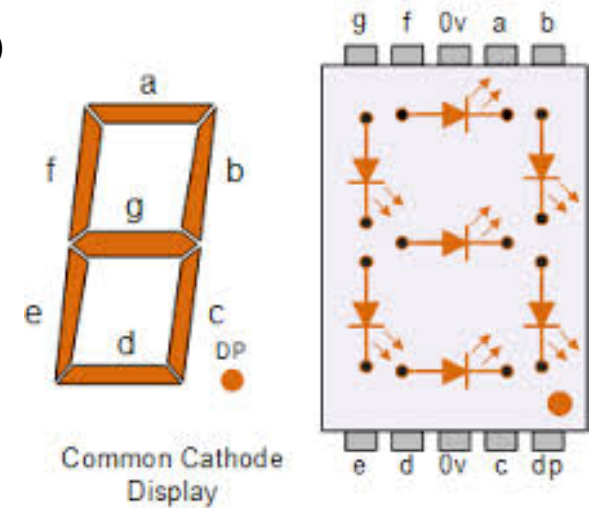
Barrier due to depletion region very small  
→ large current can flow

- Reversed biased diode



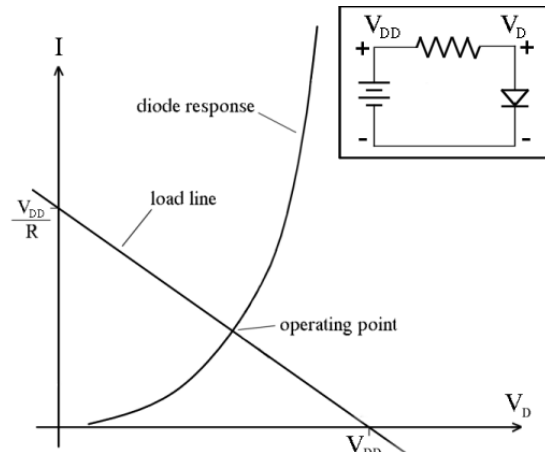
Barrier due to depletion region very large  
→ small leakage current

- 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)
    - “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!)
  - ◆ varactor (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:

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

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

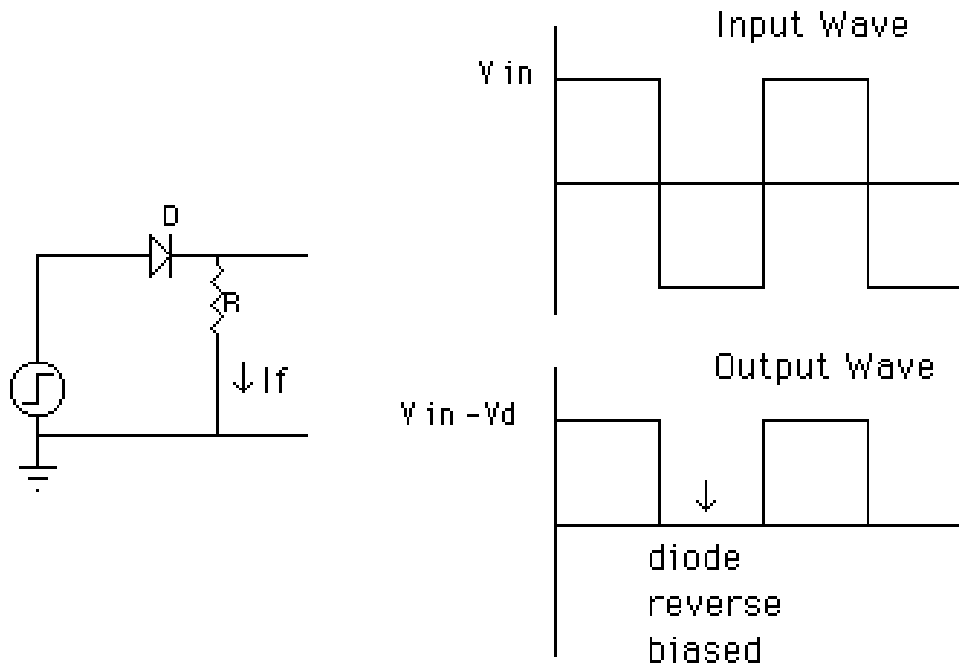
- ◆ For this circuit  $I$  vs.  $V_D$  is a straight line with the following limits:

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

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

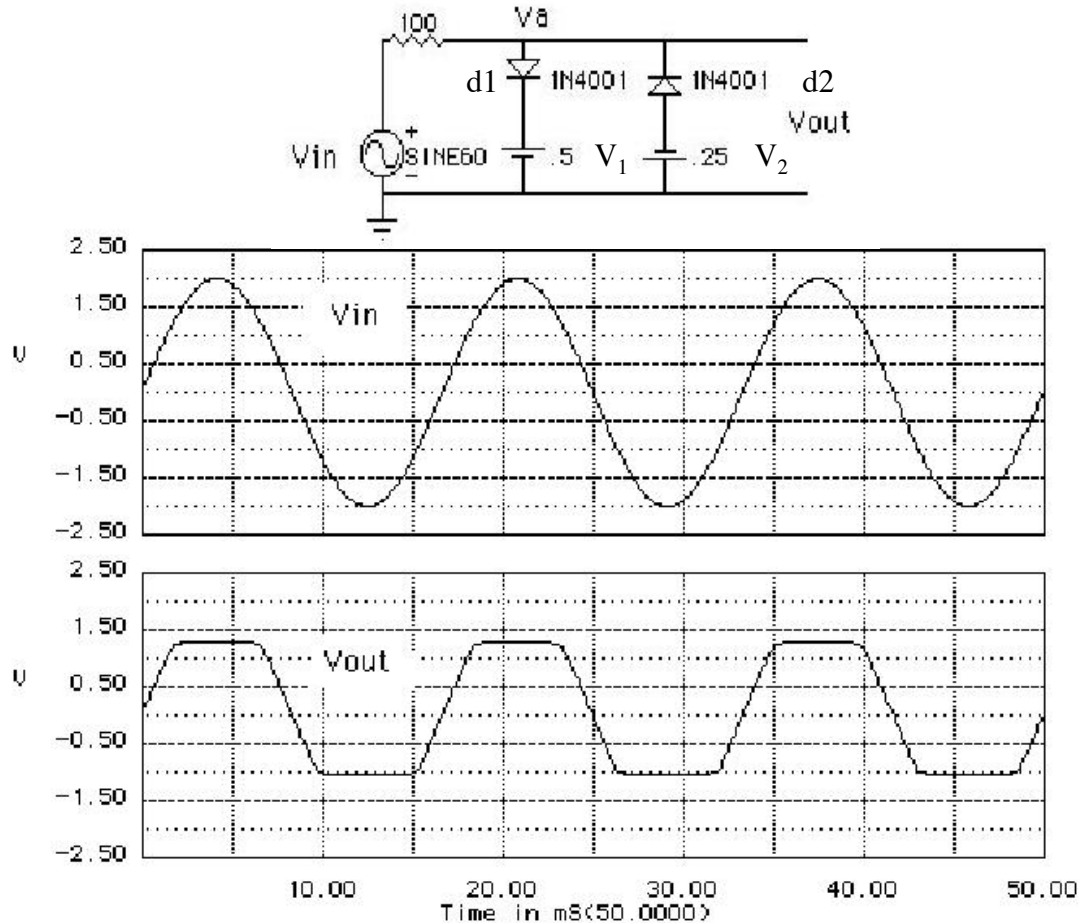
- The straight line (load line) is all possible  $(V_D, I)$  for the **circuit**.
- The diode curve is all possible  $(V_D, I)$  for the **diode**.
- The place where these two lines intersect gives the actual voltage and current for this circuit.

- 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  $V_{out} = 0$ .



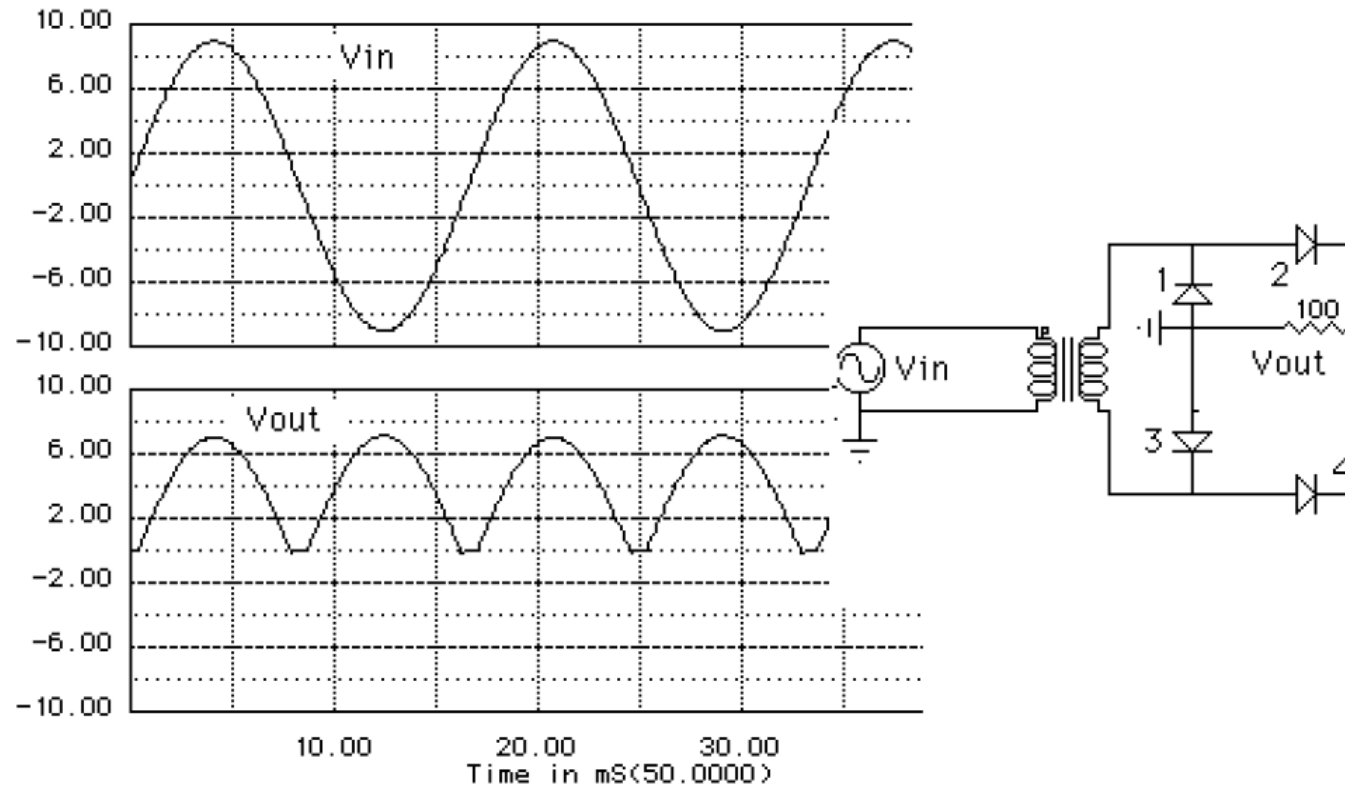


- For more protection consider the following "clipping" circuit: for silicon  $V_d \approx 0.6\text{-}0.7\text{ V}$

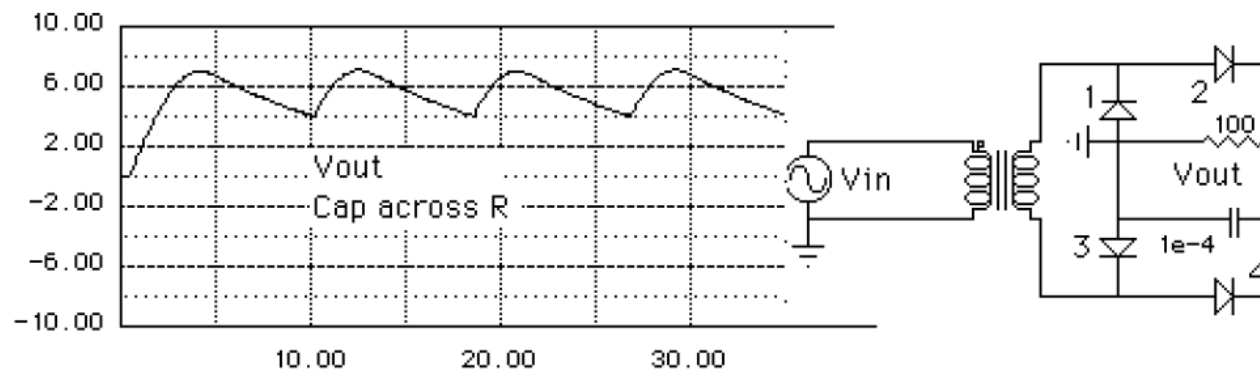


- ◆ If  $V_a > V_{d1} + V_1$ , then diode 1 conducts so  $V_{out} \leq V_{d1} + V_1$ .
- ◆ If  $V_a < -V_{d2} - V_2$ , then diode 2 conducts so  $V_{out} \geq -V_{d2} - V_2$ .
- ◆ If we assume  $V_{d1} = V_{d2} \approx 0.7\text{ V}$  and  $V_1 = 0.5\text{ V}$ ,  $V_2 = 0.25\text{ V}$ ,
  - for  $V_{in}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

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

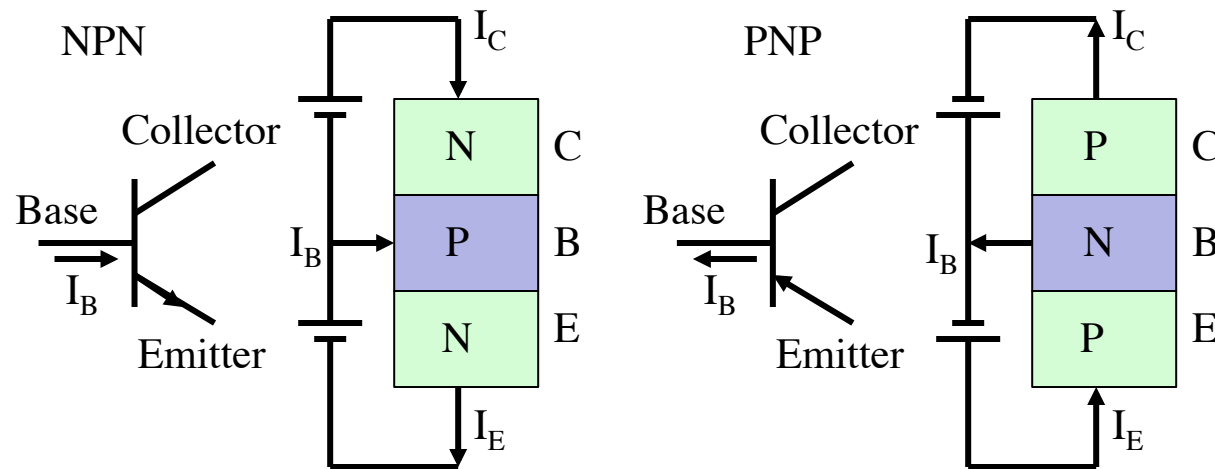


- ◆ In the positive part of  $V_{in}$ , diodes 2 and 3 conduct.
- ◆ In negative part of the cycle, diodes 1 and 4 conduct.
- ◆ This circuit has lots of ripple.
  - We can reduce ripple by putting a capacitor across the load resistor.
  - Pick  $RC$  time constant such that:  $RC > 1/(60 \text{ Hz}) = 16.6 \text{ msec}$ .
    - example:  $R = 100 \text{ } \Omega$  and  $C = 100 \text{ } \mu\text{F}$  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  $\text{mm}^2$  (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:



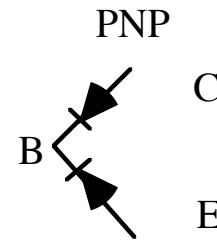
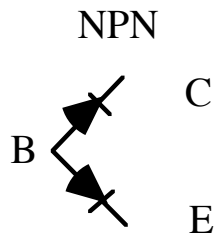
K.K. Gan

L5: Diodes and Transistors

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
  - For NPN (PNP) collector must be more positive (negative) in voltage than emitter.
  - Base-emitter and base-collector are like diodes:

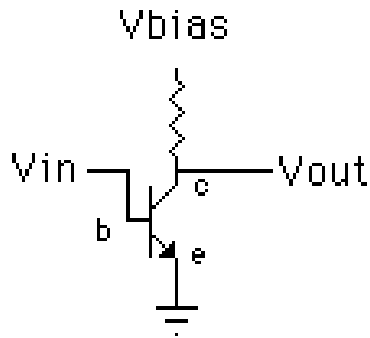


👉 For silicon transistors,  $V_{BE} \approx 0.6-0.7 \text{ V}$  when transistor is **on**.

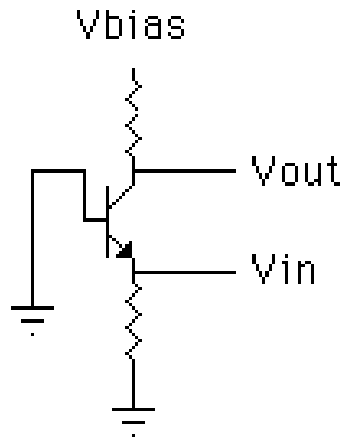
- The currents in the base ( $I_B$ ), collector ( $I_C$ ) and emitter ( $I_E$ ) are related as follows:
  - always:  $I_B + I_C = I_E$
  - rough rule:  $I_C \approx I_E$ , and the base current is very small ( $\approx 0.01 I_C$ )
  - Better approximation uses 2 related constants,  $\alpha$  and  $\beta$ .
    - $I_C = \beta I_B$ 
      - $\beta$  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!
- 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*).

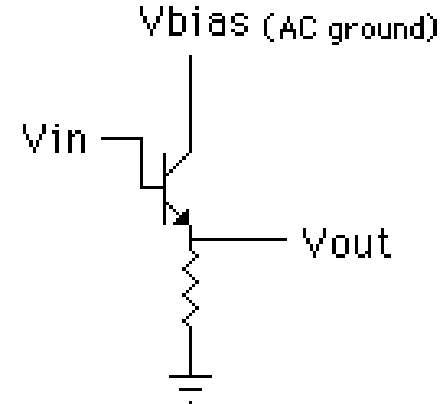
Common Emitter



Common Base



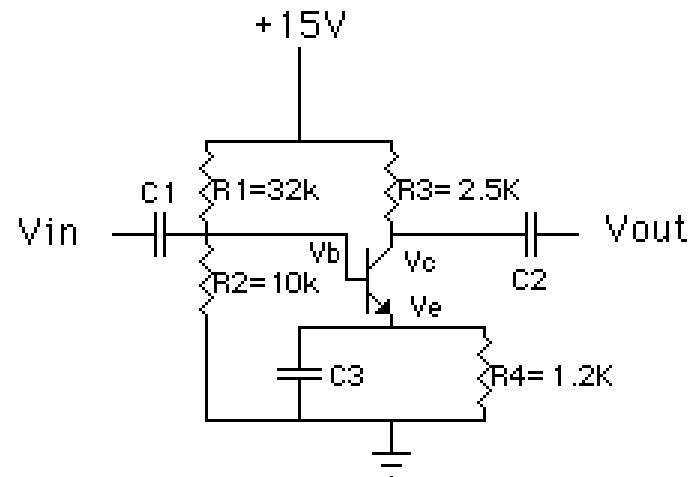
Common Collector  
(emitter follower)



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	$\approx 3.5 \text{ k}\Omega$	$\approx 30 \Omega$	$\approx 500 \text{ k}\Omega$
Output impedance	$\approx 200 \text{ k}\Omega$	$\approx 3 \text{ M}\Omega$	$\approx 35 \Omega$
Output voltage phase change	$180^\circ$	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  $V_{BE} \approx 0.6\text{-}0.7\text{ V}$ ).
  - ◆ 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:



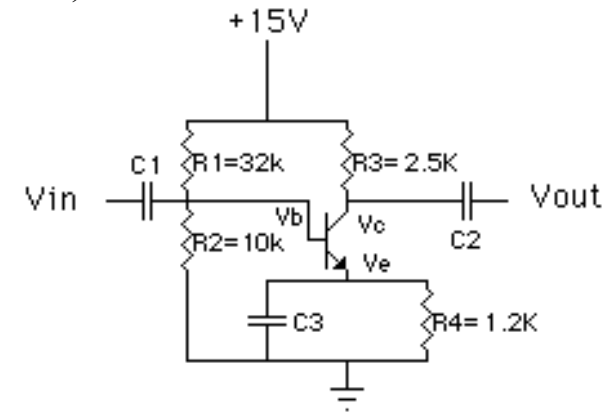
Common Emitter Amp

- ◆ 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.
  - 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  $I_E$ .
  - If transistor is “working” then  $V_{BE} \approx 0.6\text{-}0.7\text{ V}$  (silicon transistor).
  - Determine  $V_B$  using  $R_1$  and  $R_2$  as a voltage divider

$$V_B = 15\text{ V} \frac{R_2}{R_1 + R_2} = 3.6\text{ V}$$

- Find  $V_E$  using  $V_B - V_E = 0.6\text{ V} \Rightarrow V_E = 3\text{ V}$ .
  - $I_E = V_E / R_4 = 3\text{ V} / 12\text{ k}\Omega = 2.5\text{ mA}$ .
  - Use the approximation  $I_C = I_E \Rightarrow I_C = 2.5\text{ mA}$ .
  - $V_C = 15\text{ V} - I_C R_3 = 15 - 2.5\text{ mA} \times 2.5\text{ k}\Omega = 8.75\text{ V}$ .
  - $V_{CE} = 8.75 - 3 = 5.75\text{ V}$ .
- 👉 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

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

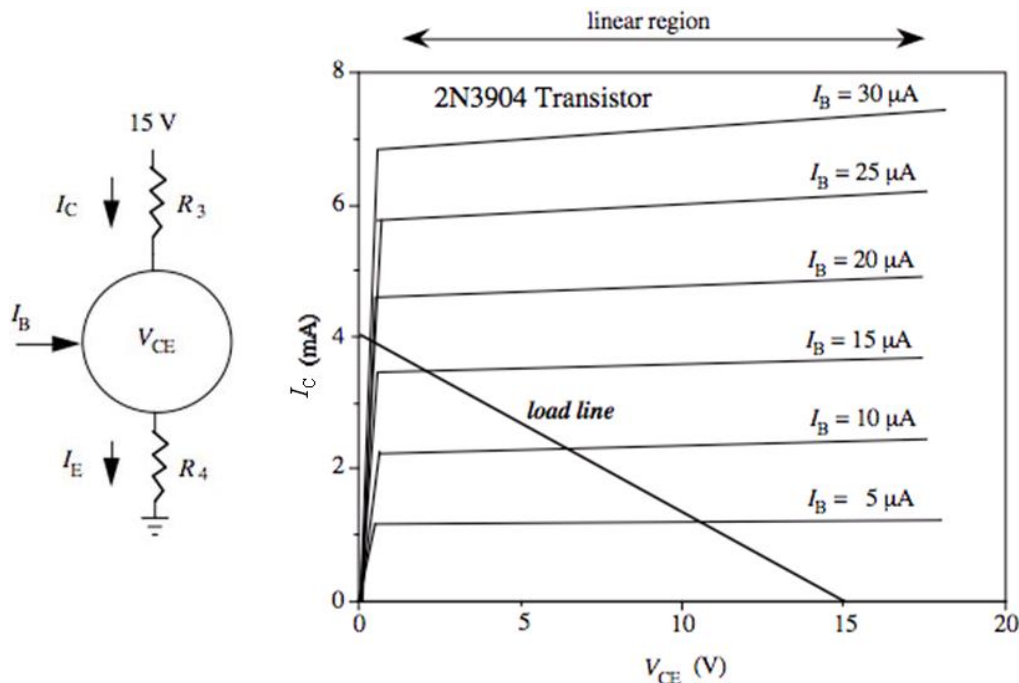
$$I_C = 15 / (R_3 + R_4) - V_{CE} / (R_3 + R_4)$$

- ◆ 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:

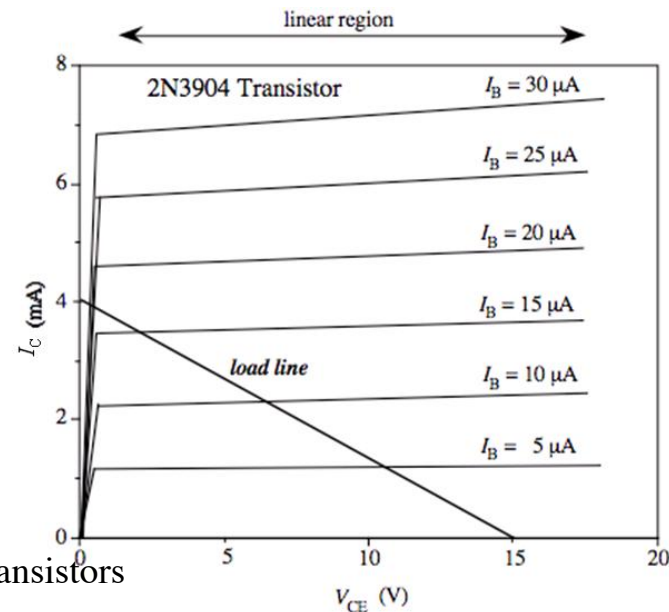
$$I_C = 0, V_{CE} = 15 \text{ V} \quad \text{and} \quad V_{CE} = 0, I_C = 15 \text{ V} / 3.75 \text{ k}\Omega = 4 \text{ mA}$$



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  $I_B = 10$ - $11$   $\mu$ 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:

$$G = \Delta I_{\text{out}} / \Delta I_{\text{in}}$$

- 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 ( $V_{CE} > 0.5 \text{ V}$ ) 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.
  - ☞  $G = (2.2 - 1.1 \text{ mA}) / (10 - 5 \mu\text{A}) \approx 200$
- ◆ Like almost all transistor parameters, the exact current gain depends on many parameters:
  - frequency of input voltage
  - $V_{CE}$
  - $I_C$
  - $I_B$

