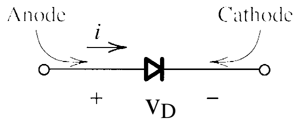
ECE2280 FUNDAMENTALS OF ELECTRICAL ENGINEERING

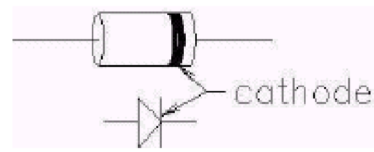
What are diodes?

Definition: A diode is a semiconductor device that passes current only in 1 direction. A "one-way" current valve

<u>Ideal Diode</u>

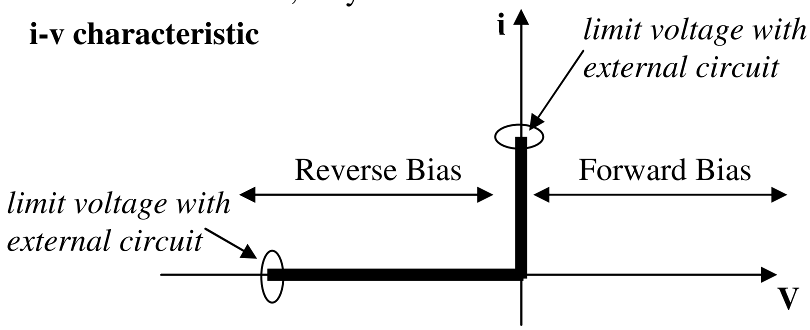
Circuit Symbol:

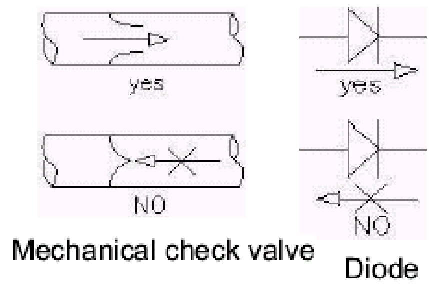




- Like resistors, they have 2 terminals

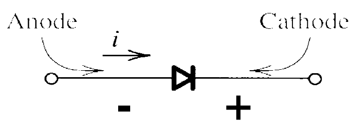
i-v characteristic





- Unlike resistors which have a linear relationship, the diode has a **<u>nonlinear</u>** characteristic

<u>Reverse Bias:</u>



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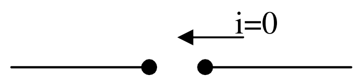
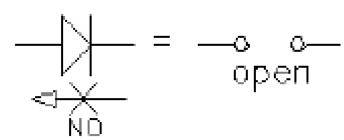
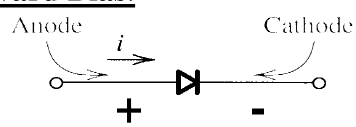


$r_d = \infty$
open
v_D determined by external circuit



<u>Forward Bias</u>:



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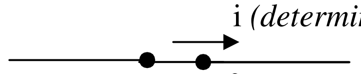
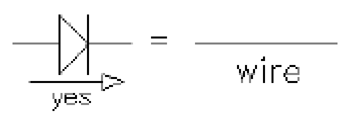
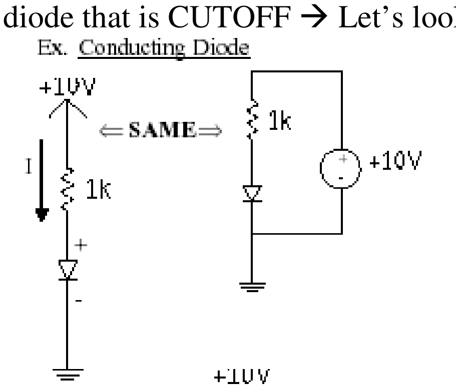
i *(determined by external circuit)*

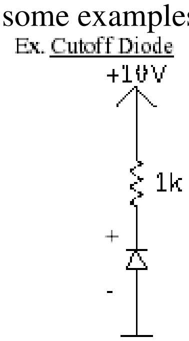


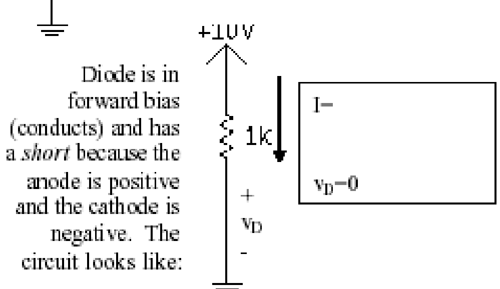
r_d=0
short
$v_D = 0$

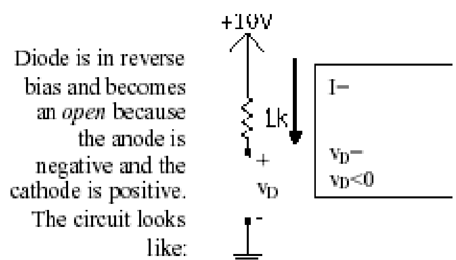


External circuit – needs to limit the forward current through a diode that is ON and limit the reverse voltage across a diode that is CUTOFF → Let's look at some examples of diodes in a circuit









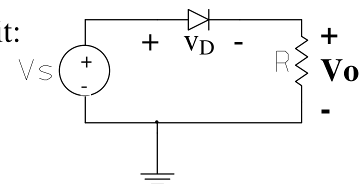
Summary of 2 modes of operation for Diode:

Forward-Biased	**Reverse-Biased**
Conducting	Cutoff
ON	OFF
Short Circuit	Open Circuit
i=value	i=none
v_D=0	v_D=open

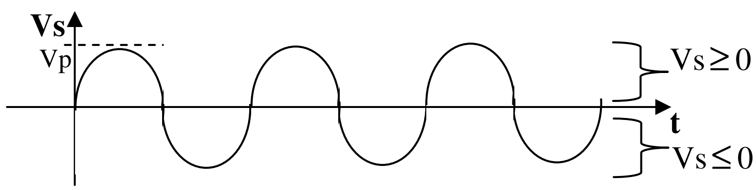
Example: Rectifier

- The word "rectify" means to made unidirectional → keep this in mind
- Makes use of nonlinear characteristic of diodes
- Assume ideal diode

1). Circuit:

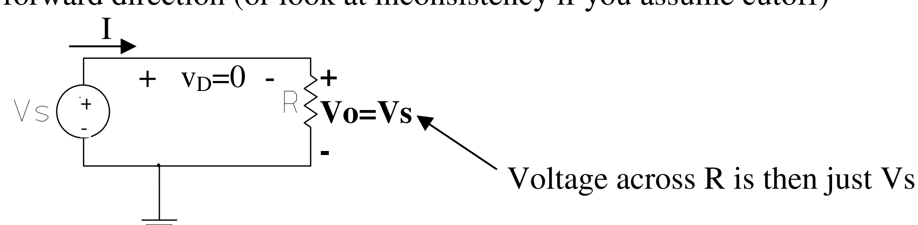


2). Input signal Vs: *sinusoid*

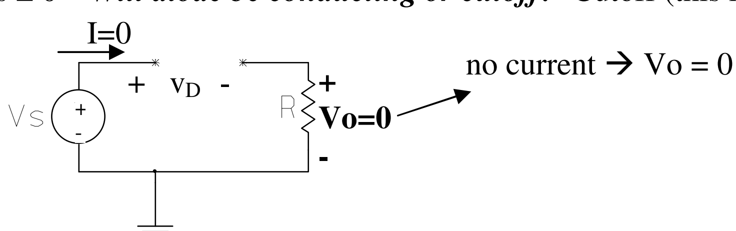


Two regions to consider:

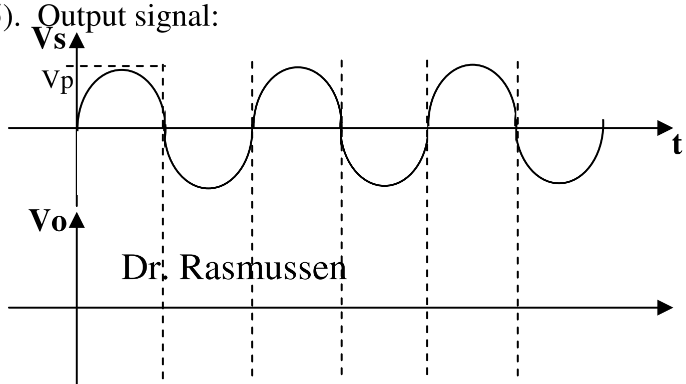
3). Vs>0 – ***Will diode be conducting or cutoff?*** Conducting because current flows through diode in its forward direction (or look at inconsistency if you assume cutoff)

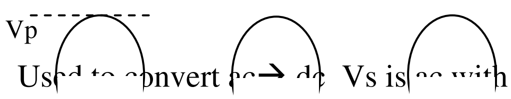


4). Vs ≤ 0 – ***Will diode be conducting or cutoff?*** Cutoff (this is consistent)



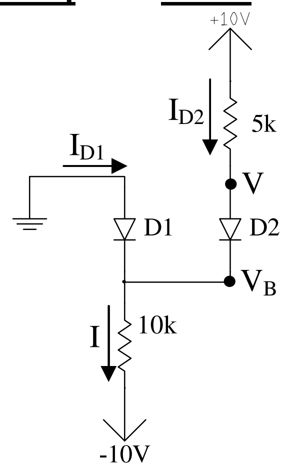
5). Output signal:



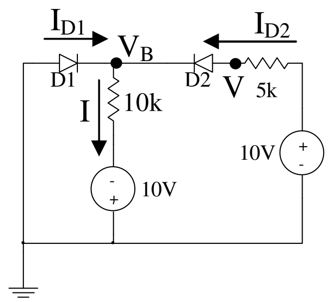


6). Used to convert ac → dc. Vs is ac with 0 average value. Can see Vo has a dc component.

Examp   Two d



⇐**SAME**⇒



Find I and V. Assume the diodes are ideal.
Not always obvious if diodes are ON or OFF → make an assumption and test it!
Assume both are ON for starters → Short them

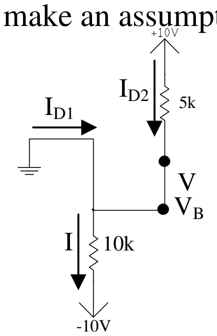
$V_B=0$

$V=0$

$I_{D2}=\frac{10-0}{5k}=2mA$

$I=\frac{0-(-10)}{10k}=1mA$

$I_{D1}+I_{D2}=I \Rightarrow I_{D1}=-I_{D2}+I=-2m+1m=-1mA$



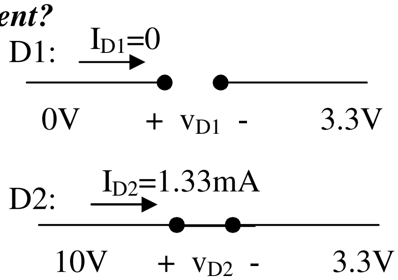
Is this possible?
Diode ON: Need I>0 for V=0

We have V = 0, but I < 0 → contradiction
(Also think of it as saying a negative current is flowing through D1 → not possible)

Instead, say D1 is OFF and D2 is ON. Then $I_{D2}=\frac{10-(-10)}{15k}=1.33mA$

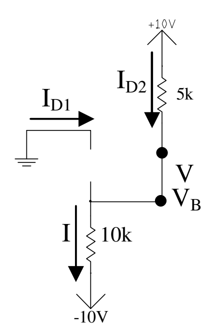
Voltage at B: $V = V_B = -10+10k(1.33mA)=3.3V$

I = 0 and D1 is Reverse-biased
Is this consistent?
check:



$v_{D1}=-3.3V<0 \Rightarrow I_{D1}=0$

$I_{D2}>0 \Rightarrow v_{D2}=0$



Think of finding I and V like solving a puzzle…

Method for analyzing diode circuit:

1). Assume each diode is either ON or OFF

2). Find i_d and v_d for each diode to see:

- Is solution consistent with

  OFF: $v_D \leq 0$ (ideal) or $v_D \leq v_{DO}$ (real) $\Rightarrow I_D=0$

  ON: $I_D>0 \Rightarrow v_D=0$(ideal) or $v_D=v_{DO}$ (real)

*Make sure you are looking at voltage across the diode and current through the diode when you are checking for this! NOT the I and V necessarily that you were asked to find.

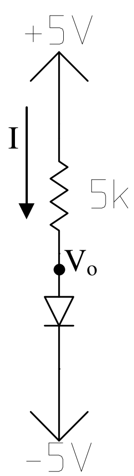
3). If so, assumption was correct (check consistency) – only one solution possible, so STOP

4). Find the requested I and/or V

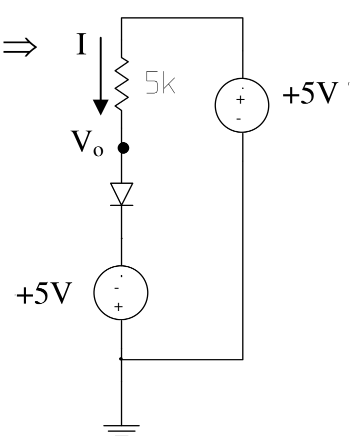
5). If not, start again with new assumption (NOTE: I and V values are no longer valid, so you have to discard those previous values)

Example 18

Find I and Vo



⇐SAME⇒



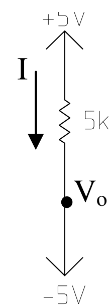
Assume "ON":

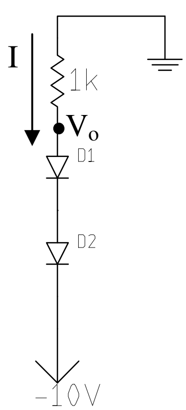
Vo=-5V

$I=\frac{5-(-5)}{5k}$ =2mA

check:

$I_D>0 \Rightarrow v_D=0$





Find I and Vo

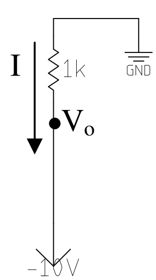
Assume both "ON"

Vo=-10V

$I=\frac{0-(-10)}{1k}$ =10mA

check:

$I_D>0 \Rightarrow v_D=0$



Analysis of Diode Circuits

For hand calculations, we have 4 main models to use:

1). Ideal model for diode:

Reverse Bias: OFF/cutoff/open circuit

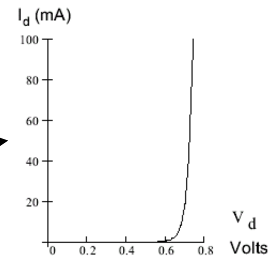
Forward Bias: ON/conducting/short circuit

2). Use full diode equation: $i_D = I_S(e^{V_D/nV_T} - 1)$

(Reverse Bias: $i_D \sim= -I_S$)

Forward Bias: $i_D \approx I_S(e^{V_D/nV_T})$

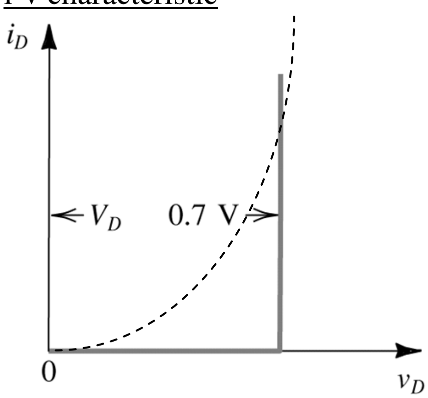
Use an iterative method and solve



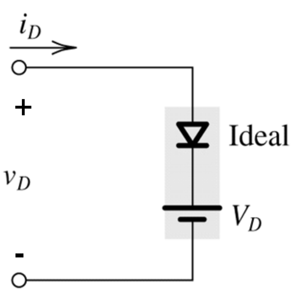
3). ***Constant-voltage-drop model*** for diode (apply for forward bias):

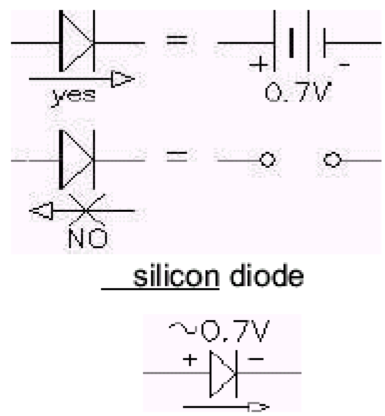
- Replace real diode with an ideal diode and a voltage drop V_D

i-v characteristic

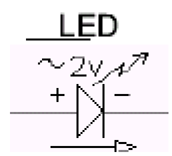


model





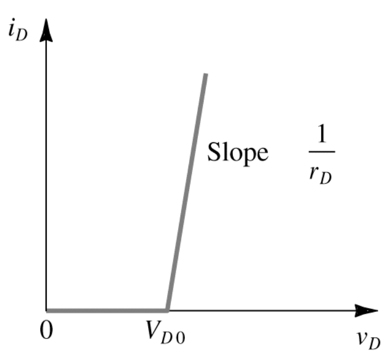
light-emitting diodes (LEDs) are modeled by 2v drop in forward direction:



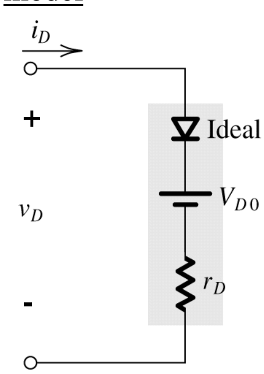
4). Piecewise-linear model for diode (apply for FB):

- Replace real diode with an ideal diode, a voltage drop V_{D0}, and a resistor, r_D

i-v characteristic



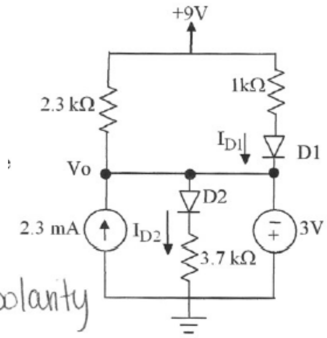
model



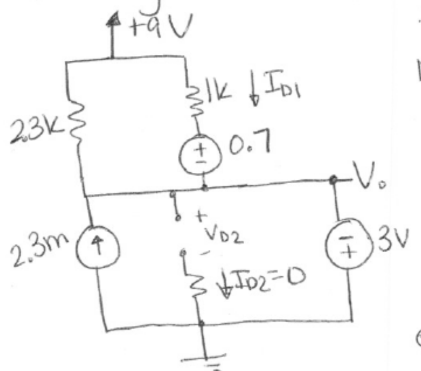
Example 19;

Assume all diodes are identical and have V_{DO}=0.7V, n=1, and V_T=25mV. Use the constant voltage drop method. Verify that your assumption for the diode operation(i.e. on or off) are correct. Find the following making sure you find the correct operation of the diodes.

a) State your assumptions (diode is on/off).
b) The current I_{D1}
c) The current I_{D2}
d) The voltage Vo
e) Your verification to prove your assumptions for the diodes are correct.



a) D1 on, D2 off (D2 will have -3V across it from observation- voltage polarity is wrong direction).



$+9 - I_{D1}(1k) - 0.7 + 3 = 0$

b) $I_{D1} = \frac{11.3}{1k} = \boxed{11.3mA} > 0$

So assumption for D1 ON correct. ✓

c) $\boxed{I_{D2} = 0}$

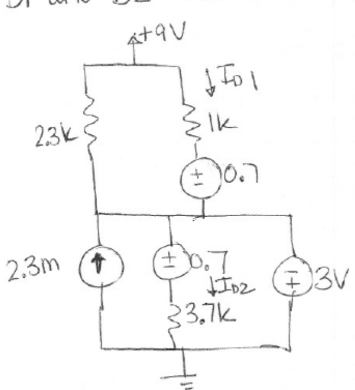
d) $\boxed{V_o = -3V}$

e) $-3V - V_{D2} = 0 \Rightarrow \boxed{V_{D2} = -3V} < 0$

∴ Assumption D2 on correct

$I_{D1} > 0$, D1 ON

D1 and D2 ON ⇒



$+9 - 0.7 + 3 - I_{D1}(1k) = 0$

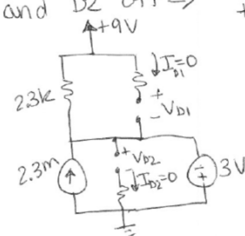
$I_{D1} = \frac{11.3}{1k} = 11.3mA$

$-3V - 0.7 - I_{D2}(3.7k) = 0$

$I_{D2} = \frac{-3.7}{3.7k} = -1mA < 0$ ✗

∴ Wrong Assumption

D1 and D2 off ⇒



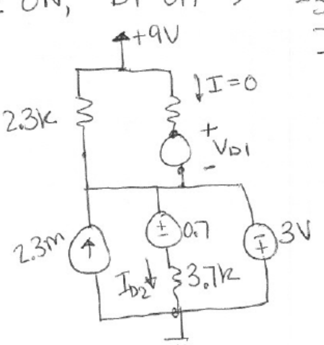
$+9 - V_{D1} + 3V = 0$

$V_{D1} = 12V$ (NOT NEGATIVE)
→ wrong assumption

$-3V - V_{D2} = 0$

$V_{D2} = -3V < 0$ (correct)

D2 ON, D1 off ⇒



$-3 - 0.7 - I_{D2}(3.7k) = 0$

$I_{D2} = \frac{-3.7}{3.7k} = -1mA < 0$ ✗ WRONG Assumption

$+9V - V_{D1} + 3V = 0$

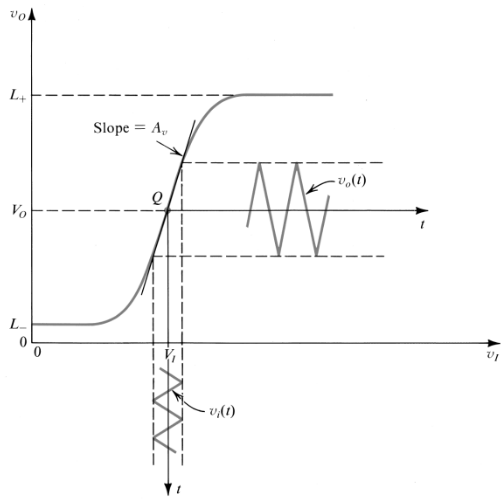
$V_{D1} = +12V$ which is NOT negative ⇒ WRONG ASSUMPTION

<u>Small-Signal Analysis of Diodes</u>

- So far we have looked at ***dc models*** for diodes
- For some applications it is necessary to also use a ***"small-signal" ac*** model
- If we use a small-signal model that linearizes the components, we can apply regular linear circuit analysis!
- We can then separate ac and dc analysis

The technique used to linearize a nonlinear characteristic is called ***biasing***.

Biasing:



- Biasing is achieved by operating the circuit with the nonlinear characteristic in a point near the middle
- From the graph, at dc voltage input V_I the dc voltage output is V_o.
- The point Q is known as the **quiescent point**, the **dc bias point**, or the **operating point**
- By limiting the amplitude of a ac time varying input signal, $v_I(t)$ the operating point is limited to a linear region of the curve.
- Note that this only works when the input signal is kept sufficiently small

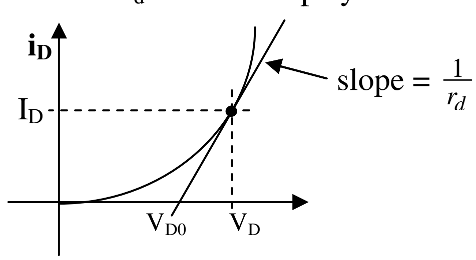
Derivation of the small-signal is done in the book (pg. 160).

The meaning of CAPITALS and lower case letters

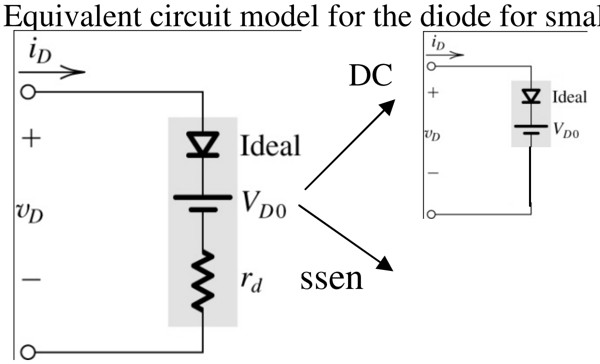
	examples		meaning
CAP_{CAP}	V_D	I_D	DC, Bias quantity
sm_{sm}	v_d	i_d	AC, signal
sm_{CAP}	v_D	i_D	DC and AC together

- Hard to analyze circuit with both signals together
  - Result of derivation: Can separate analysis into DC then AC!
  - $r_d = nV_T/I_D$ = small-signal resistance {result of analysis}

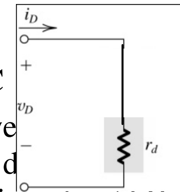
NOTE: This r_d is different than r_D from dc model
This r_d comes into play as the slope of the line tangent to the operating point:



<u>Equivalent circuit model</u> for the <u>diode for small</u> changes around the operating point:



$$v_D = V_{D0} + i_D r_d$$
$$= V_{D0} + (I_D + i_d) r_d$$
$$= (V_{D0} + I_D r_d) + i_d r_d$$
$$= V_D + i_d r_d \ \textit{(DC + AC)}$$

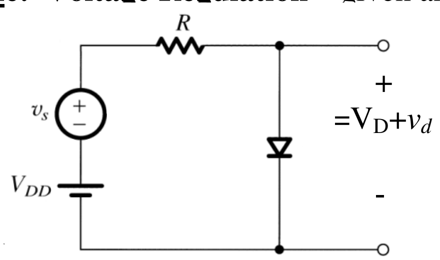


Procedure: (not r_D!) AC

1). Do dc analysis first (what we … o far) to find I_D
2). Use dc current value (I_D) to d … all-signal model parameter $r_d = nV_T/I_D$
3). Then do ac analysis to find i_d and v_d (AC values)

<u>Example</u>: Voltage Regulation – given an ac input voltage, povides ≈ constant dc voltage at output

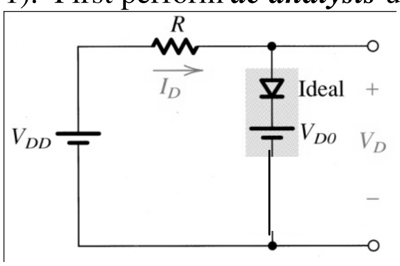
Circuit:



R=5k, $v_s=\sin(2\pi 60t)$, V_{DD}=10V
Assume diode has 0.7V drop at 1mA and n=2

Find dc … eak-to-peak signal voltage v_d across diode

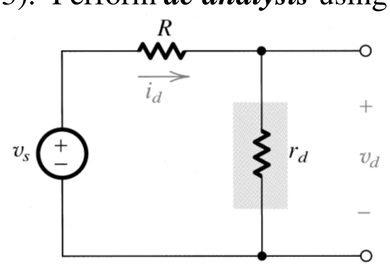
1). First perform ***dc analysis*** using constant voltage drop model- dc circuit model:



$-V_{DD}+I_D(R)+V_{D0}=0$
$I_D=(10-0.7)/5k=1.86mA$
V_D=0.7V

2). Calculate small-signal resistance(depends on dc current!): $r_d = \frac{nV_T}{I_D} = \frac{2(25mV)}{1.86m} = 26.8\Omega$

3). Perform ***ac analysis*** using small-signal model small-signal circuit model:



$v_s + i_d(R+r_d) = 0 \Rightarrow i_d = v_s/(R+r_d)$

v_d (peak-to-peak)$= i_d(r_d) = \frac{v_s r_d}{(R+r_d)} = \frac{2(26.8)}{(5k+26.8)} = 10.7$mVac

Input: 10Vdc + 2$V_{p\text{-}p}$ ac → i.e. ac is 10% of dc
Output 0.7Vdc + 10.7m$V_{p\text{-}p}$ ac → ac is ≈ 0.8% of dc

<u>PHYSICS OF DIODE</u>

link can be used to understand more about the PN junction: **<u>g.buffalo.edu/applets/education/fab/pn/diodeframe.html</u>**

Physical properties of a diode => A diode is made up of what is called a pn-junction.

What is one main characteristic of a metal? Metals: tend to be good conductors because they have "free electrons" that can move easily between atoms; *flow of electrons → current flow*

Insulators: electrons in covalent bonds, so they can't move around; no flow of electrons → no current flow

A pn-junction has two different pieces of silicon(between a metal and insulator)that when put together and applying a forward voltage of approximately > 0.7V, we will have a conducting device that has current flow through it fully in one direction and very minutely in the reverse direction

→ You can change the behavior of silicon by ***doping*** it

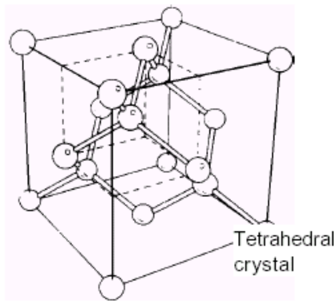
Doping: mix small amount of impurities into the silicon which changes its charge

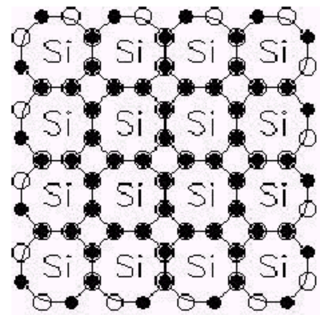
Silicon atoms

Silicon atoms each have 4 valence electrons (electrons in their outermost shell). That leaves 4 spaces in the outer shell of 8. This makes silicon a very reactive chemical, like carbon, which has the same valence configuration.

Silicon crystals

Each atom covalently bonds with four neighboring atoms to form a tetrahedral crystal, which we'll represent in 2D.

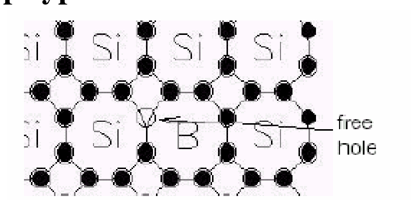




2-dimensional representation

<u>Two types:</u>

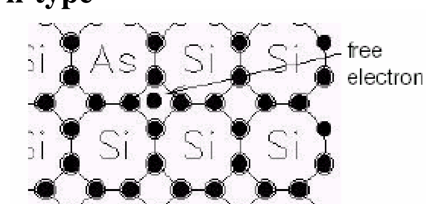
p-type



n_{p0}: concentration of free electrons in p-type
p_{p0}: concentration of holes in p-type
N_A: concentration of acceptor atoms

- p-type silicon ~ **<u>Positive</u>** charge
  - {holes are **<u>majority</u>**}
- $P_{po} \cong N_A \rightarrow n_{po} \cong \frac{n_i^2}{N_A}$
- n_{p0} is a function of temperature, p_{p0} independent of temperature

n-type



n_{n0}: concentration of free electrons in n-type
p_{n0}: concentration of holes in n-type
N_D: concentration of donor atoms

- n-type silicon ~ **<u>Negative</u>** charge
  - {e^- are **<u>majority</u>**}
- $n_{n0} = N_D$ $p_{n0} \cong \frac{n_i^2}{N_D}$
- p_{n0} is a function of temperature, n_{n0} independent of temperature

- A ***diffusion current*** I_D results in the forwar
- ***Minority carriers*** drift: Thermally generated holes in n material (electrons in p material) diffuse to edge of depletion region → electric field causes them to be swept across to the p side (n side)

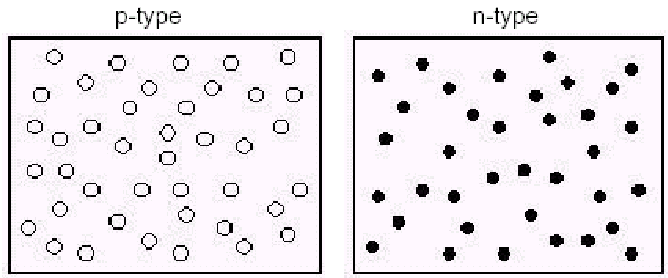
  → ***Drift current*** I_S is due to ***minority carriers*** diffusion (Temperature dependent since minority carriers are thermally generated)

  If no external current/voltage is applied, the above two currents will be equal:
  $I_D = I_S$ (Note: Can say diode current is $i_D = I_D - I_S = 0$)
  The built-in voltage, V_O, keeps this equilibrium.

  There is a **"built-in" voltage** (V_O) across the depletion region – acts as a barrier that diffusing holes or electrons have to overcome → larger it is → harder to overcome → fewer carriers diffuse → smaller I_D

Summary: electrons and holes have high mobility and result in current flow with applied current or voltage

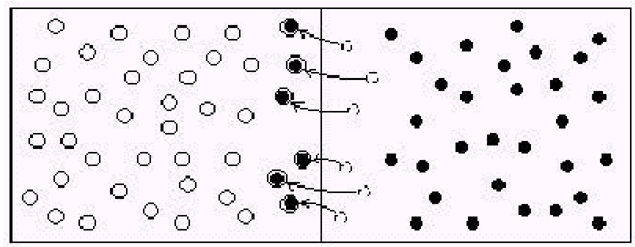
It turns out that the free carriers are the most important things in the semiconductor crystals, so we can simplify the drawings to show only these free carriers.



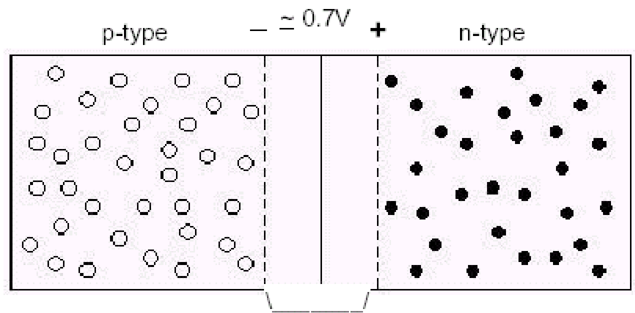
circles represent free holes   dots represent free electrons

PN Junction

When a p-type semiconductor is created next to an n-type, some of the free electrons from the n side will cross over and fill some of the free holes on the p side. This makes the p side negatively charged and leaves the n side positively charged. When the voltage across the junction reaches about 0.7 V the electrons find it too difficult to move against the charge and the process stops.



A region near the junction is now depleted of carriers and (surprise) is called the depletion region.



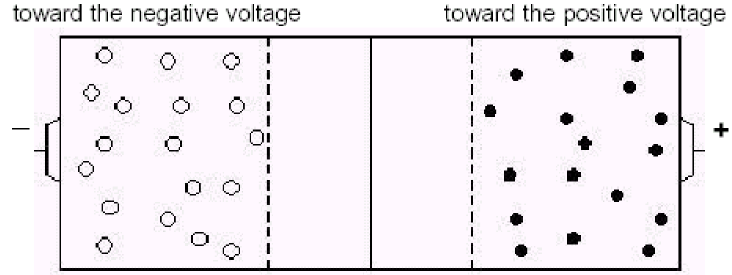
Reverse bias

This pn junction is now a diode. If you place an external voltage across the diode in the reverse bias direction, the depletion region gets bigger and no current flows.

This reverse bias region can be can be used as a heat or light sensor since the only current flow should be due to a few carriers produced by these effects.

The reverse biased diode can also be used as a voltage variable capacitor since it is essentially an insulator (the depletion region) sandwiched between two conducting regions.

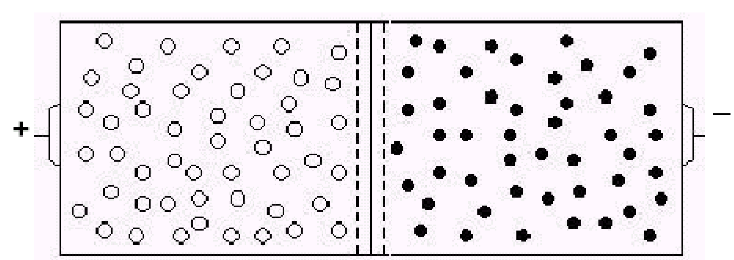
"positive" holes move toward the negative voltage   negative electrons move toward the positive voltage



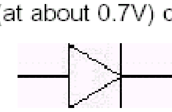
With reverse bias the depletion region gets bigger

Forward bias

If you place an external voltage across the diode in the forward bias direction, the depletion region shrinks until your external voltage reaches about 0.7V. After that the diode conducts freely..



With forward bias the depletion region gets smaller and eventually (at about 0.7V) conducts freely.



Diode