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Advice:

Get papers back from TAs.

'Best' labs posted across hall from 111 labs in glass case each week. No labs accepted after solution posted. Anyone objecting to having their labs posted – let me know via email.

Today:	lec 4	Diodes	
	lec 5	TH	Feb 1
	lec 6	TH	Feb 8
	lec 7	TH	Feb 15

Utility of following discussion:

Complaints about not enough solid state detail ⇒ small signal models not well motivated.
I will give some detail, but you promise to remember:

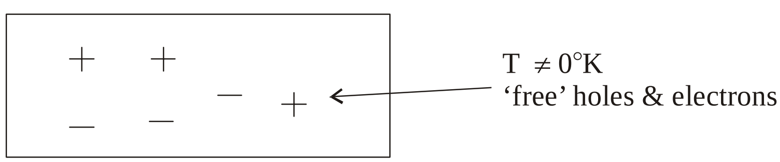
good design ⇒ circuit NOT sensitive to details of device parameters

Instruments & Devices:

Semiconductor Diode

Pure semiconductor: covalent bonds, (all 4 valence electrons used), 1.1 eV band gap (silicon)

⇒ thermal excitations important



$\approx 10^{10}$ carriers/cm^3 for Si @ 300°K ($\sim 10^{23}$ for metal)
⇒ semiconductor

Doping

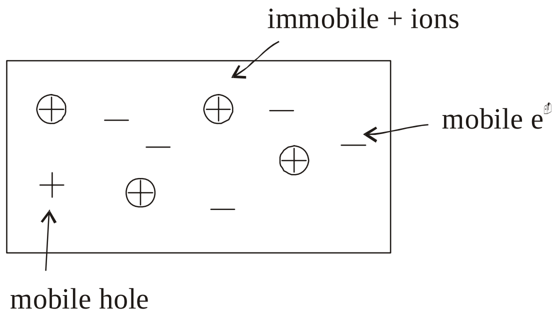
Add impurities to control the e-hole balance.

5 valence electrons ⇒ extra electron gets loose (donor)
3 valence electrons ⇒ extra hole gets loose (acceptor)

- Donor – phosphorus, arsenic, antimony
  electrons majority carrier, holes minority carrier ≡ n-type

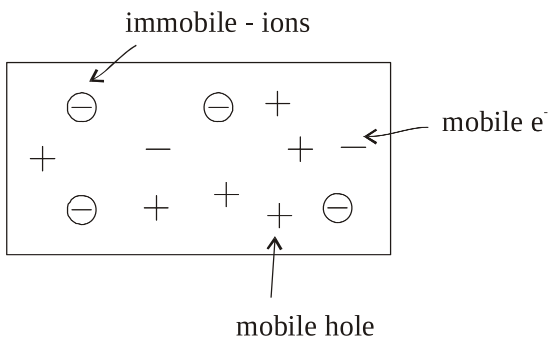
- Acceptor – boron, gallium, aluminum, indium
  holes majority carrier, electrons minority carrier ≡ p-type

N-TYPE



net charge = 0

P-TYPE

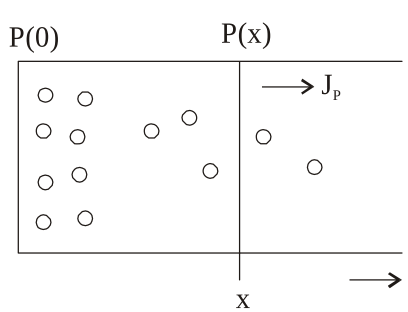


10^{15} carriers ⇒ ≈ 10^{15} donor atoms/cm^3
Si has ~ 5 x 10^{22} atoms/cm^3 ⇒ 1 impurity/50 x 10^6 Si
20 μg of phosphorus/kg SI ⇒ extreme care in manufacture

Application of a voltage causes a drift of charge, carried by both holes & electrons. Total current is the sum of the 2 currents.
* As in a metal, but 2 carriers

Diffusion Current

Suppose concentration of holes varies with position:



⇒ ∃ concentration gradient dP/dx

Density of holes on one side of surface > on the other. Because of random thermal motion, they want to drift toward lower concentration region. This current is proportional to the concentration gradient:

$J_P = -qD_P \, {dP}/{dx}$ D_P = diffusion constant for holes

$\left({dP}/{dx} < 0,\ J_P > 0\ in + x\ direction \right)$

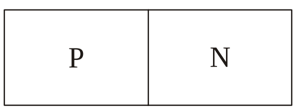
An electric field will be set up within the Si block to hold the equilibrium current to zero.
* Very different from metal

NB: Drift current density under influence of $\vec{E}$ given by $\vec{J}_{drift} = q\left(p\mu_p + n\mu_n\right)\vec{E}$

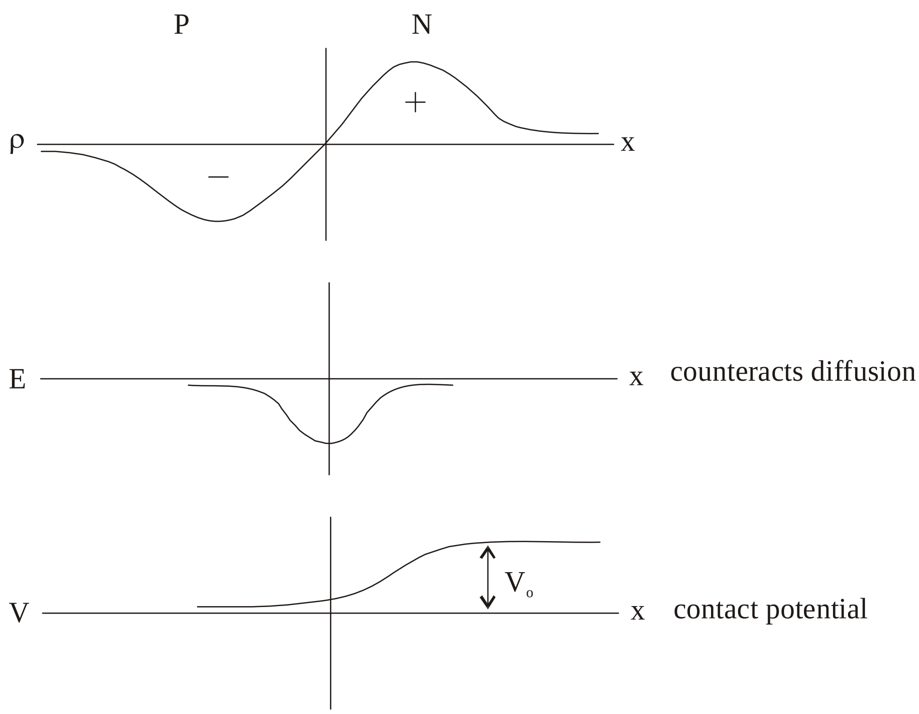
p/n = hole/electron density

μ_p/μ_n = hole/electron mobility

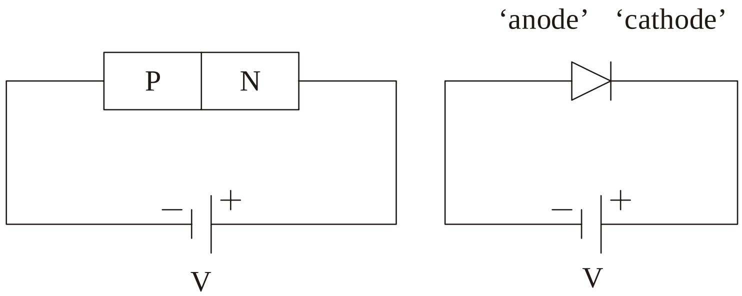
<u>P-N Junction</u>



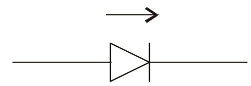
Electrons & holes diffuse both ways ⇒ depletion region (0.5 μm thick) is generated (or space charge layer)



Reverse Bias



N - electrons carry current
P - holes carry current



direction of current -
easy to remember

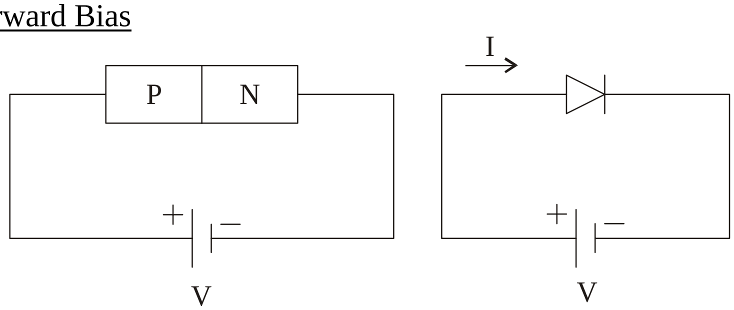
This polarity causes holes & electrons to move away from the junction.

≈ 0 current (some current because thermal e-hole generation. Holes anywhere on n side drift to gap & are then pulled by the field).

= reverse saturation current ≡ I_S (≈ independent of V, depends on T)

(N.B. Addition of minority carriers (T, …) inferences this i_{sat} – important for transistor operation)

Forward Bias



Now current flows -
sum of electron & hole current.

Contacts metal – semiconductors are ohmic, voltage drop across crystal (ideally) 0, then applied V appears to add to junction potential.

- Time varying signals: charge goes into/out of space charge layer ⇒ looks like a capacitance ≡ transition capacitance C_T, function of reverse voltage. (10 → 200 pF). Important for transistor operation
- Field is reduced in the space-charge layer, allows majority carriers to diffuse across the junction to the side where they are in the minority (injection of minority carriers).
- Time varying signals: diffusion, or storage capacitance C_D (more later). $C_D \gg C_T \sim 10\ \mu F$ (however, $rC_D = \tau \sim$ nsec, so time constant is small)

Diode behavior in both regions described by ('exponential diode')

$$I = I_S\left(e^{qV/kT} - 1\right)$$

$$q = electron\ charge$$

$$k = boltzmann's\ constant \quad 1.38\times10^{-23}\ J/°K$$

$$T = °K$$

$$kT/q = 26\,mV \ @\ 300K$$

$$V >> kT/q \Rightarrow neglect\ (1)$$

Forward bias $\Rightarrow\ I = I_S e^{qV/kT} >> I_S$

Reverse bias $\Rightarrow V << kT/q \Rightarrow i = -I_S$

Silicon: I_S ~ 10 pA

$$\ln\left(I/I_S\right) = \ln\left(e^{qV/kT} - 1\right)$$

$$\ln\left(I/I_S\right) \approx qV/kT$$

$$V = \frac{kT}{q}\ln\left(I/I_S\right) \quad \left(I_S \sim 10\,pA\right)$$

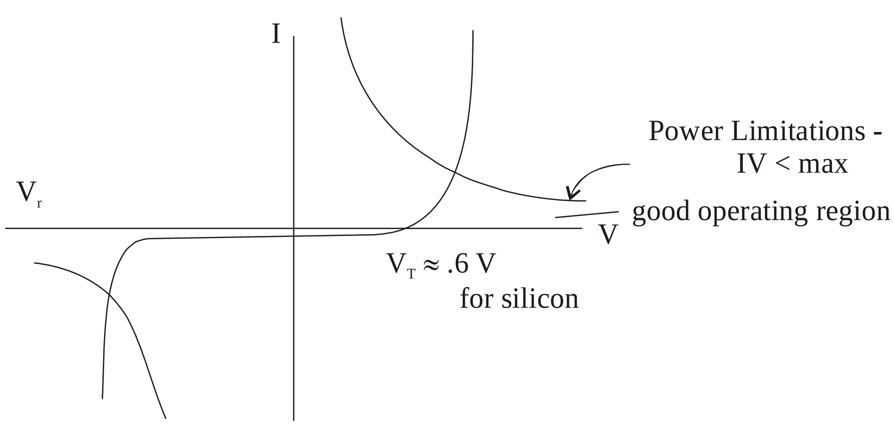
$$V\left(I = 20mA\right) \sim 26mV\ln\left(\frac{20mA}{10\,pA}\right)$$

$$\sim .56V \equiv V_T$$

on $\Rightarrow$ ~ 0.6V drop

off $\Rightarrow$open

Real Diode Characteristics:

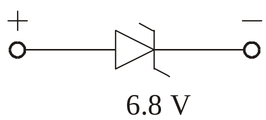


High forward currents: ohmic contacts take over & diode behaves as a resistor.

High reverse voltages: minority carriers gain sufficient speed to knock loose additional electrons (in deplection region where field is high) ⇒ larger reverse current – avalanche multiplication

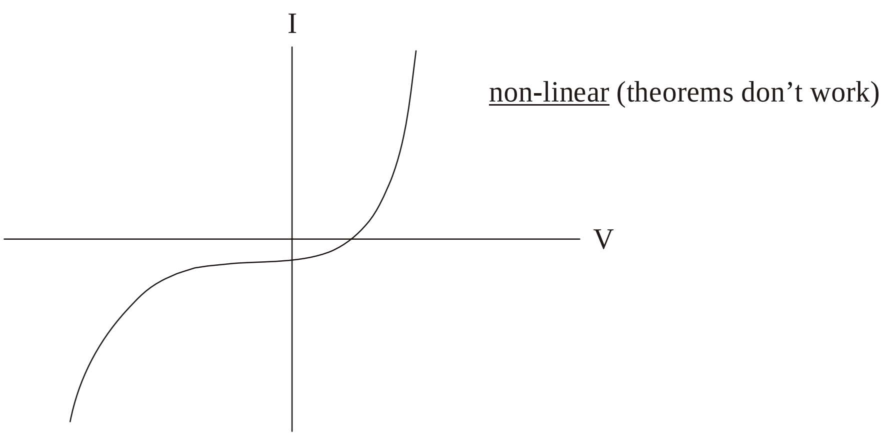
Maximum reverse voltage $V_R \equiv$ maximum reverse blocking voltage.

Zeners have a well controlled V_R (independent of *i*), can be used as a voltage references

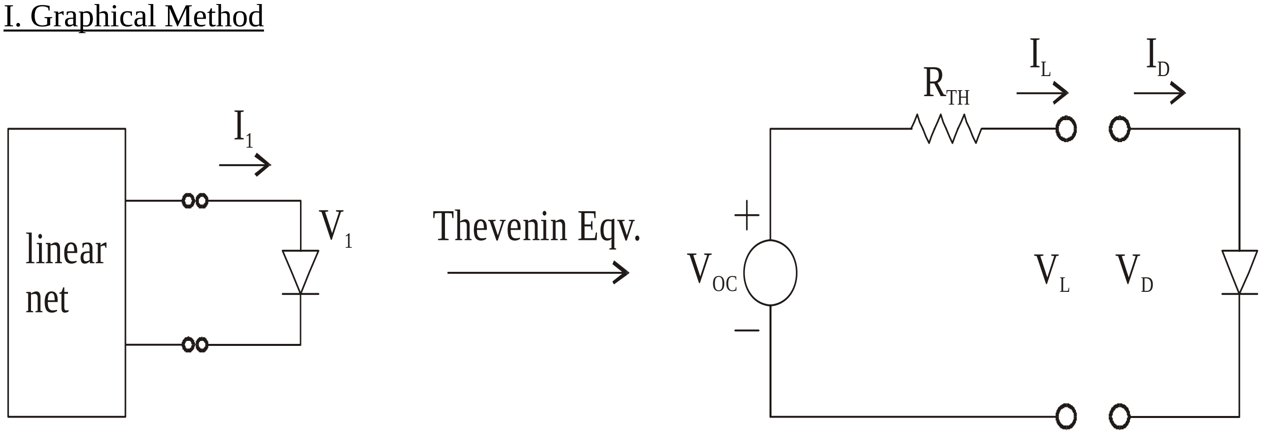


Instruments & Devices + Circuit Analyses

Diodes as Network Elements

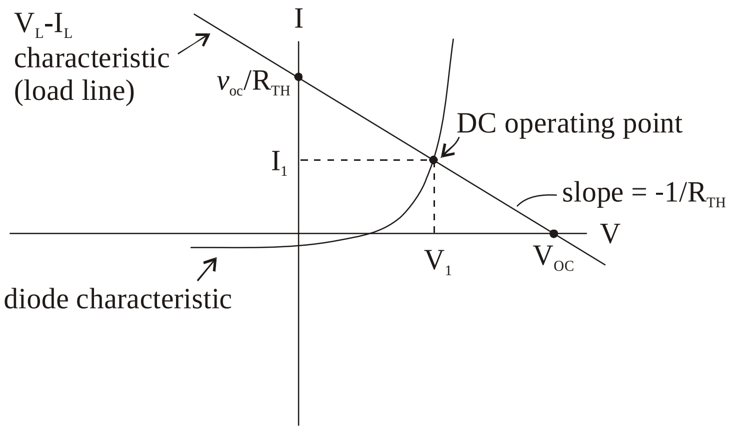


I. Graphical Method



If we can find I_1, V_1, we are done.
We know V_D vs. I_D from characteristic curve (manufacturer's or measured)
We know $V_L = V_{OC} - I_L R_{TH}$
Plot this on the *i*-*v* characteristic line.
2 points = open circuit voltage & short-circuit current

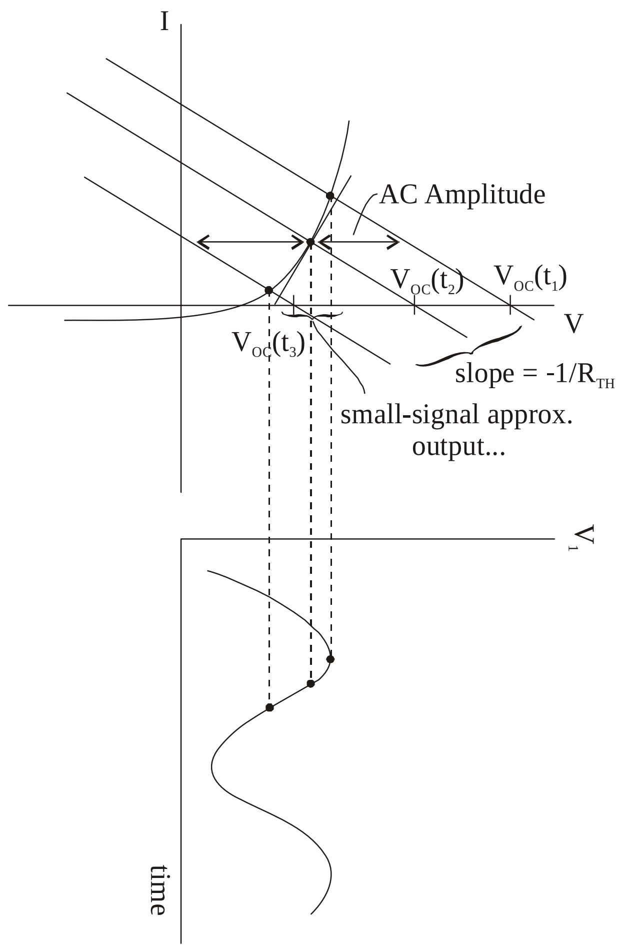
$$v_{oc},\ i_{sc} = v_{oc}/R_{TH}$$

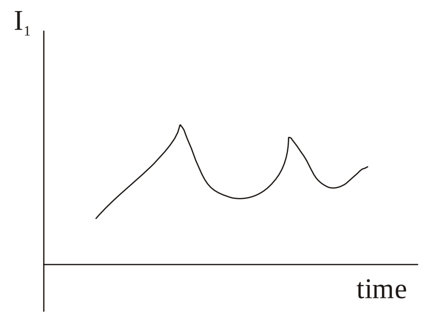


see example page 157 S&S

Source is time varying: (see page 164 S&S)
R_{TH} remains constant, V_{OC} varies

⇒ Load line has constant slope $\left(-1/R_{TH}\right)$, but the intercept (V_{OC}) moves as a function of time, so the operating point moves:



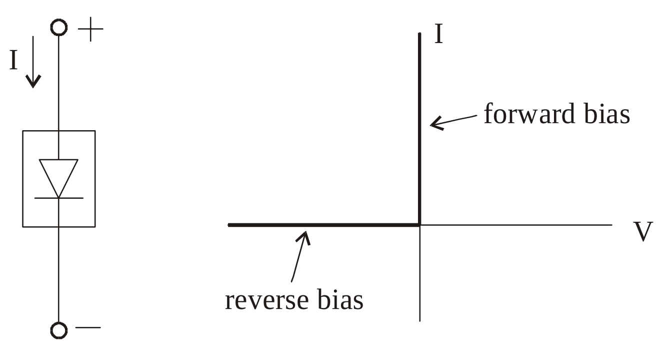


Small Signal Approx:

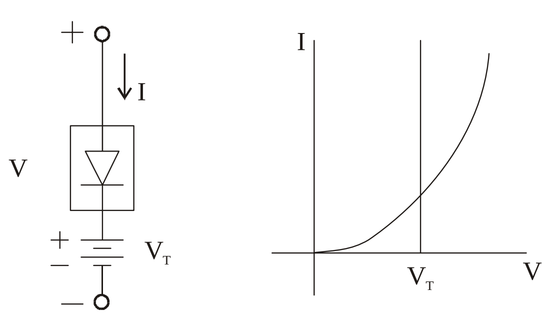
Taylor expand about some operating point ⇒ use tangents to curve at that point to describe the behavior.
⇒
rescue linear circuit laws by <u>linearizing</u>.

<u>II. Linearize</u> (the behavior for small deviations about the operating point.)
⇒ taylor expand, keep 1^{st} term. N.B. doesn't work over whole range!
Approximate diode behavior with linear elements over limited *i*-*v* range.

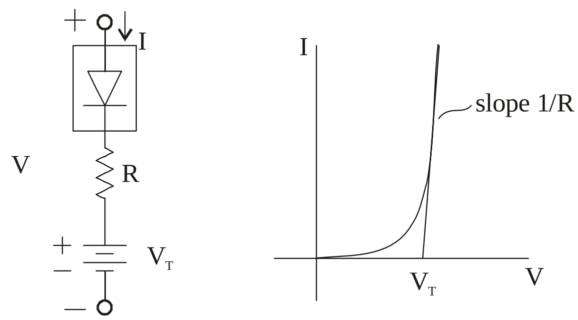
Ideal diode: (switch)



If voltages not large compared to .6 V, then:



OR



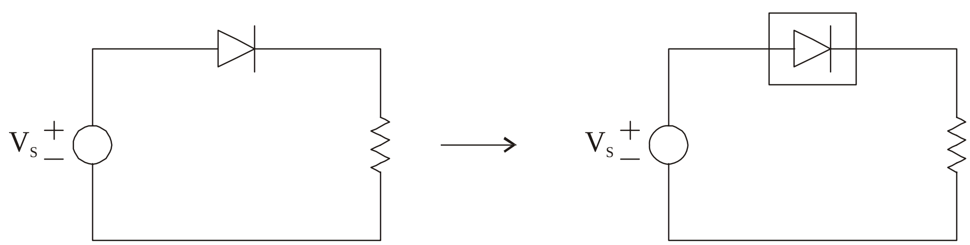
Reverse current zero usually ok.

Use simplest model to meet your needs!

Circuit Analyses

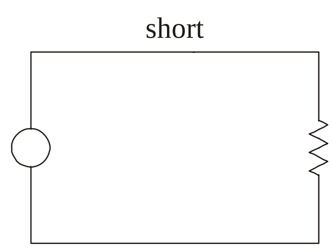
<u>Examples:</u>

<u>Rectification</u>:

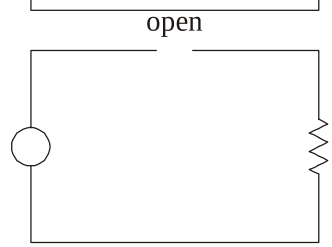


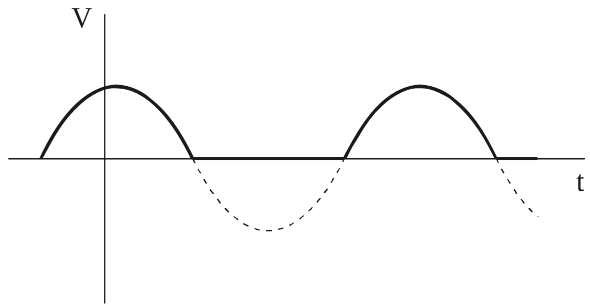
$V_S \gg V_T$ (.6V) $\Rightarrow$

$V_S > 0$



$V_S < 0$

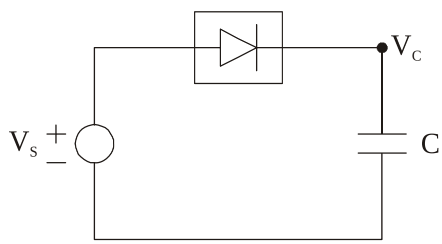


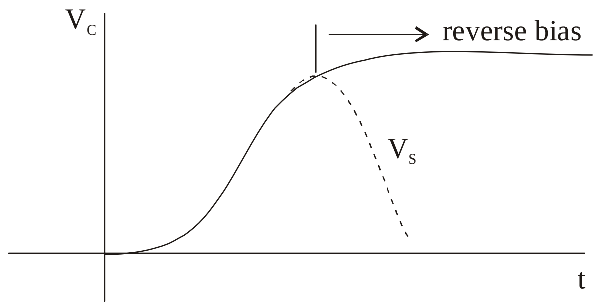


rectifier

Another example: matched pairs pg. 49 H&H

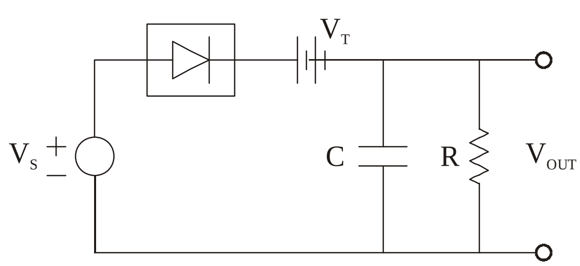
Peak Sampler

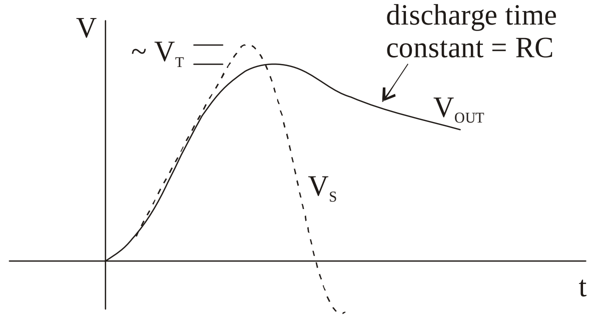




- V_S gives positive, diode a short.
- Past V_S max, diode is reverse biased & we are stuck.

More realistic:





Amount that it drops depends on frequency of V_S & RC time constant (NB – RC comes from step response).

LEDs

Same as ordinary diodes, but forward voltage drop in range 1.5 – 2.5 V,
5 – 20 mA of current causes light to be emitted. (electron-hole recombination)
Inverse also works – reverse-biased diode can be light-sensitive (photodiode). Important for 'electric eyes'. Also, basis for light & particle detection - liberate e-h pairs within depletion region.

Summary

Reverse bias = open
Forward bias = closed
(>0.6V) = .6V drop = good diode model for most uses