ESC201T : Introduction to Electronics

Lecture 19: Semiconductors

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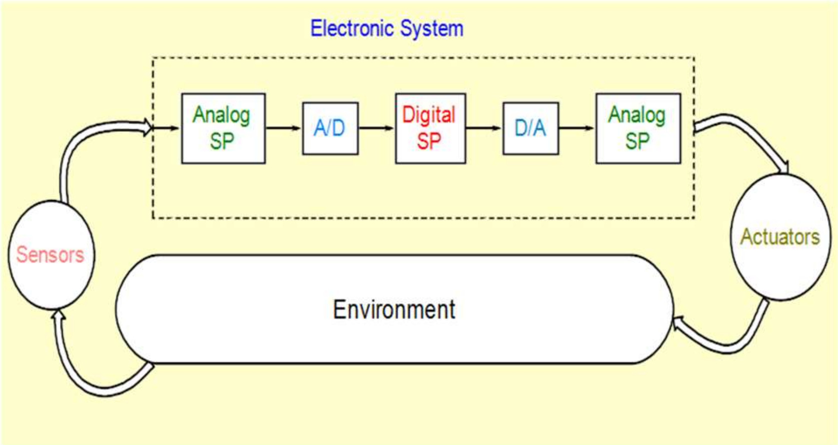
Course Objective : Learn how electronics enables use of electricity to solve problems



Learn how analog and digital circuits work

Learn by analyzing and designing analog and digital circuits

Tools for circuit Analysis

- ❑ Fundamentals of electrical circuits--3
- ❑ Transient Analysis of RLC Circuits--2
- ❑ Sinusoidal Steady State Analysis--4

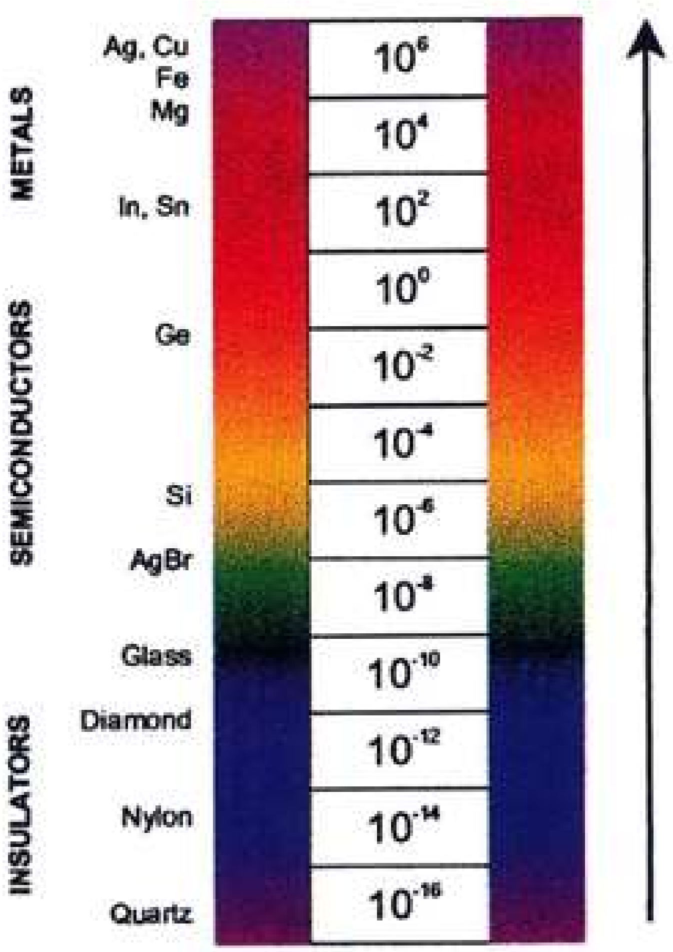
Analog Circuits

- ❑ Semiconductors, Diodes, Circuits-----3
- ❑ Transistors and Amplifiers---4
- ❑ Operational Amplifier based Analog circuits -4

Digital Circuits

- ❑ Logic gates, Combinational circuits ---4
- ❑ Flip-flops, Sequential Circuit---4
- ❑ Data Converters----3

Semiconductor



semiconductor

Conductivity (S/cm)

$Resistivity\ (\Omega cm)$

“Any sufficiently advanced technology is indistinguishable from Magic”

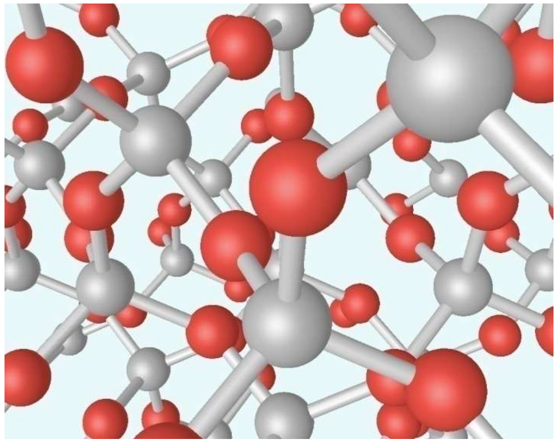
(“Profiles of the Future: An Inquiry into the Limits of the Possible”, by Arthur C. Clarke)

Semiconductors have allowed us to perform magic

Sand

Quartz

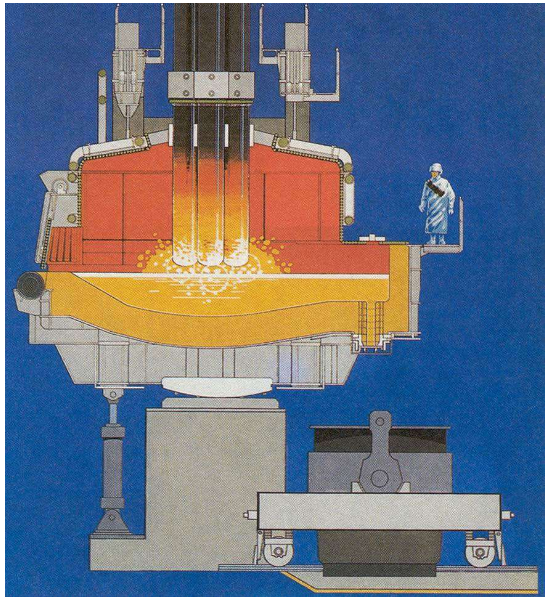
SiO_2



Quartzite

Metallurgical Grade Silicon (95-98% pure)

$SiO_2 + C \rightarrow CO_2 + Si$



About 60 000 tons of quartzite (about 45 per cent silicon) and 25 000 tons of charcoal (made from 90 000 tons of timber) are required to produce the 28 000 tons of silicon. About 13 megawatt hours of electricity to produce one ton of silicon. At the industry standard of A$0.06 per kWh, electricity represents around 40 per cent of the market value of silicon

Metallurgical grade Silicon

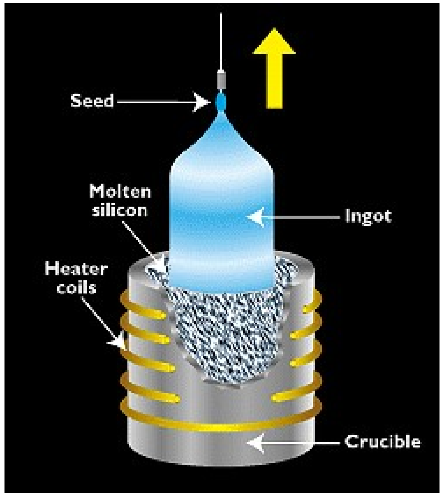
$\downarrow$ $Si + 3\,HCl \rightarrow SiHCl_3 + H_2$

Trichlorosilane

$\downarrow$ Vapor deposition

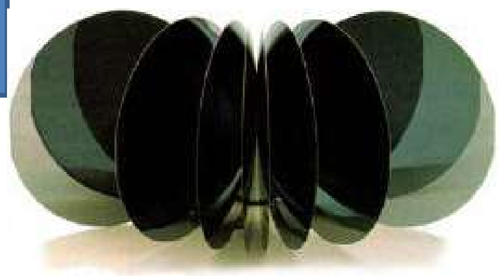
Electronic Grade Polysilicon

Electronic Grade Poly-Silicon



Pure Silicon Crystal

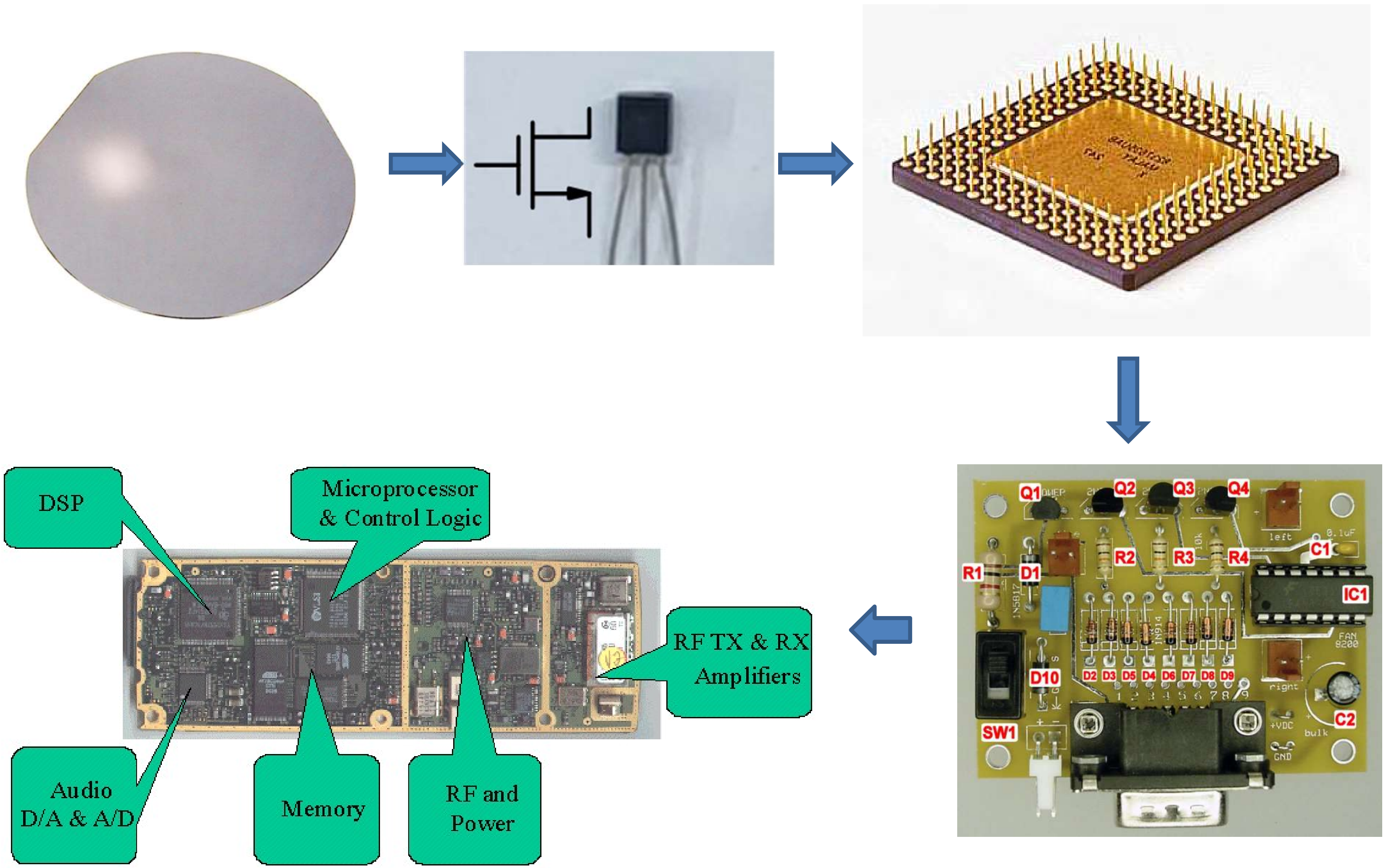
Silicon Wafer



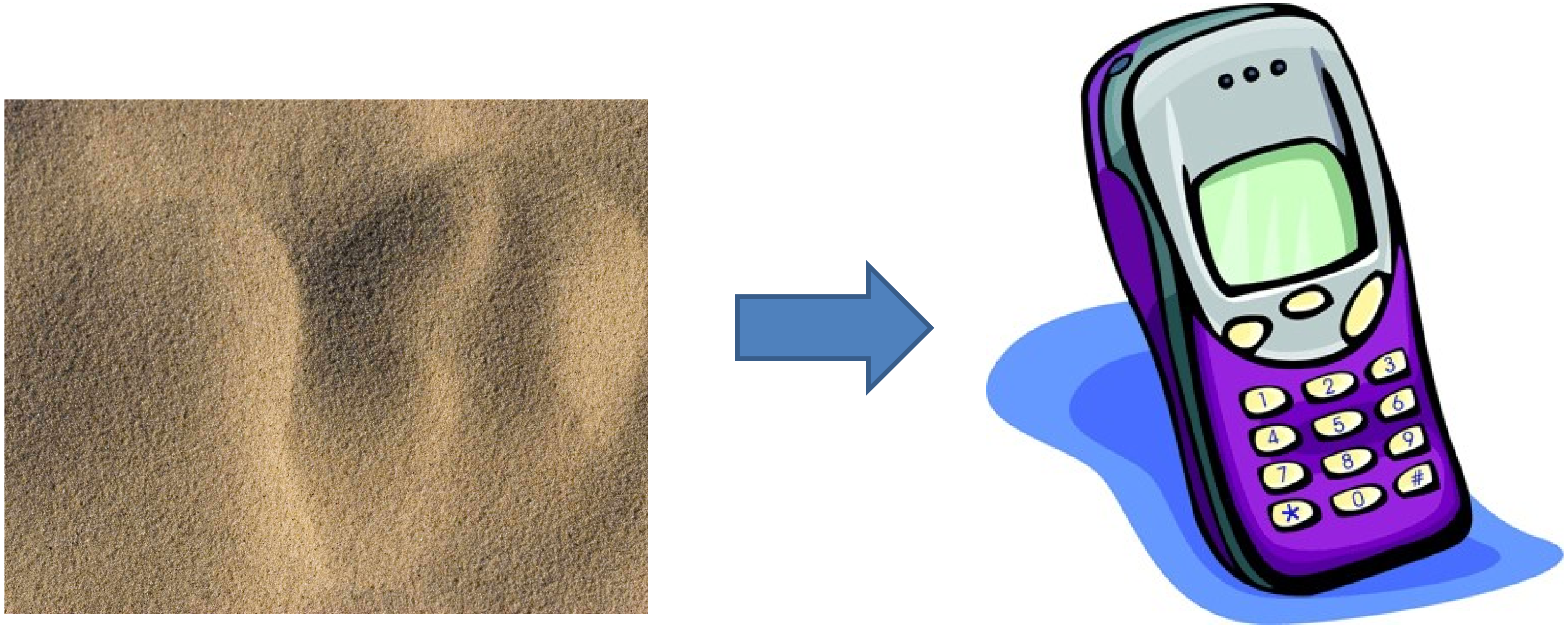
~400um thick

$1400/Kg !!

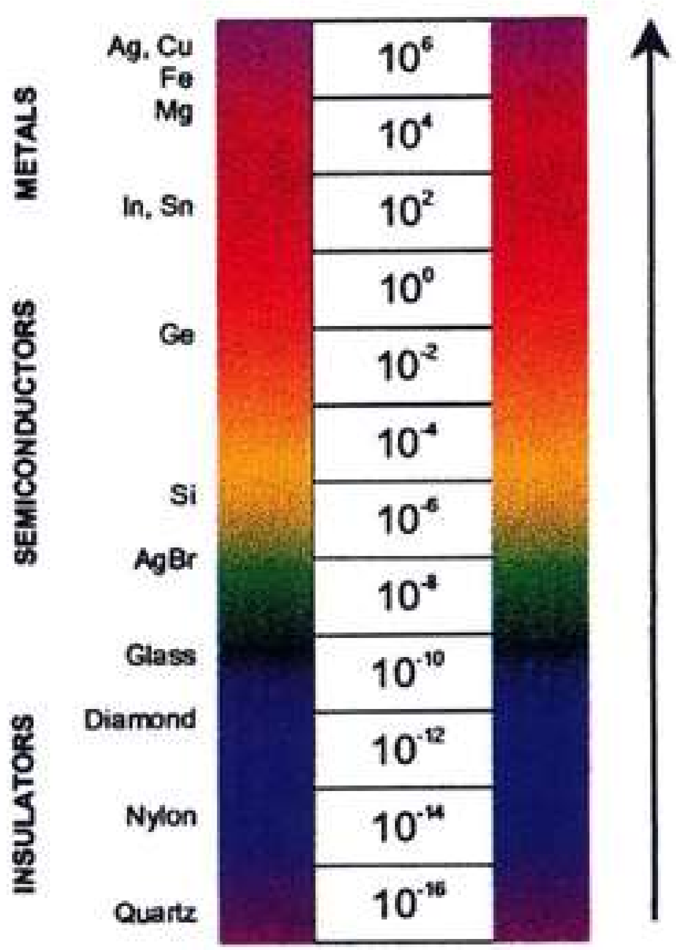
A 200mm wafer cost $45 in 2006


Q1
Q2
Q3
Q4
R1
D1
R2
R3
R4
C1
IC1
D10
D2 D3 D5 D4 D6 D7 D8 D9
SW1
C2
DSP
Microprocessor
& Control Logic
RF TX & RX
Amplifiers
Audio
D/A & A/D
Memory
RF and
Power

Electronics Revolution



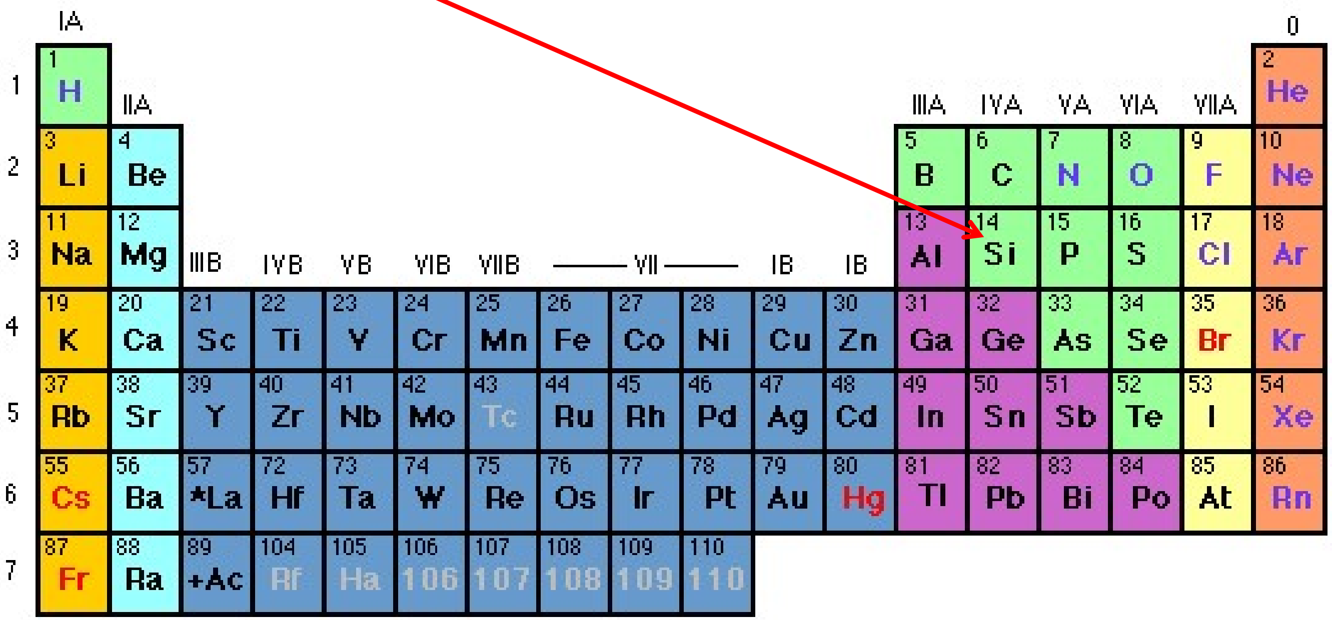
Silicon is a semiconductor



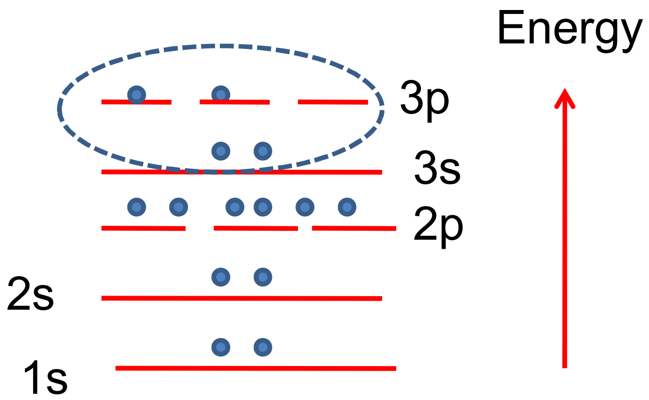
Conductivity (S/cm)

- ❑ More importantly, its conductivity can be altered and controlled
- ❑ It allows us to **control** current !

Silicon

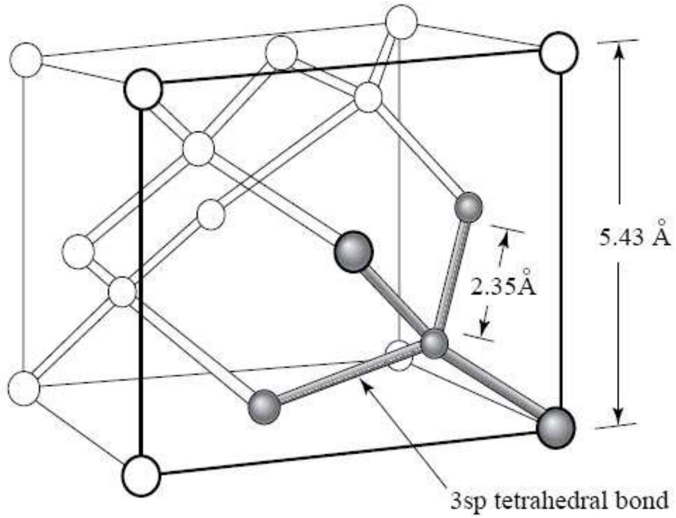


Electronic structure $1s^2 2s^2 2p^6 3s^2 3p^2$



4 outer shell electrons from 4 covalent bonds

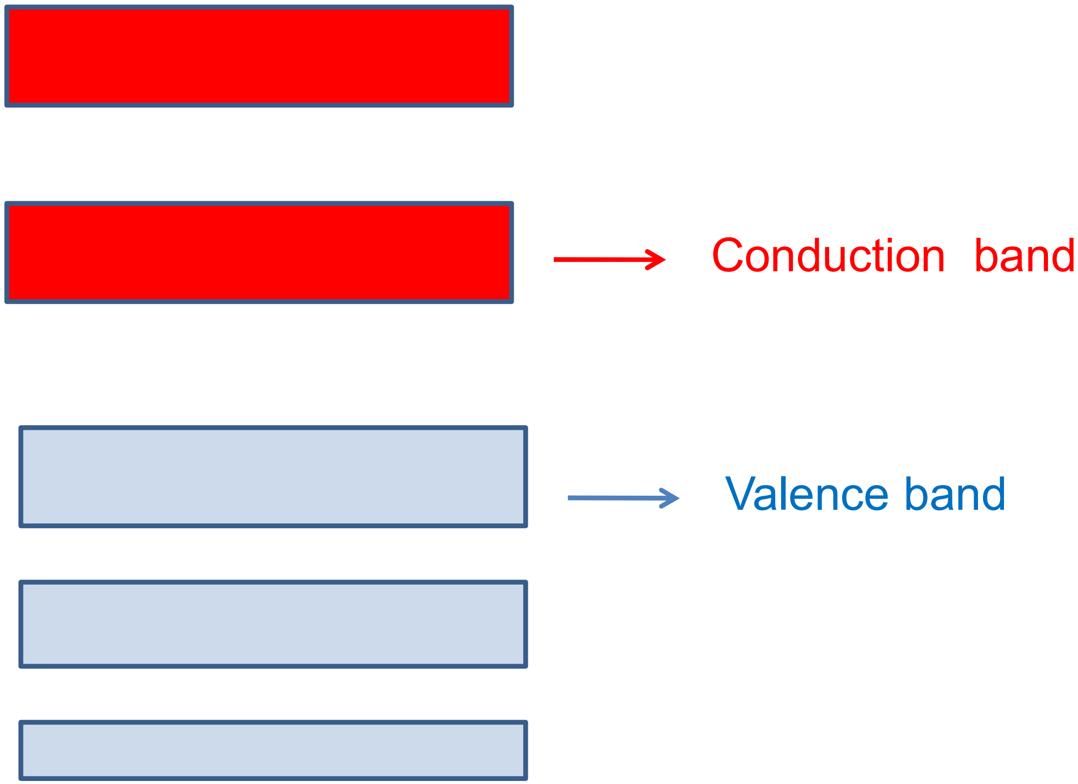
Silicon Crystal



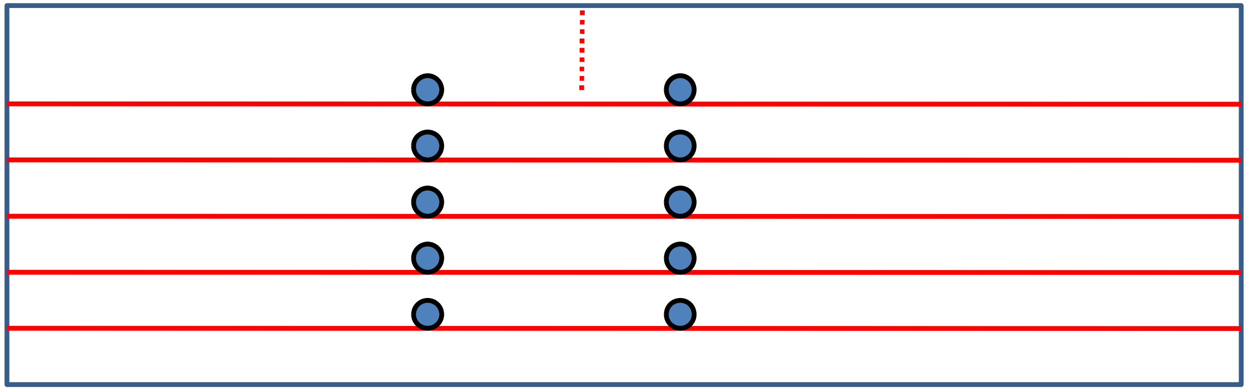
Electrons in a silicon crystal occupy bands of energies

Bottom most empty band is called conduction band

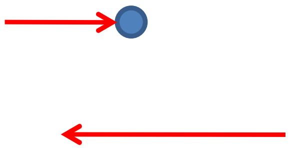
Top most filled band is called valence band



Electrons in a completely full band cannot contribute to current conduction !



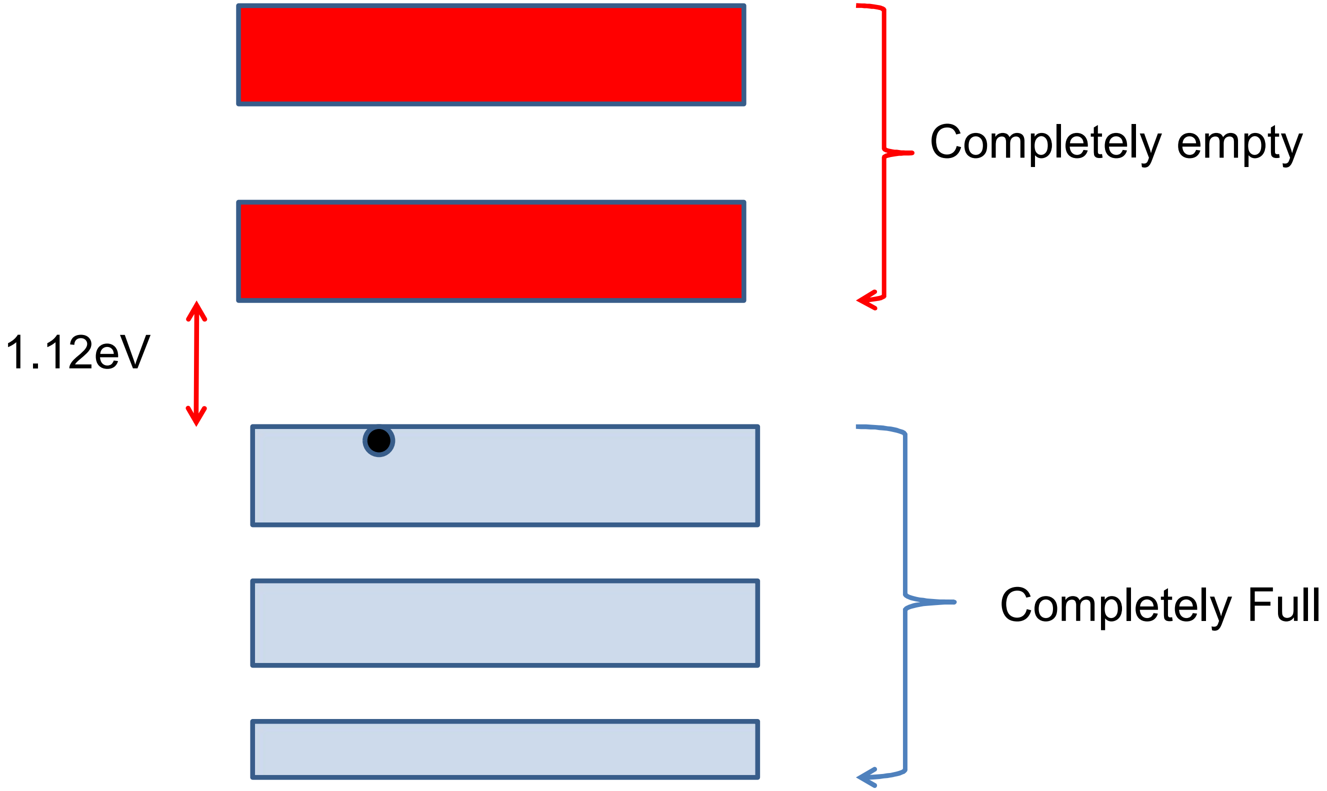
F = qE



E

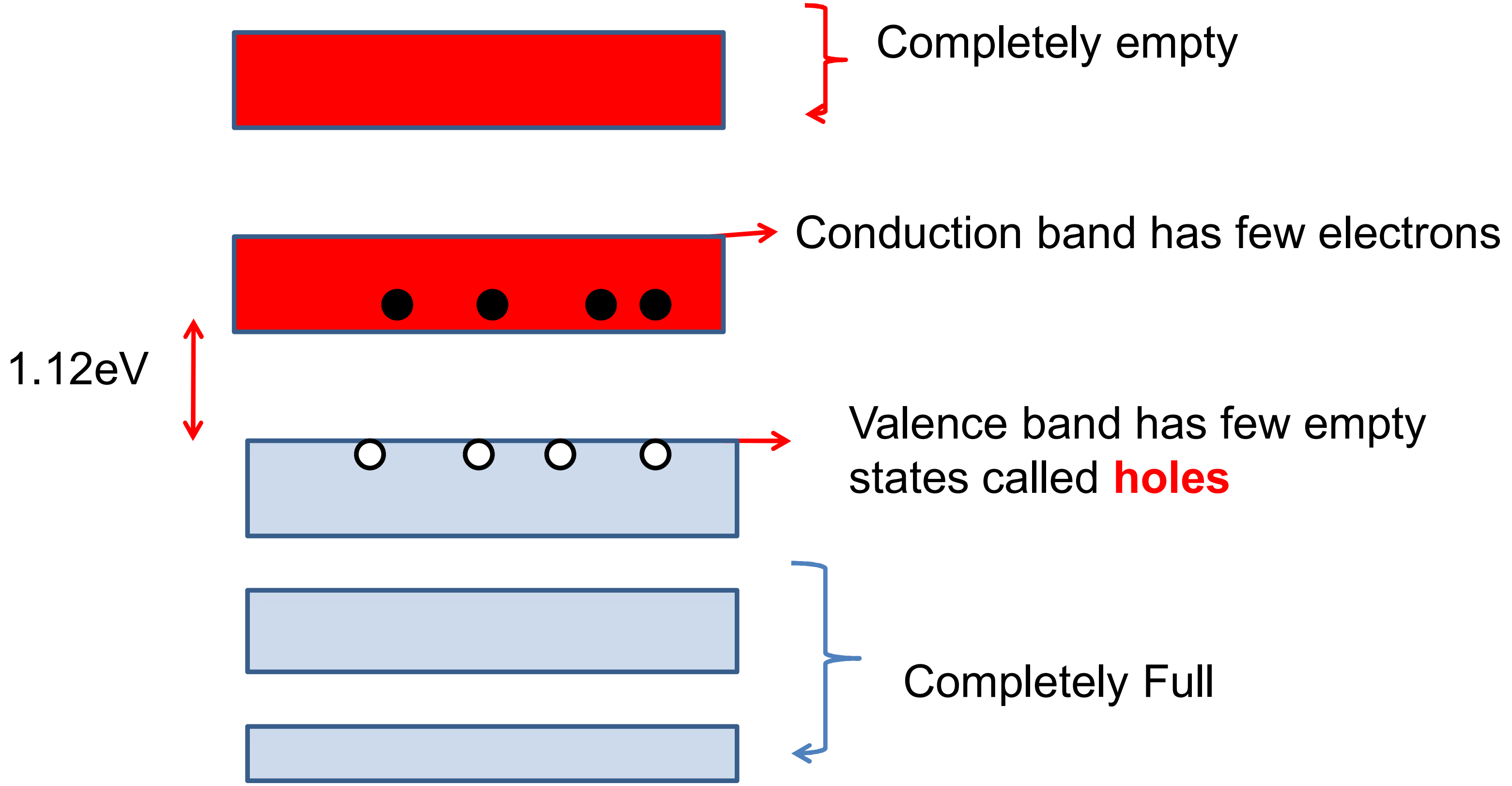
Energy of the electron should increase but all the higher energy states are occupied !

Picture of Silicon Crystal at 0^oK



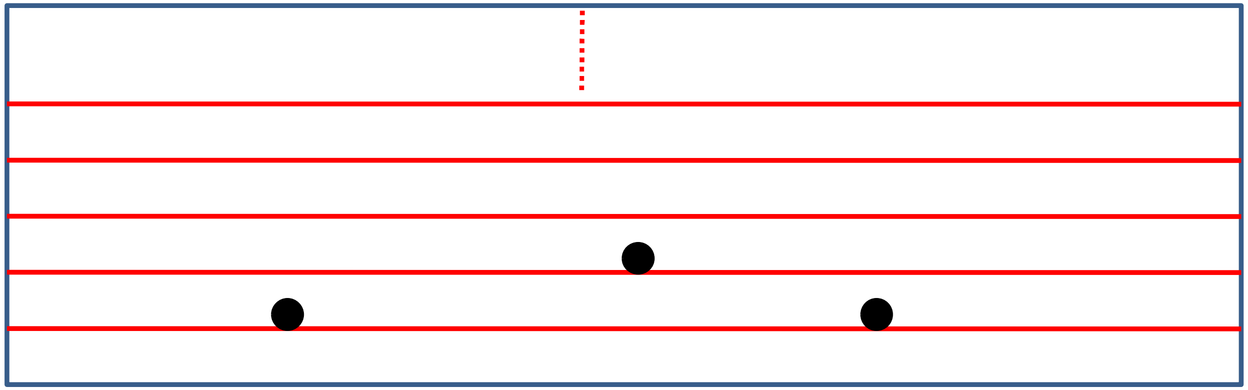
No current flows and Silicon acts like a perfect Insulator !

Picture of Silicon Crystal at 300°K



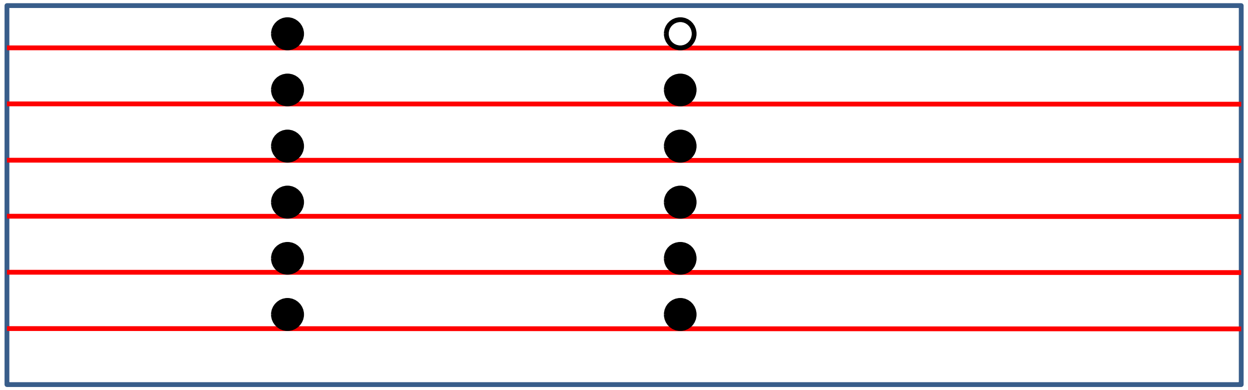
Electrons in conduction and valence band can now contribute to current flow

Conduction Band



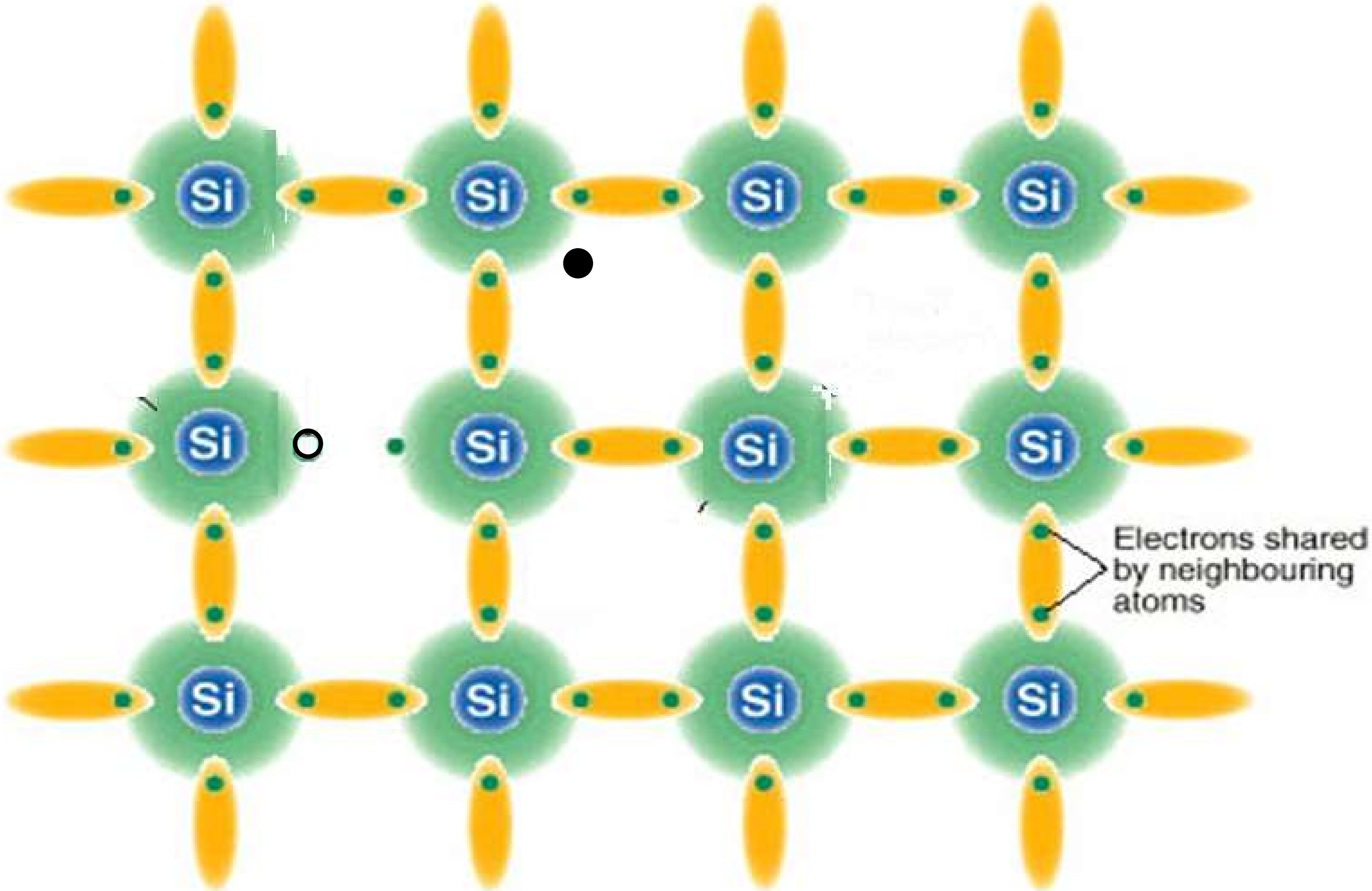
Conduction band electrons are free to move in whatever direction they wish

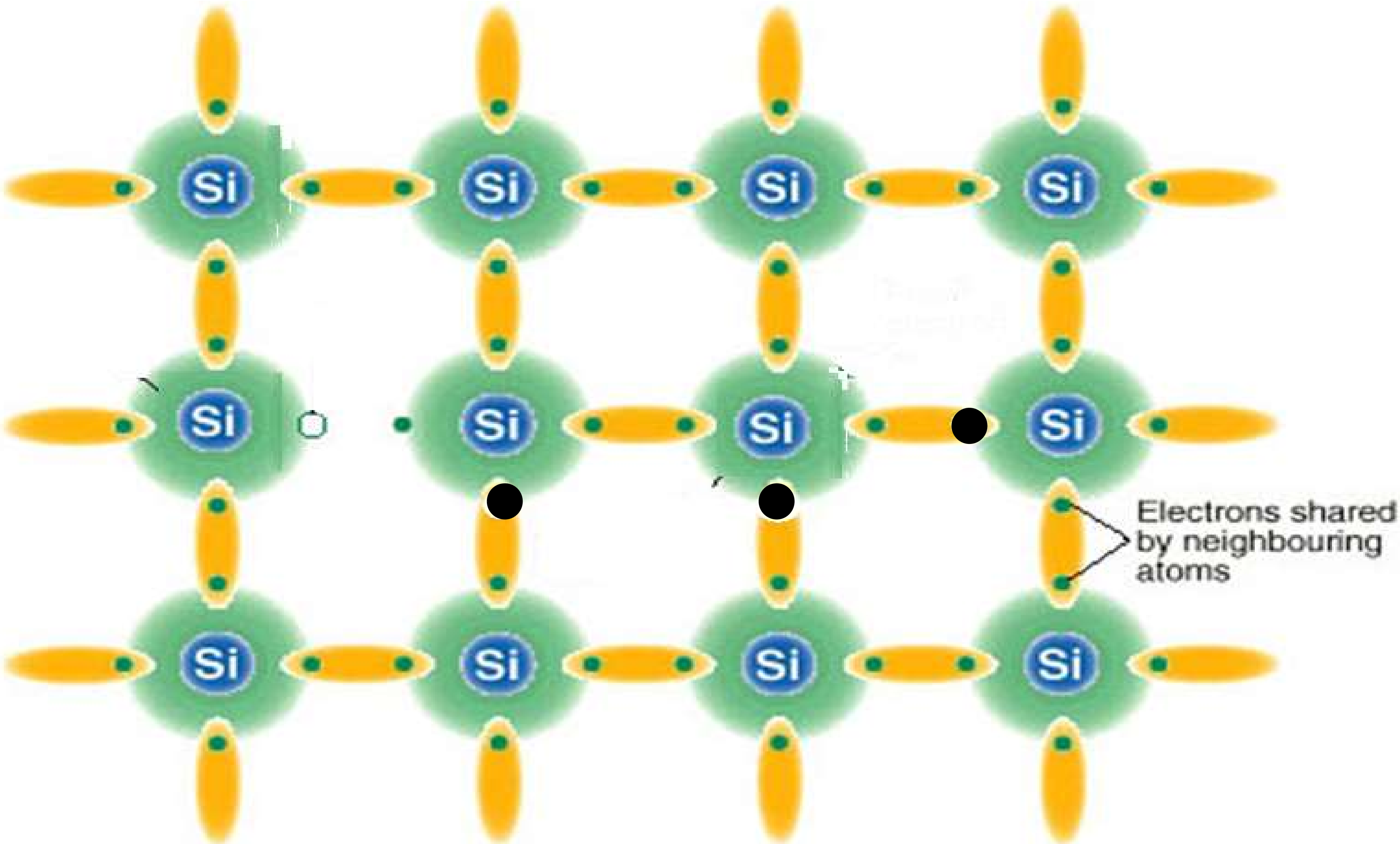
Valence Band



Electrons can now flow and contribute to current conduction

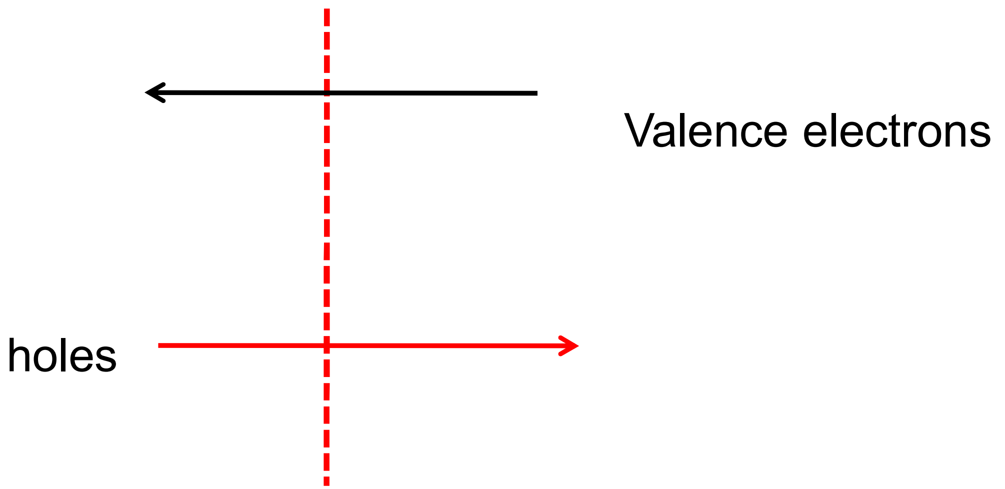
Simplified Picture




Si
Electrons shared
by neighbouring
atoms

The motion of valence band electrons is equivalent to motion of vacant states called holes

Suppose an n_v number of net valence band electrons cross the area from right to left in time t, then



$$I = -\frac{-q \times n_v}{t} = \frac{q \times n_v}{t}$$

It also means p = n_v number of holes cross from left to right in time t.

$$I = \frac{q \times n_v}{t} = +\frac{+q \times p}{t}$$

Current carried by electrons in valence band is equal to current carried by holes if we associate positive charge with them.

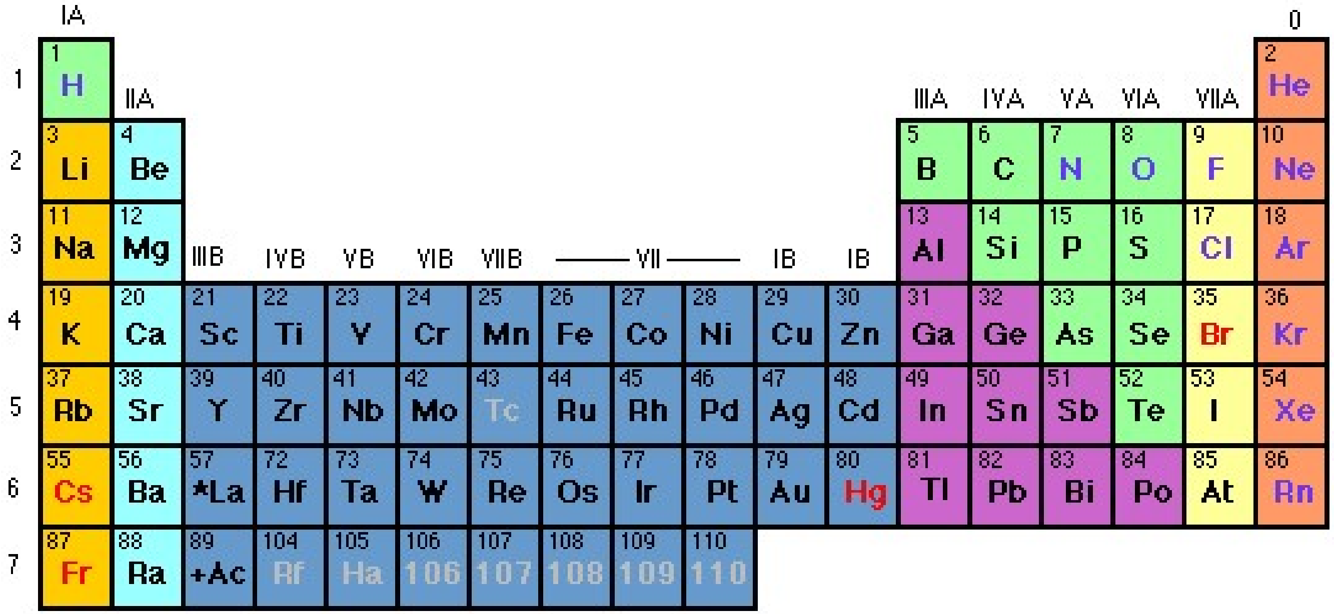
For the purpose of current flow and electronics in general, we can ignore the electrons in valence band and think only in terms of holes.

We should think of holes as particles carrying a positive charge of $+1.6 \times 10^{-19}$ C and moving in presence of electric field as electrons

To summarize, current in semiconductors is carried by electrons in conduction band and holes in valence band.

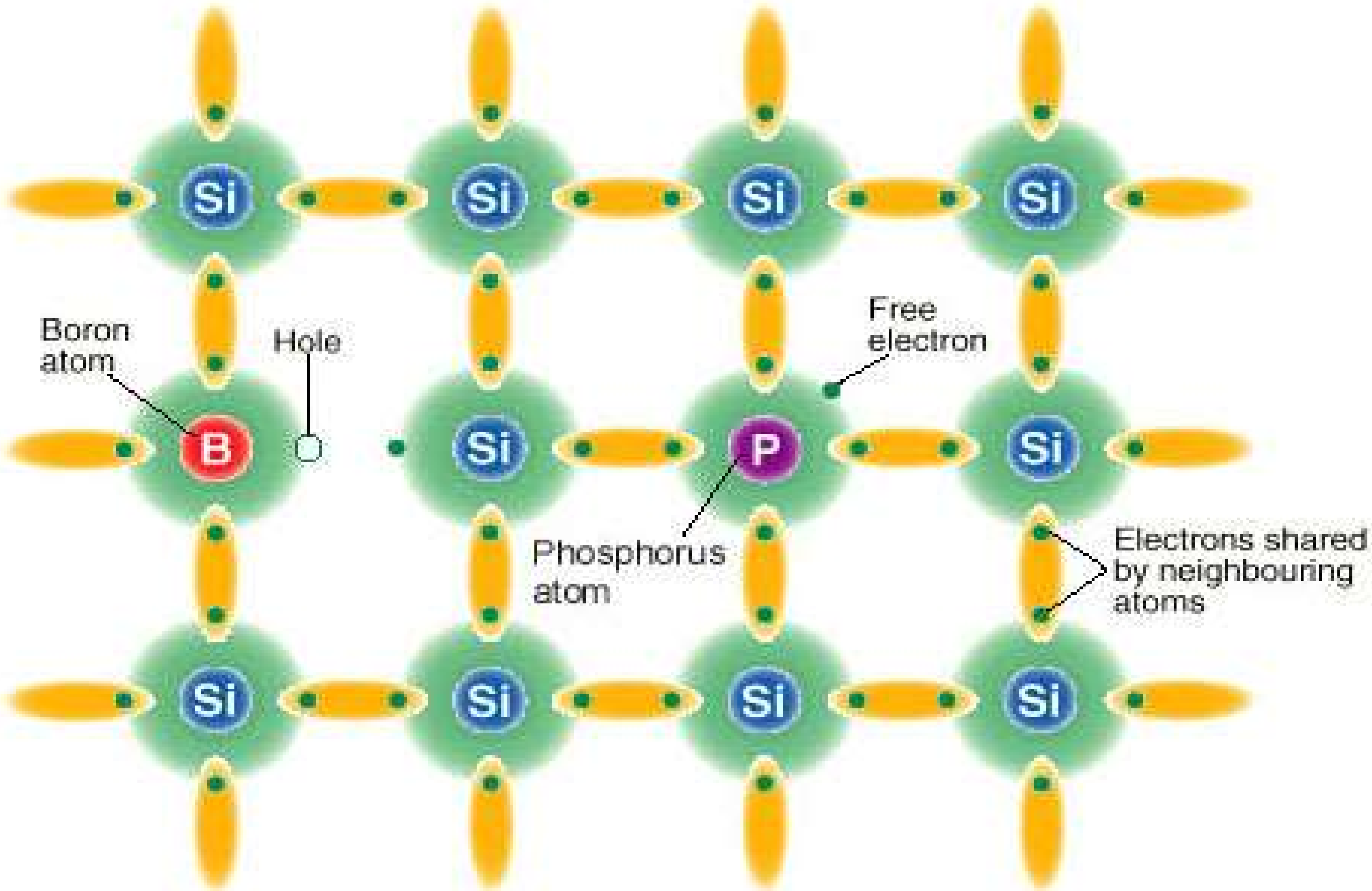
Extrinsic Semiconductors

Adding small amounts of suitable impurity atom can drastically alter number of electrons and holes in a semiconductor !



Addition of a group V element impurity to Silicon should increase electrons while addition of group III element impurity should increase number of holes

Doping



Si
Si
Si
Si
Boron
atom
Hole
Free
electron
B
Si
P
Si
Phosphorus
atom
Electrons shared
by neighbouring
atoms
Si
Si
Si
Si

N and P-type Semiconductors

N-type : n > p

A Semiconductor such as Silicon doped with a donor impurity such as Phosphorous or Arsenic from group V of periodic table. The donor impurity donates an electron to conduction band thereby increasing their concentration

P-type : p > n

A Semiconductor such as Silicon doped with a Acceptor impurity such as Boron from group III of periodic table. The acceptor impurity increases number of holes in valence band.

No. of silicon atoms per unit volume $\simeq 4 \times 10^{22} cm^{-3}$

Impurity concentration : $N_A = 10^{17} cm^{-3}$

1 in 400,000 Silicon atoms is replaced by Boron

Very small amounts of impurity atoms can cause a drastic change in electrical property of a semiconductor.

This is one of the reasons why even though sand is plentiful and ‘dirt cheap’, electronic grade silicon is so expensive

Silicon is one of the purest material on earth !

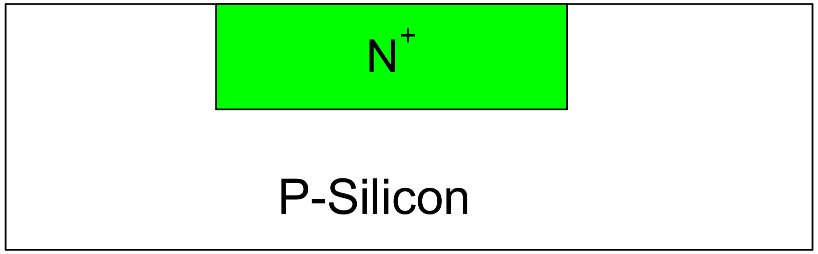
Clean Room

ISO 14644-1 cleanroom standards

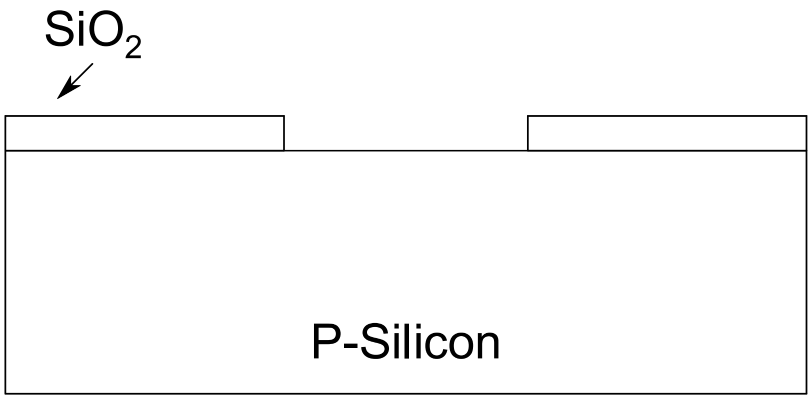
Class	maximum particles/m³						FED STD 209E equivalent
	≥0.1 μm	≥0.2 μm	≥0.3 μm	≥0.5 μm	≥1 μm	≥5 μm	
ISO 1	10	2					
ISO 2	100	24	10	4			
ISO 3	1,000	237	102	35	8		Class 1
ISO 4	10,000	2,370	1,020	352	83		Class 10
ISO 5	100,000	23,700	10,200	3,520	832	29	Class 100
ISO 6	1,000,000	237,000	102,000	35,200	8,320	293	Class 1000
ISO 7				352,000	83,200	2,930	Class 10,000
ISO 8				3,520,000	832,000	29,300	Class 100,000
ISO 9				35,200,000	8,320,000	293,000	Room air

$1\ m^3 = 35.2\ ft^3$

•Suppose we have a Silicon wafer which is P-type and we wish to create a region within it which is N-type as shown below:



•This can be done by carrying out **diffusion/implantation** of N-type dopant in the structure shown below.

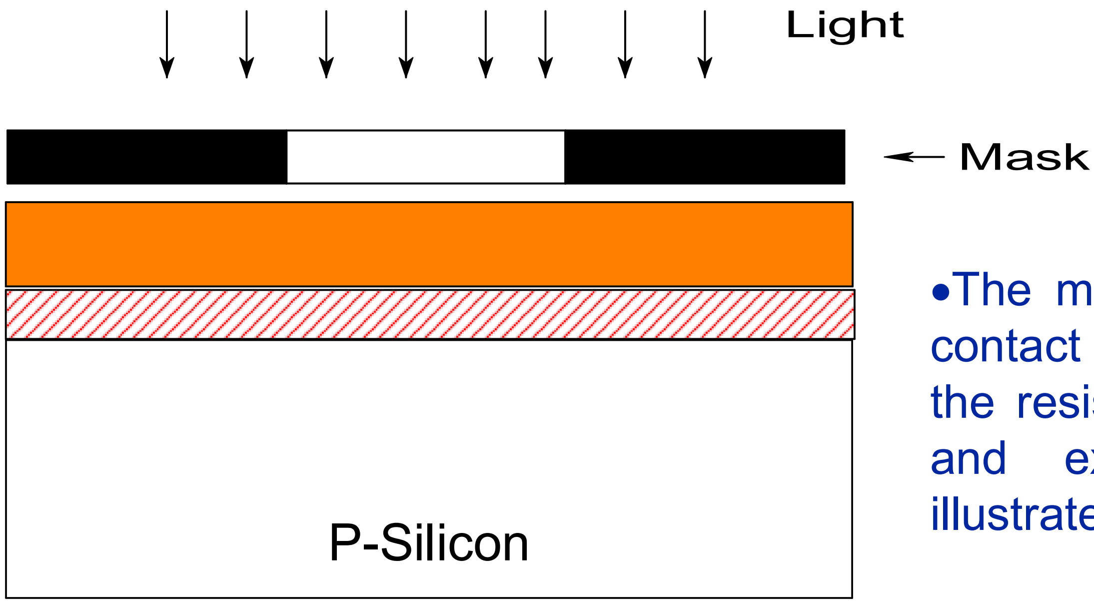


•The SiO_2 acts a as a barrier and prevents diffusion of dopants through it . As a result the N-type region is created only in the region where Silicon is exposed

•A window in SiO_2 can be created by first covering the whole Silicon surface with oxide through the **oxidation** process.

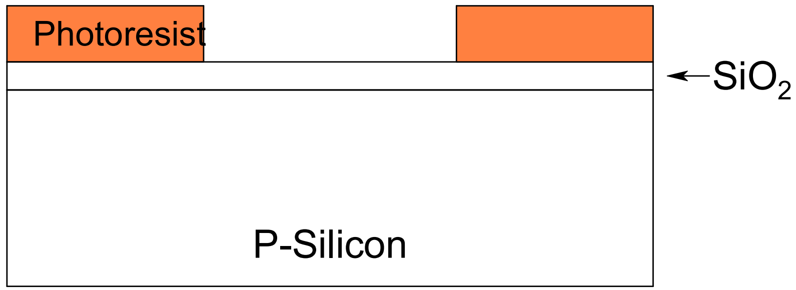
•Next the Silicon surface is coated with an organic material which is sensitive to light called **Photoresist**. A positive photoresist undergoes changes upon exposure which makes it easier to dissolve in a developer solution

•We next need a **Mask** which specifies the location and dimension of N-region. It is basically a glass plate which has opaque and transparent regions. Wherever we want the photoresist to remain, that region is opaque and wherever we wish to remove the photoresist that region is made transparent.

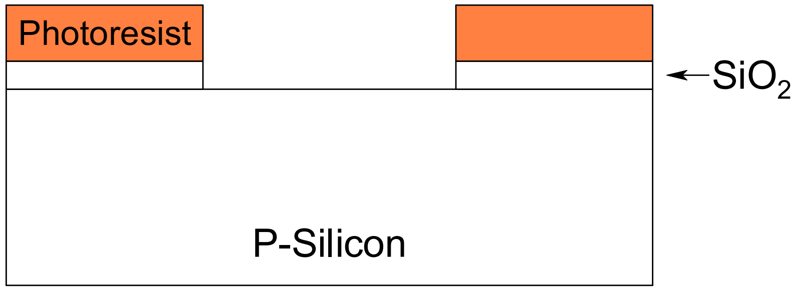


•The mask is placed either in contact or in close proximity to the resist coated Silicon wafer and exposed to light as illustrated below

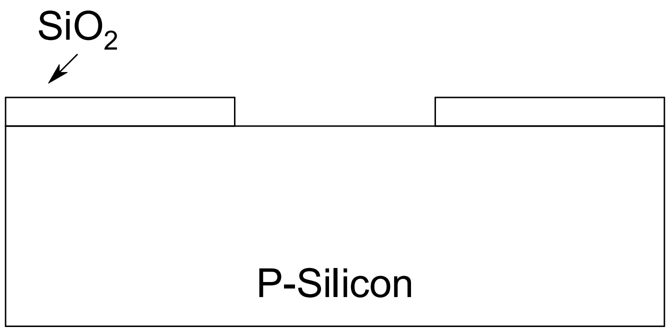
•After this step of **Photolithography** , the exposed photoresist is removed using a developer solution and we obtain the following structure:



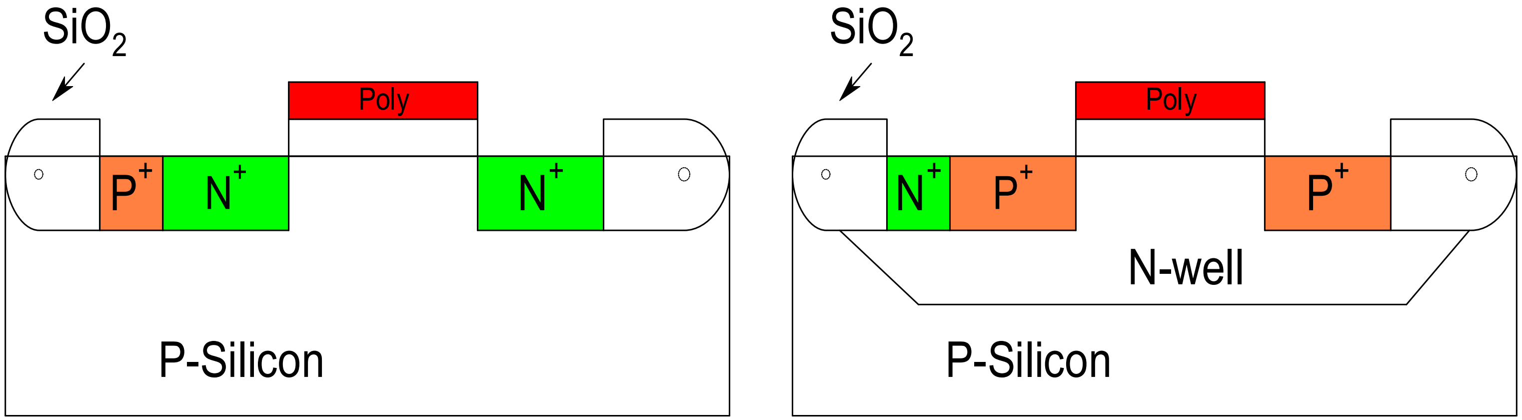
•Next the whole wafer is dipped in HF acid to **Etch** the exposed oxide to obtain the following structure:



•Next the photoresist is removed to obtain the structure required for carrying out diffusion.



Fabrication: simplified view



- Transfer of pattern from **mask to photoresist ----photolithography**

- Transfer of pattern from photoresist to silicon

- Various processing steps.

ESC201T : Introduction to Electronics

Lecture 20: Diodes

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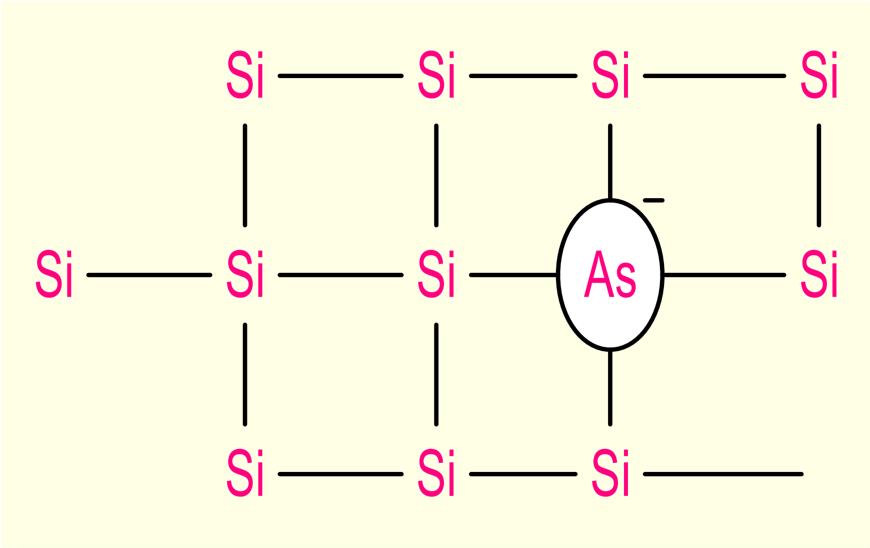
Doping

N-Type Semiconductor



$$N_D \longrightarrow N_D^{+} + e^{-}$$

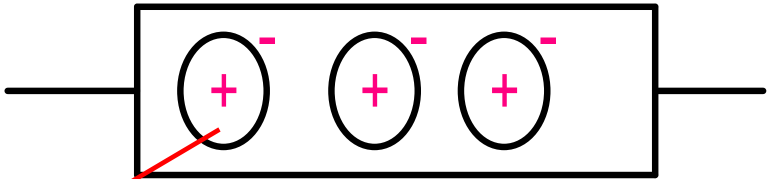
$$In\ equilibrium: \quad n \times p = n_i^2$$

$$n_i = 1.45 \times 10^{10}\mathrm{cm}^{-3} at T = 300°K$$

$$N_D = 10^{16}\mathrm{cm}^{-3}$$

$$n \approx N_D = 10^{16}\mathrm{cm}^{-3}$$

$$p = \frac{n_i^2}{n} = n_i^2/N_D \approx 2 \times 10^4\mathrm{cm}^{-3}$$



Positively charged donor atoms

$$n >> p$$

Small amount of impurity results in large change in resistivity !

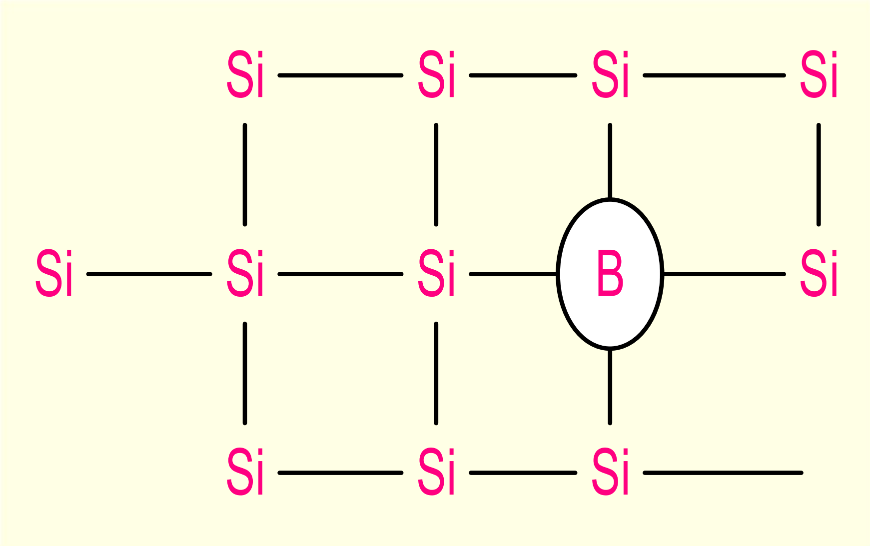
No. of Silicon atoms / volume = 5 x 10^{22} cm^{-3}

$$\frac{10^{16}}{5 \times 10^{22}} = 2 \times 10^{-7}$$ (0.2PPM)

$N_D = 10^{16}$ cm^{-3}

ρ : 2 x 10^5 Ω cm $\longrightarrow$ **1.5** Ω cm

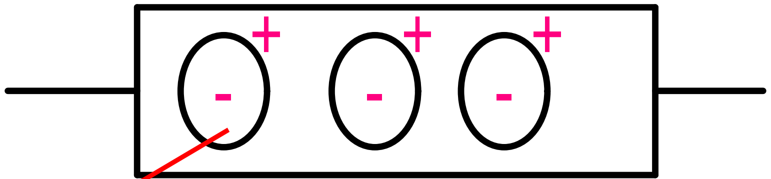
P-Type Semiconductor



$$N_A + e^- \longrightarrow N_A^- + h^+$$

$$N_A = 10^{16}\text{cm}^{-3}$$

$$\text{p} \approx N_A = 10^{16}\text{cm}^{-3}$$



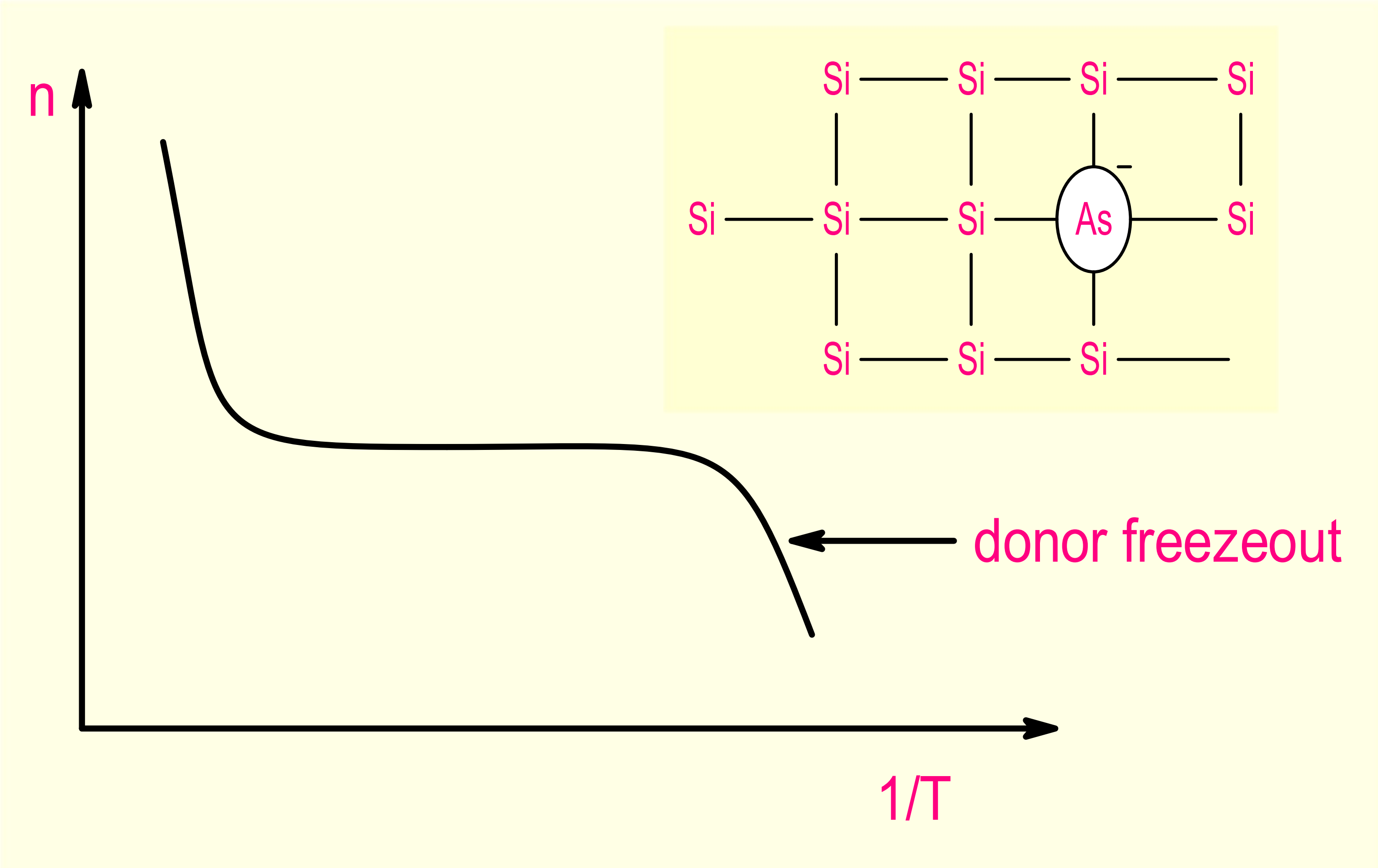
$$n = \frac{n_i^2}{p} = n_i^2/N_A = 2 \times 10^4\text{cm}^{-3}$$

Negatively charged acceptor atoms

$$p >> n$$

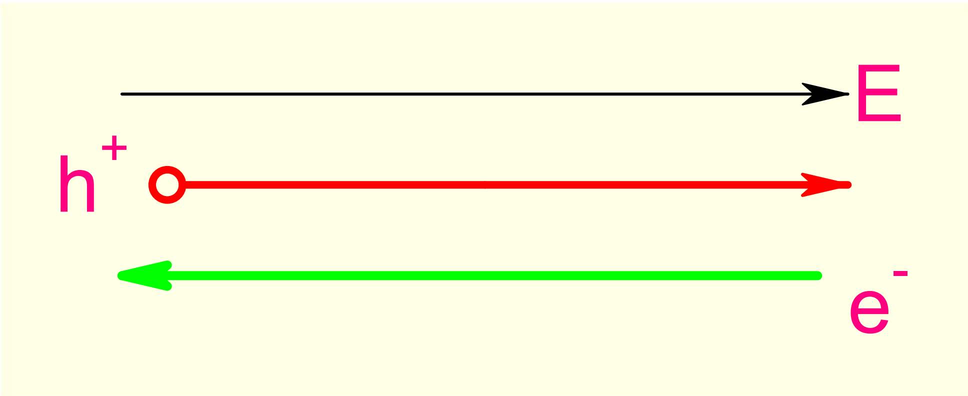
G-Number

Number of carriers is dependent on temperature !

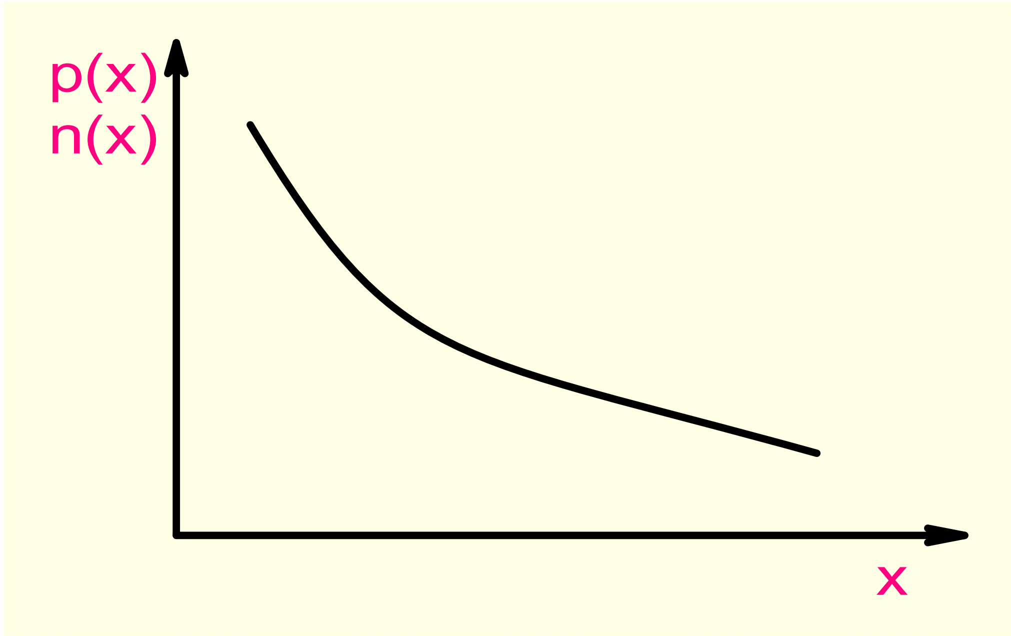


Current flow

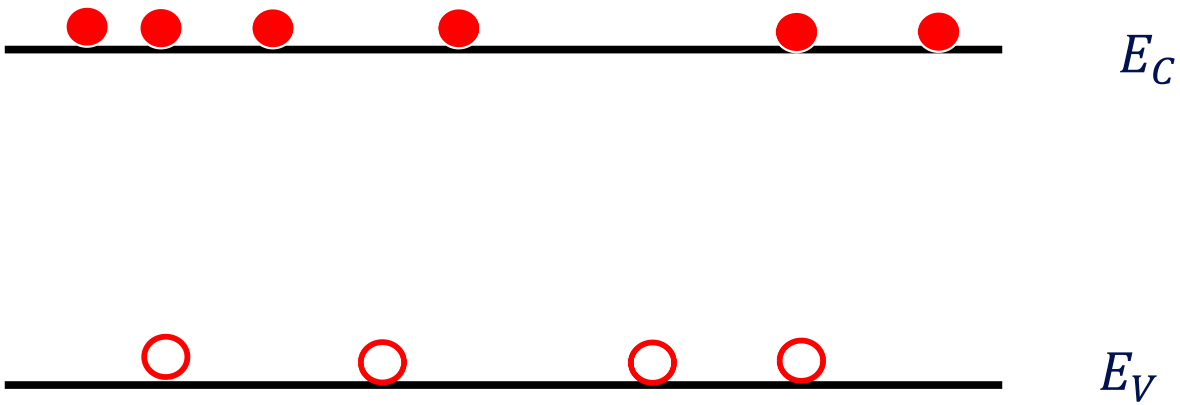
Drift current due to Electric field



Diffusion to concentration gradient



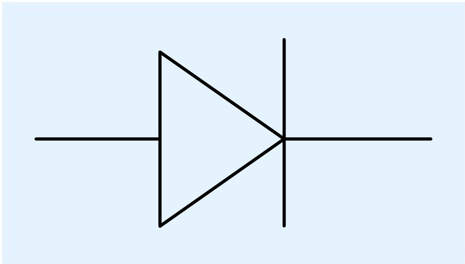
RecombinationGeneration

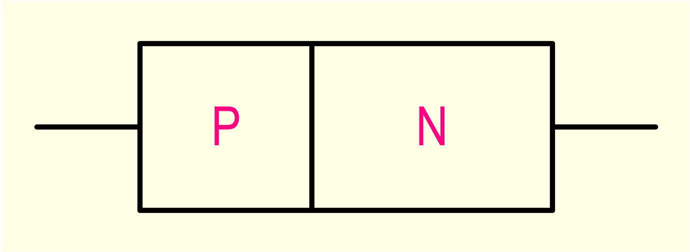


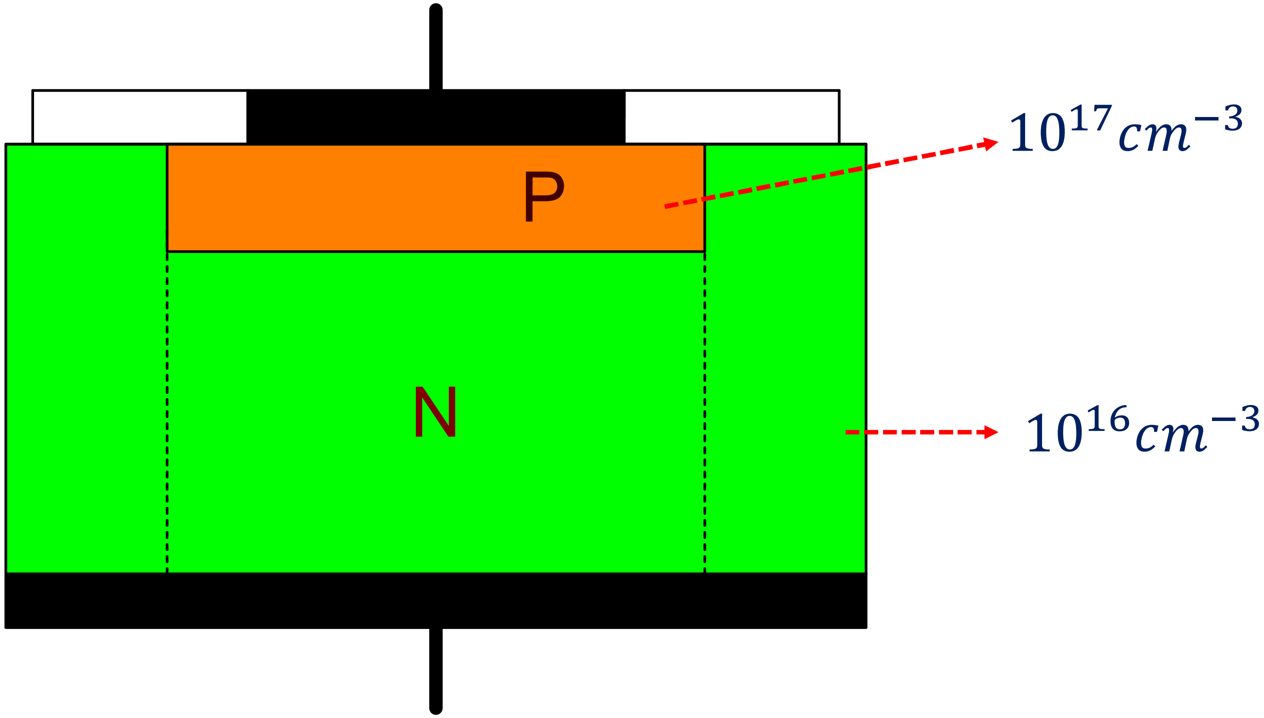
G-Number

PN Junction Diode

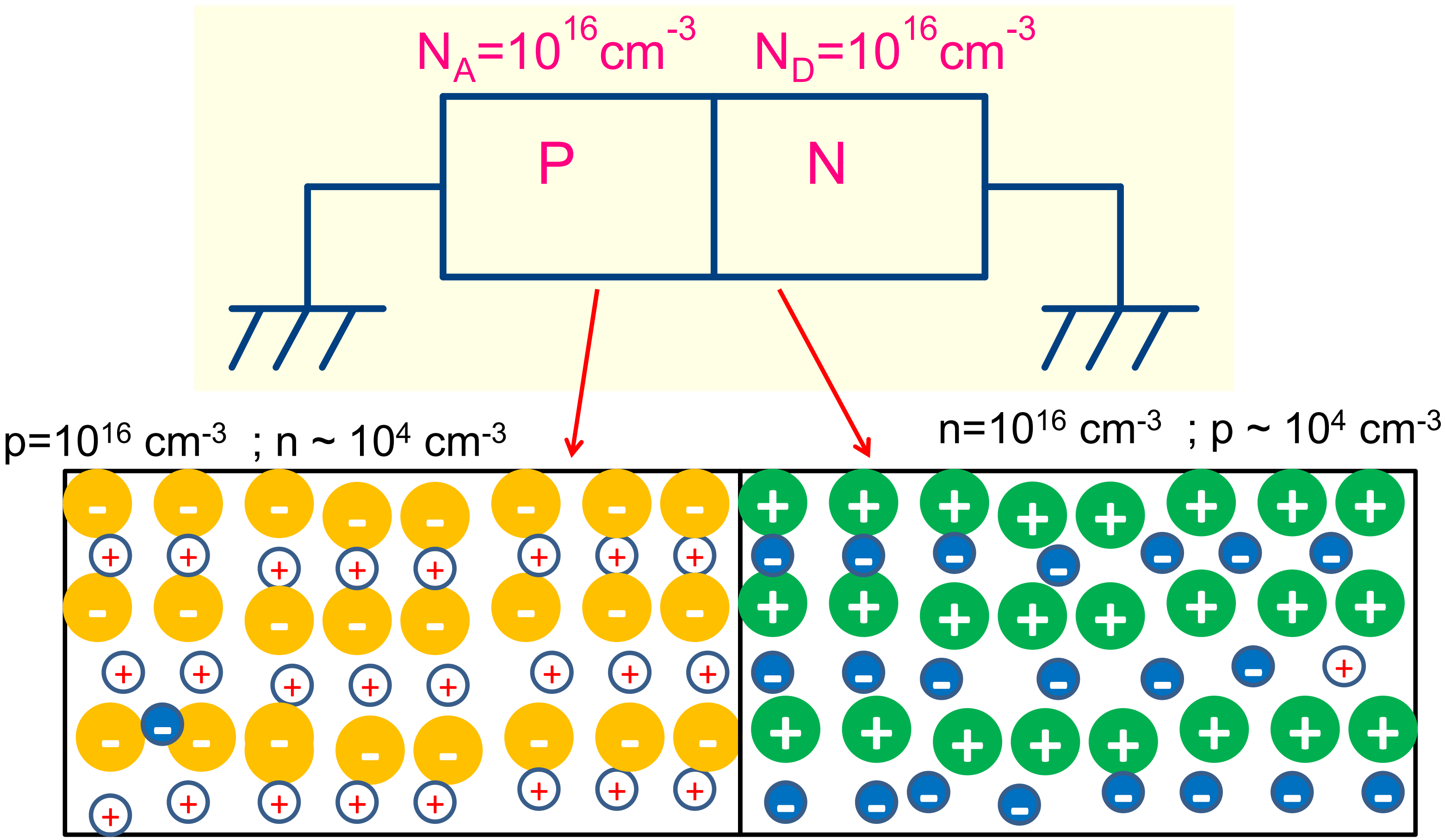
PN Junction Diode





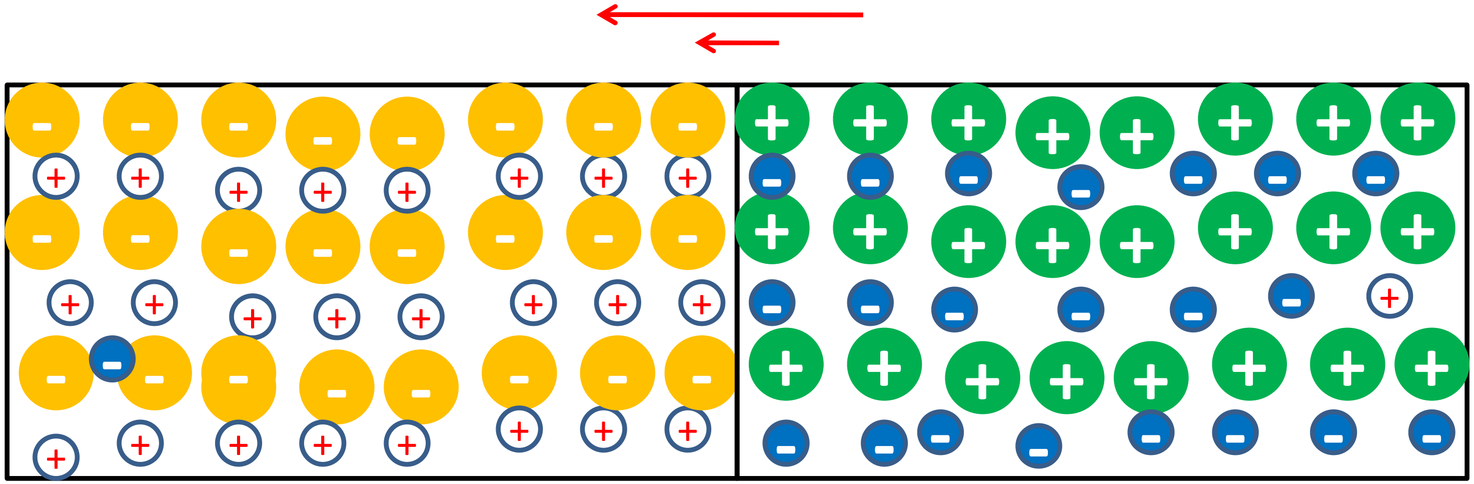


Basic Operation



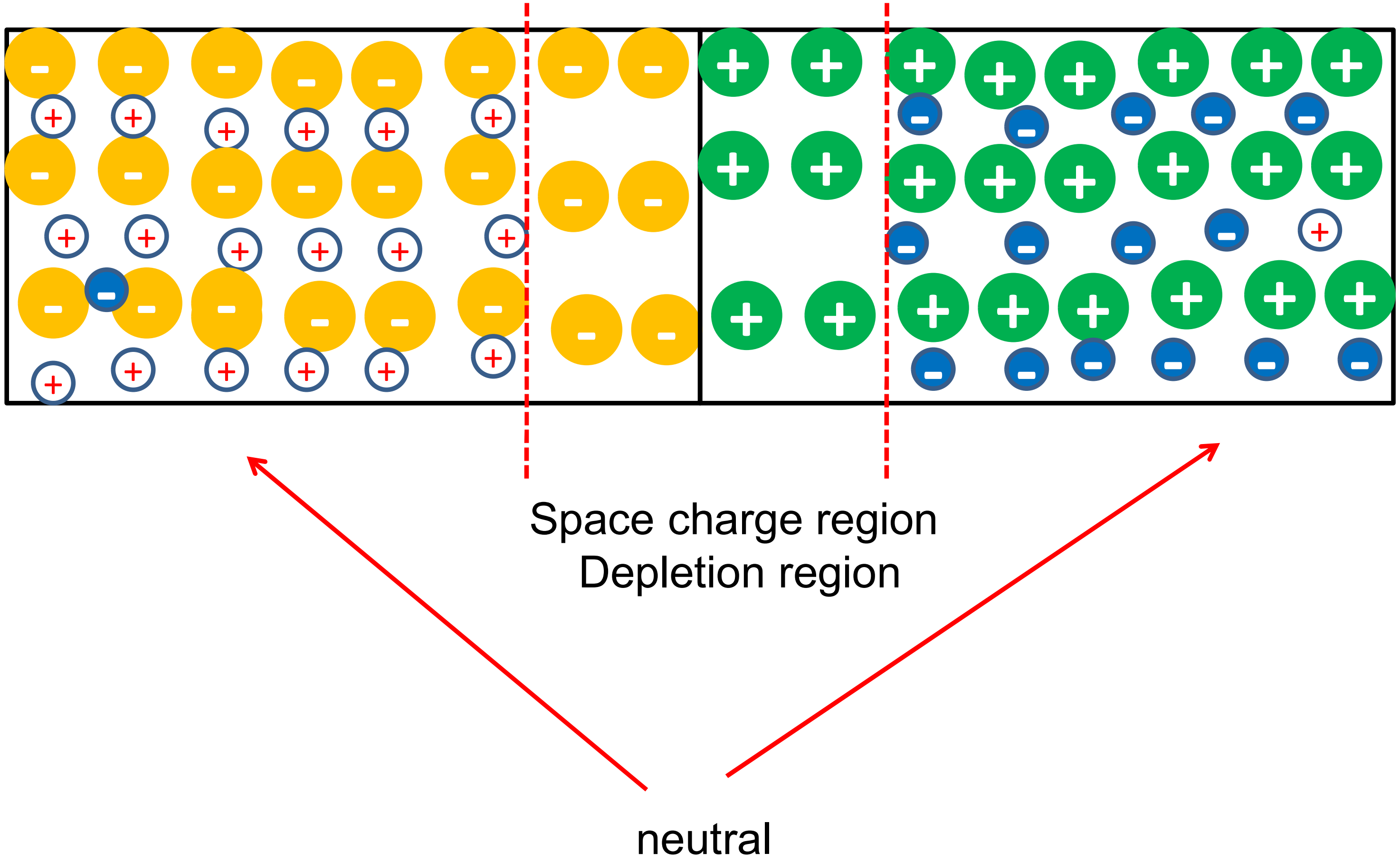
Holes will tend to diffuse from p →n and electrons from n→p

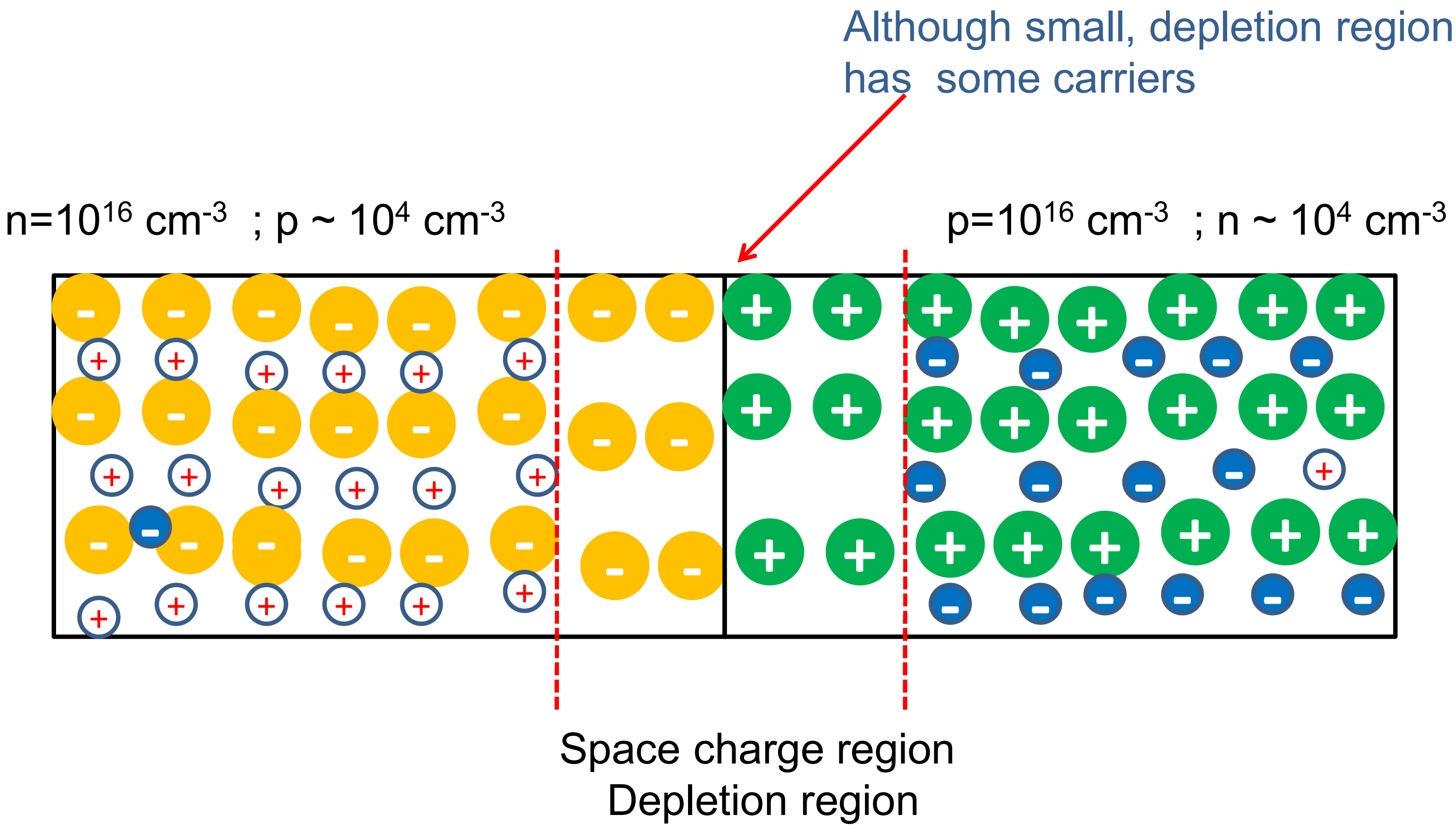
Electric field opposes flow of carriers



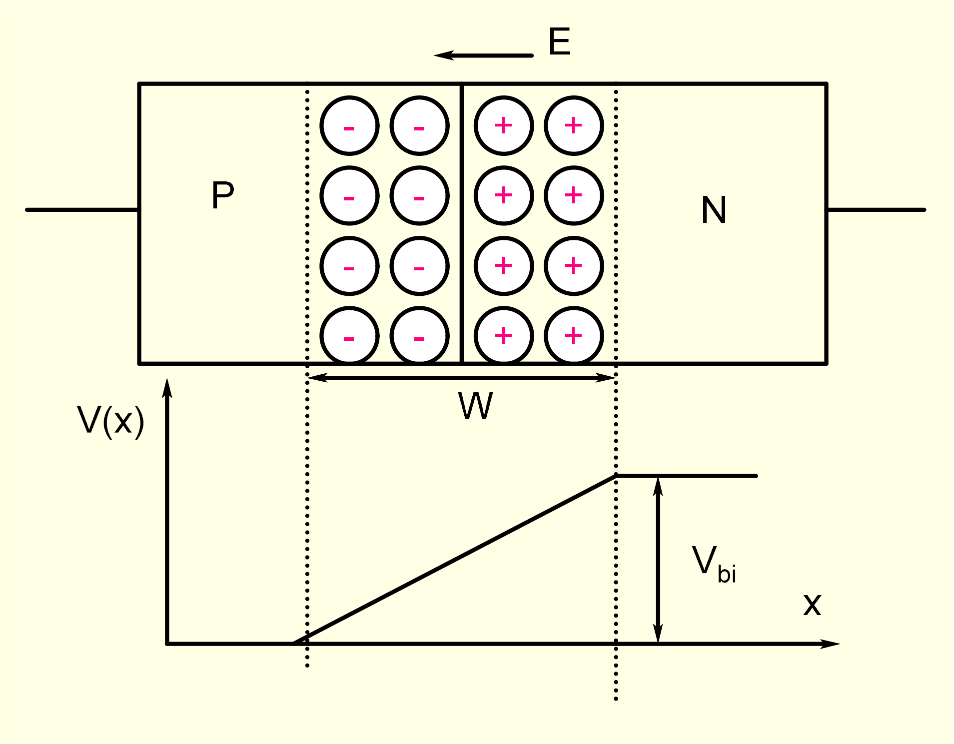
Eventually equilibrium is reached and there is no net flow of carriers across the junction

PN Junction Under Equilibrium




Although small, depletion region has some carriers
n=10^16 cm^-3 ; p ~ 10^4 cm^-3
p=10^16 cm^-3 ; n ~ 10^4 cm^-3
Space charge region
Depletion region

Built-in Potential V_{bi}



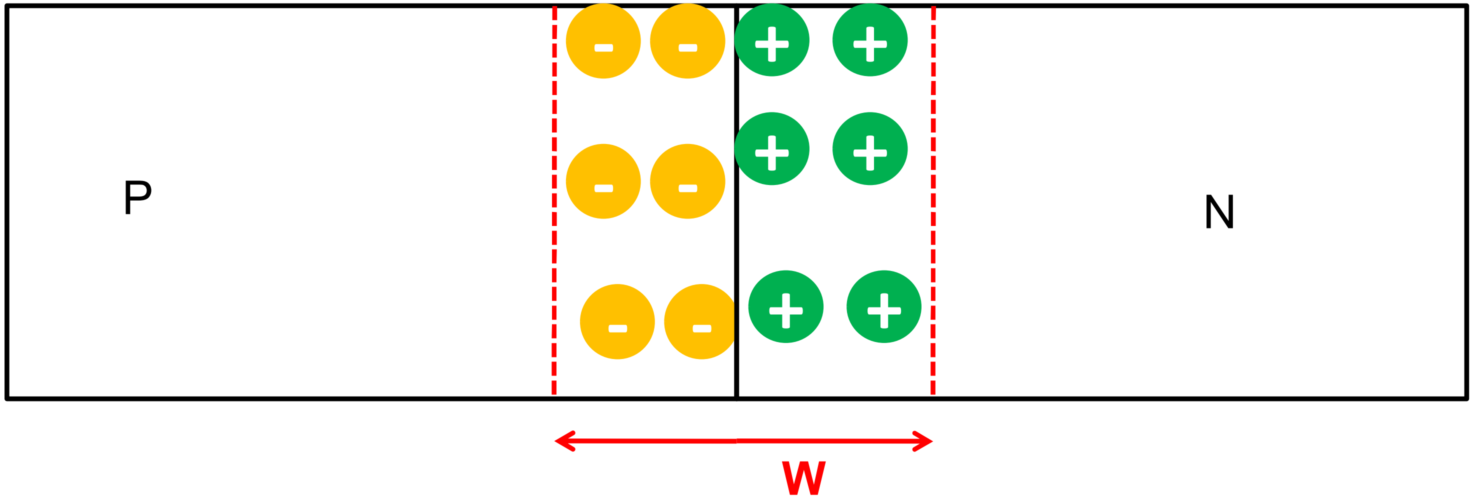
$$V_{bi} = \frac{k\,T}{q} \ln\left[\frac{N_A N_D}{n_i^{\,2}}\right]$$

$N_A = N_D = 10^{16}\ cm^{-3}$, T = 300°K

$V_{bi} = 0.86$ V

Anytime you put two different materials into contact, a potential develops between them.

Depletion region



$$W = \sqrt{\frac{2\varepsilon_s}{q} \times \left(\frac{1}{N_A} + \frac{1}{N_D}\right) \times V_{bi}}$$

$$\varepsilon_s = 11.7 \times 8.85 \times 10^{-14}\, F/cm;\ q = 1.6 \times 10^{-19}\, C$$

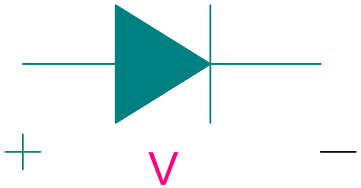
$N_A = N_D = 10^{16}\ cm^{-3}$, $T = 300°K$

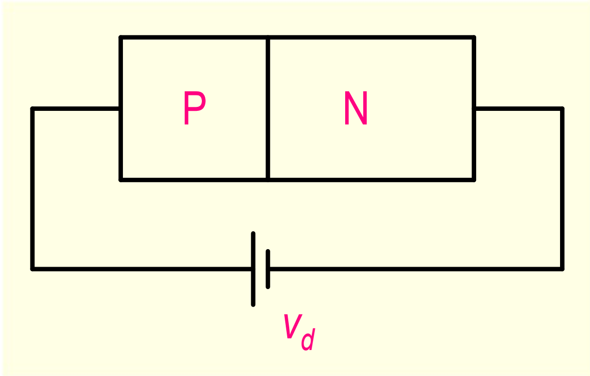
$V_{bi} = 0.86\ V$

$$W = 4300\, A^o$$

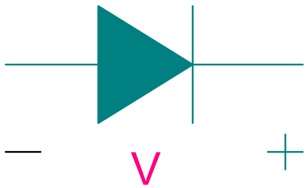
$$1A^o = 10^{-8}\, cm$$

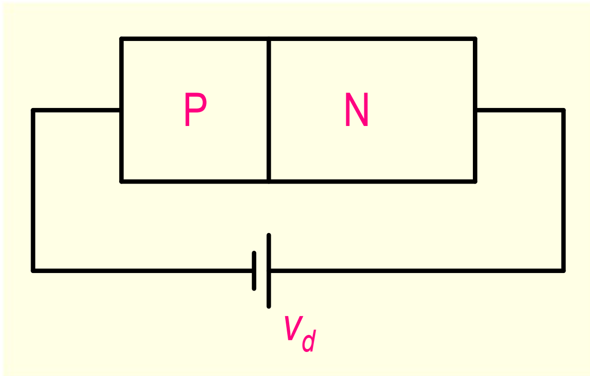
Forward and Reverse Bias



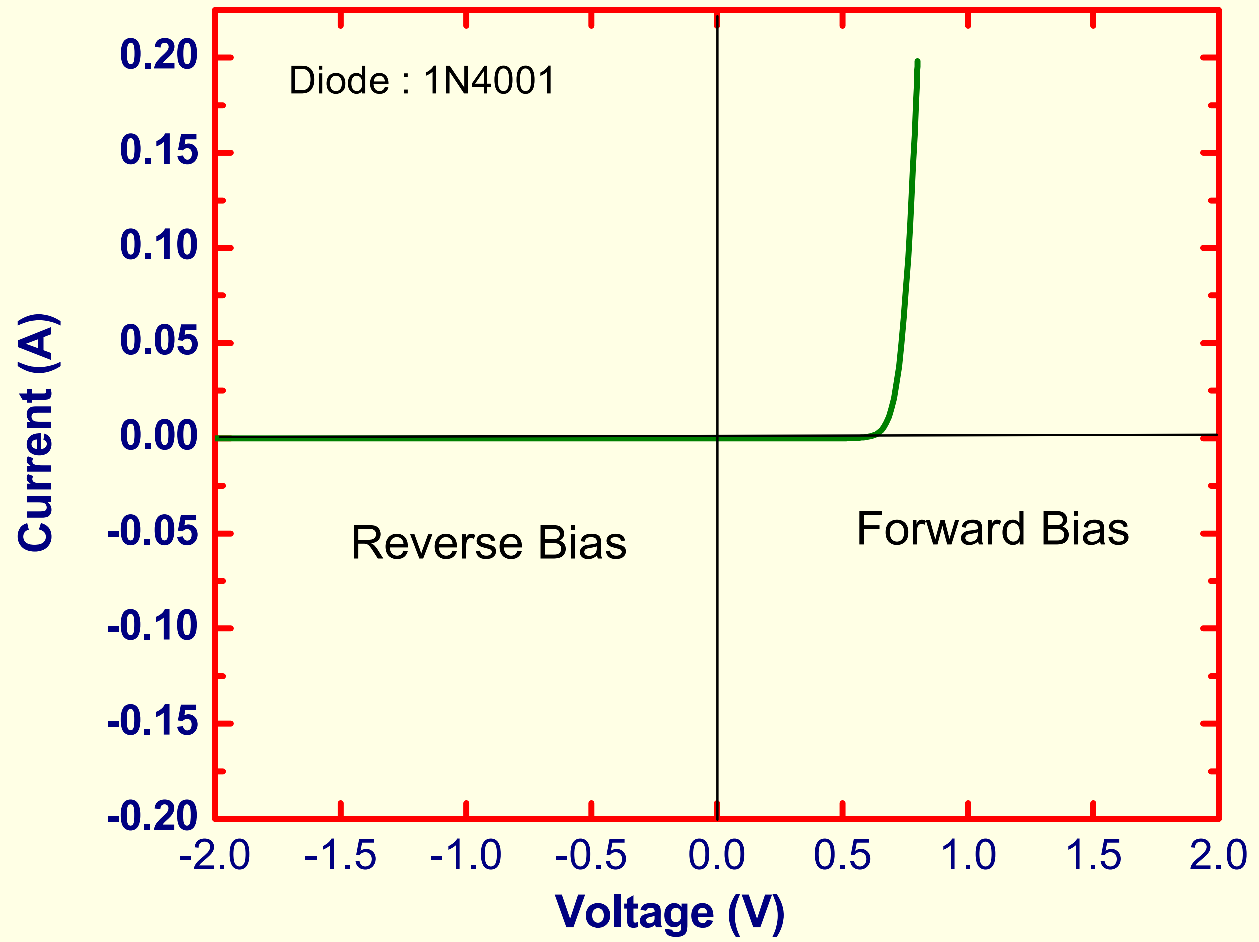


Forward Bias: P is biased at a higher voltage compared to N



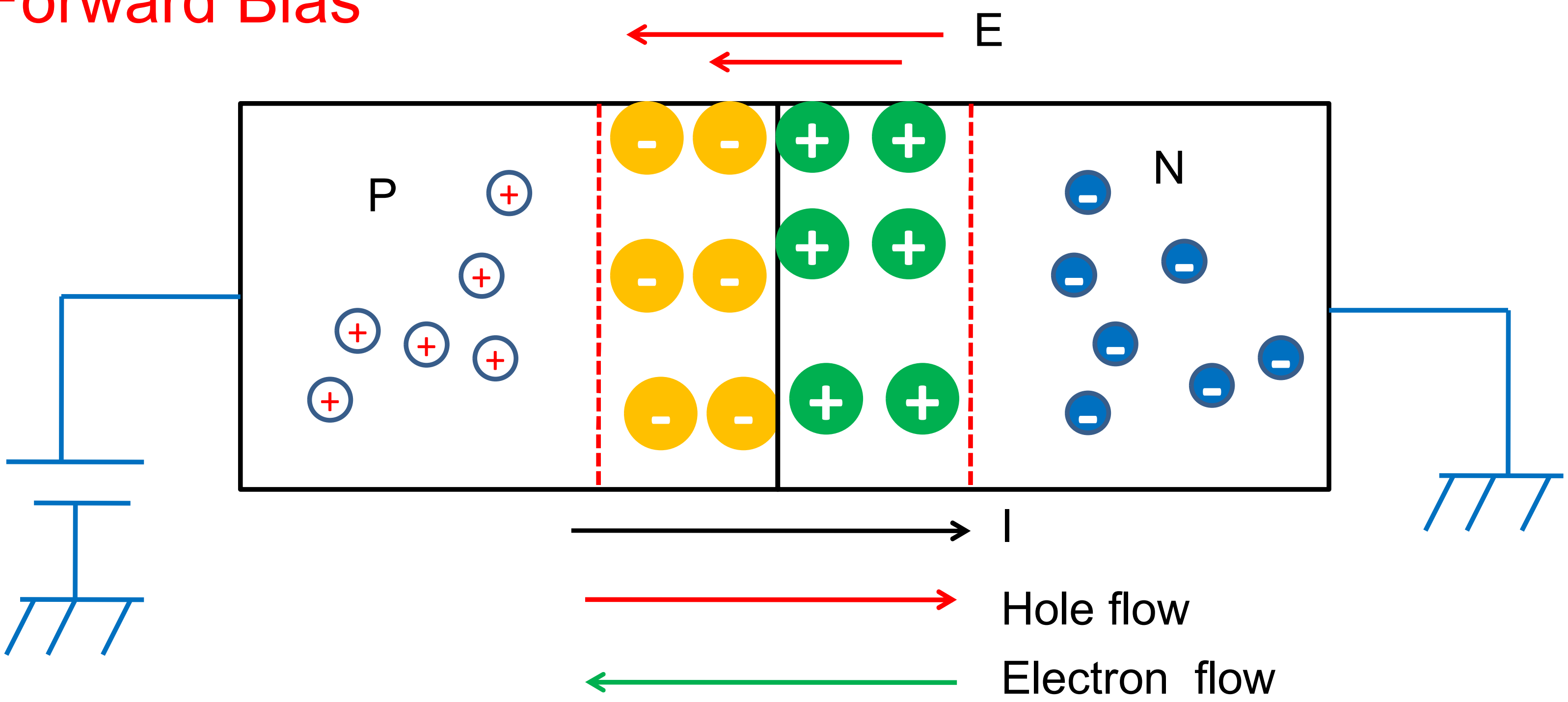


Reverse Bias: N is biased at a higher voltage compared to P

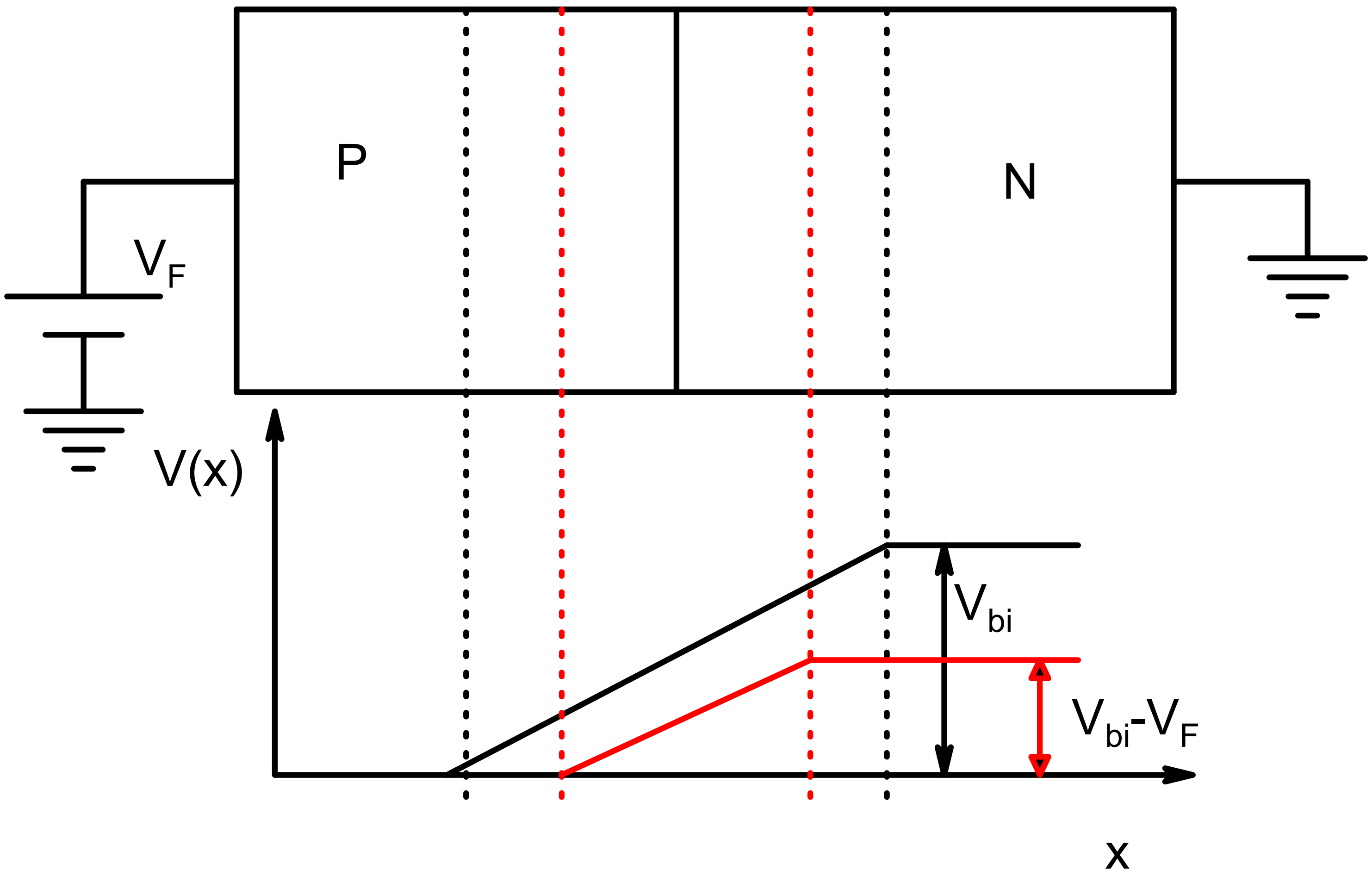


The p-n junction conducts significant current in the forward-bias region.

Forward Bias

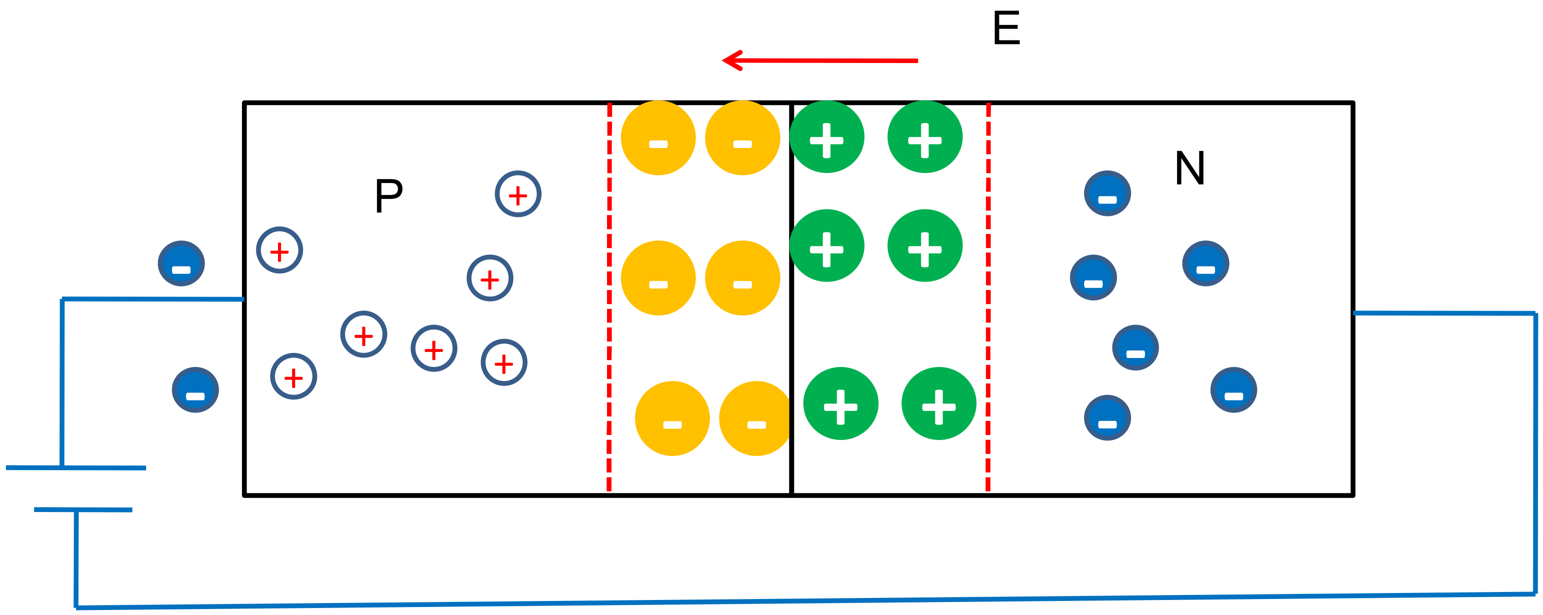


Application of forward bias lowers the built-in potential and allows holes and electrons to cross the junction and result in current flow



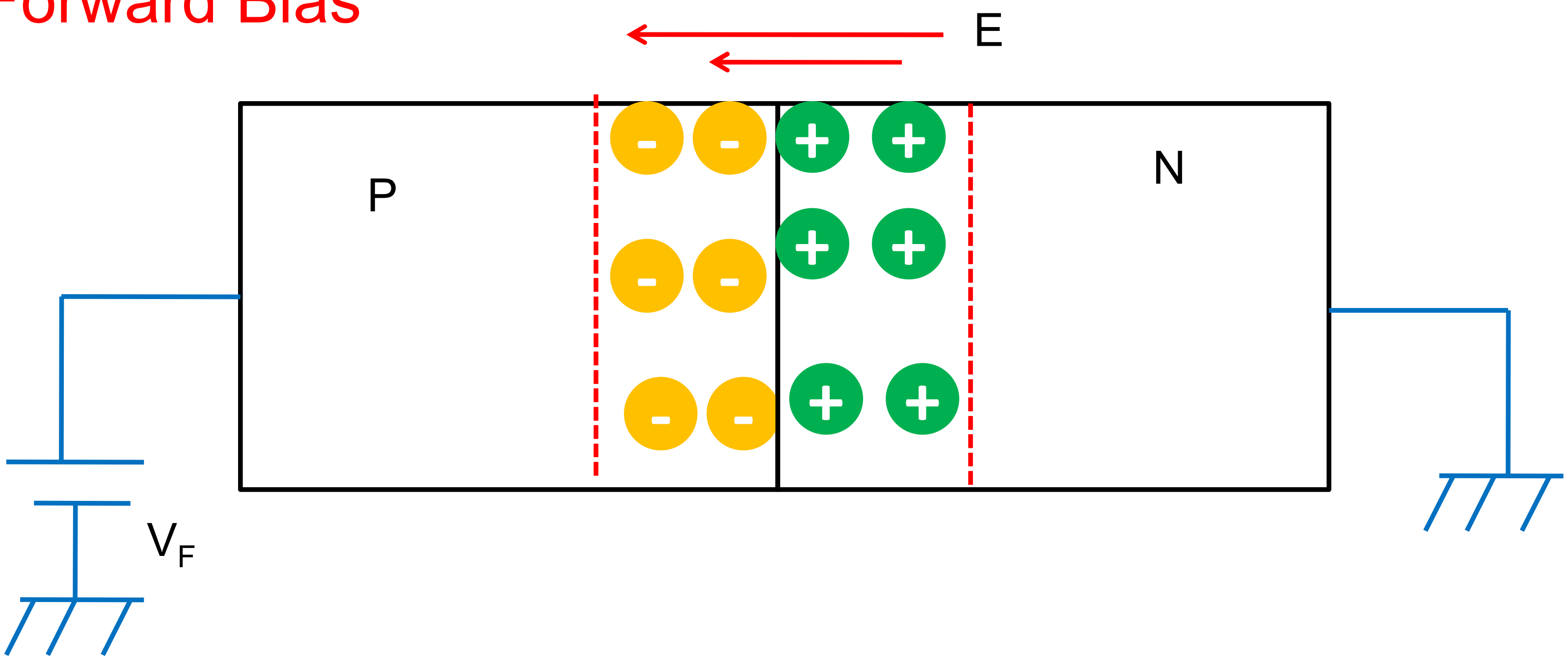
P
N
V_F
V(x)
V_{bi}
V_{bi}-V_F
x

Mechanism of Current flow



Current flows through carrier **injection** and **recombination**

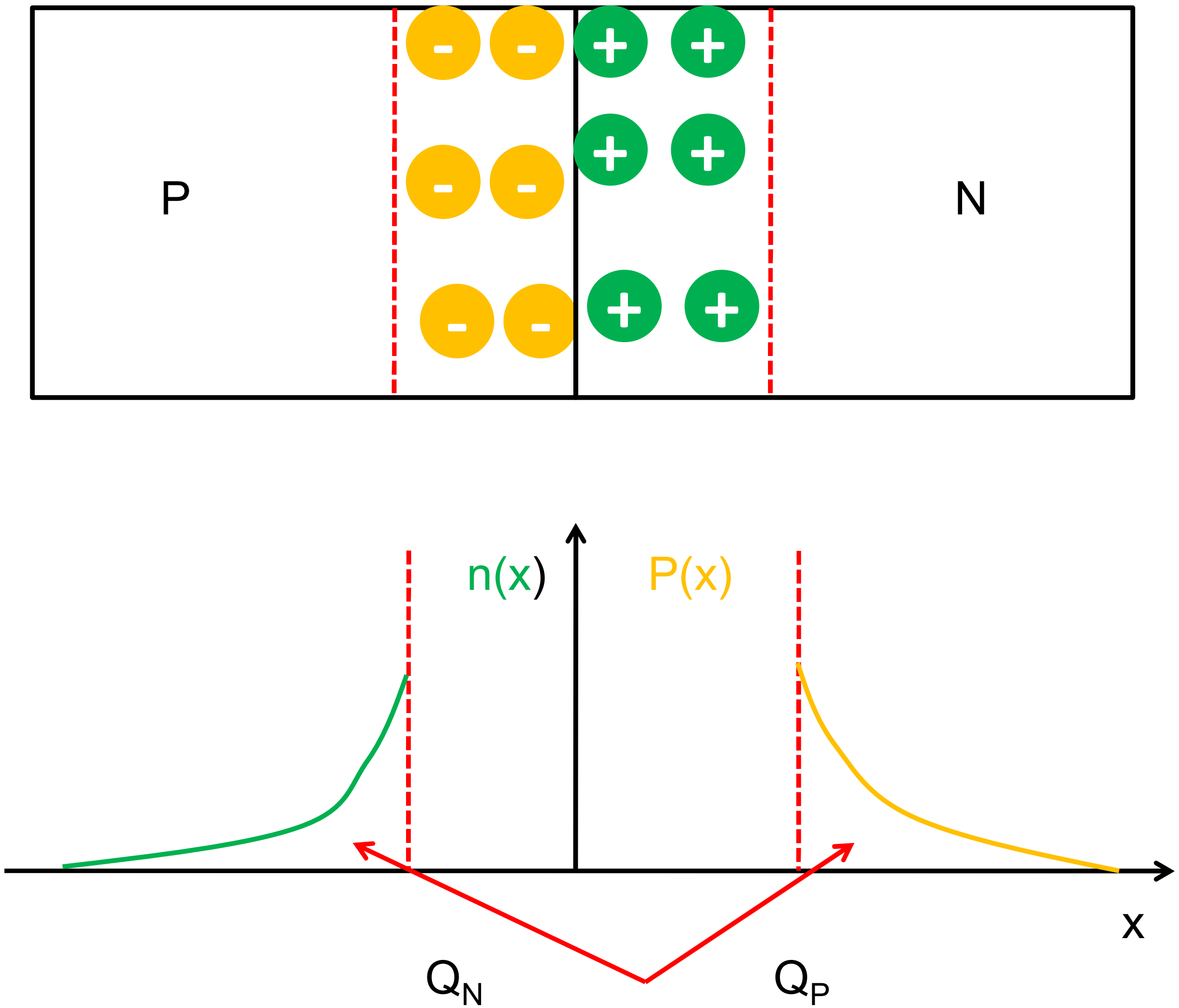
Forward Bias



Application of forward bias reduces depletion width.

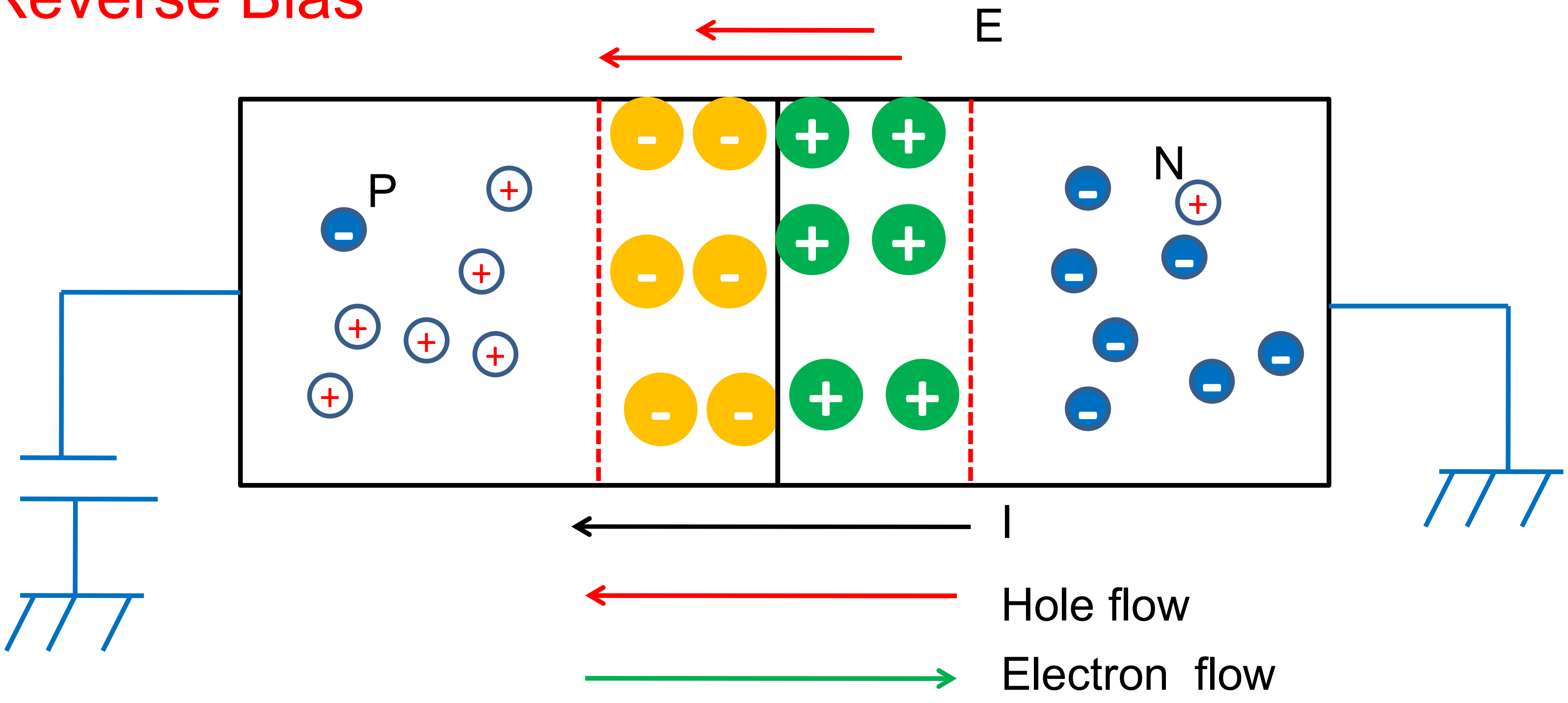
Change in depletion charge with voltage gives rise to junction capacitance (also called depletion capacitance) C_J

Excess carriers in P and N regions



Diffusion capacitance

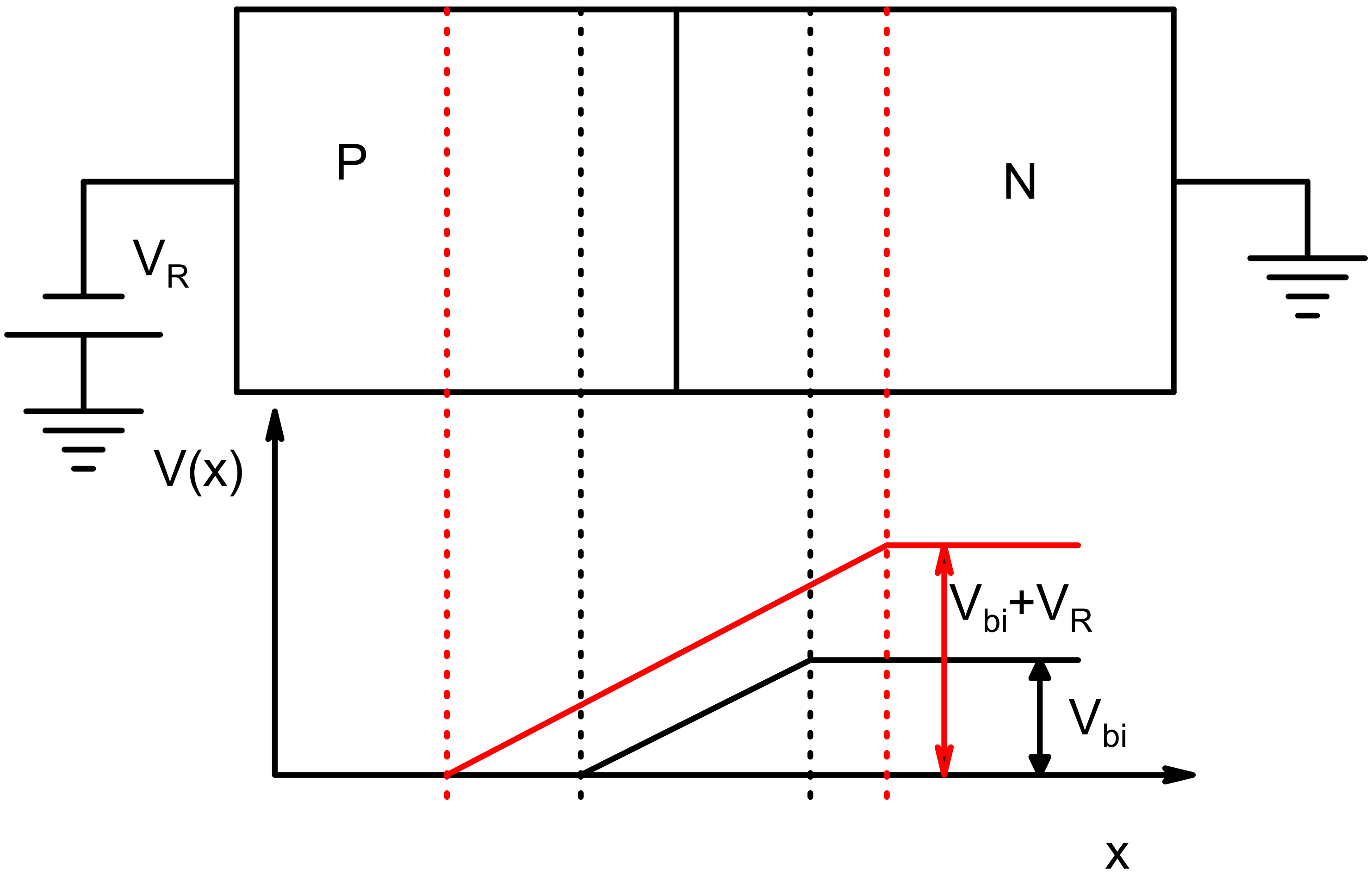
Reverse Bias



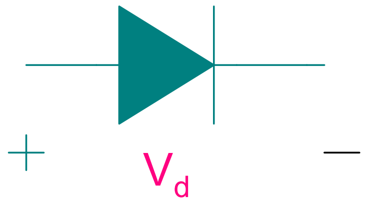
Because of very few electrons in p-type and holes in N-type current is very small !

Application of reverse bias increases the built-in potential

Reverse Bias



Diode : I-V Characteristics



$$I = I_S \times \{\exp(\frac{V_D}{nV_T}) - 1\}$$

I_S : Reverse Saturation Current

$V_T = kT/q \cong 26mV$ at T = 300K

n is called ideality factor and is equal to 1 for ideal diodes

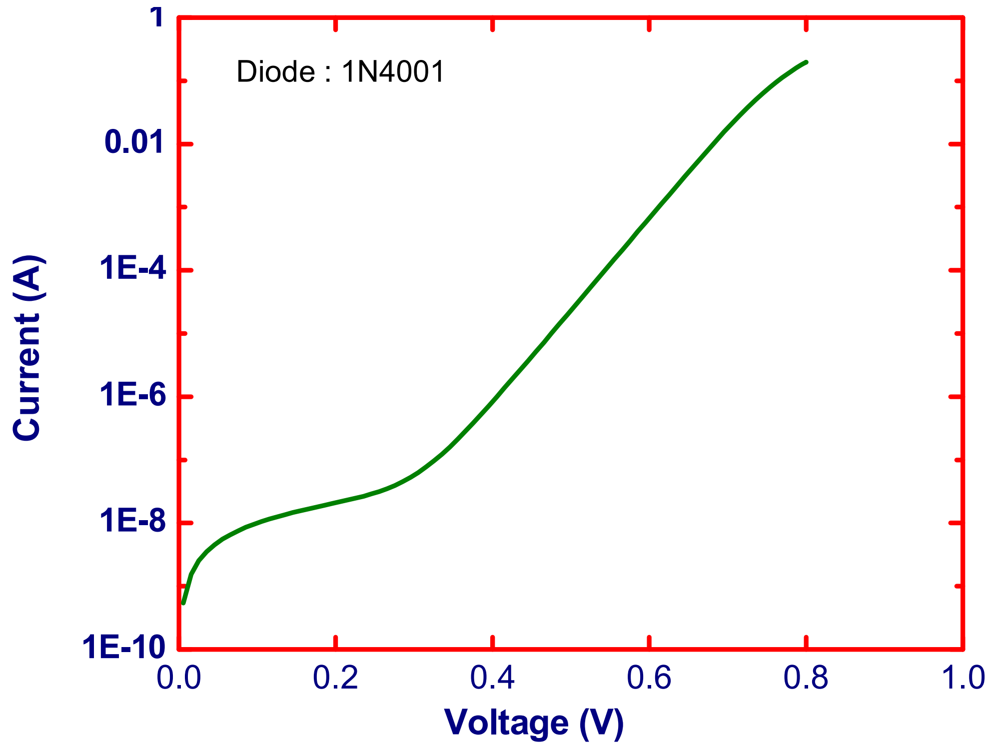
Forward Bias

$$I = I_S \times \{\exp(\frac{v_d}{V_T}) - 1\}$$

$$v_d >> V_T = 26mV$$

$$I \cong I_S \times \exp(\frac{v_d}{V_T})$$

$$\ln(I) = \ln(I_S) + \frac{v_d}{V_T}$$

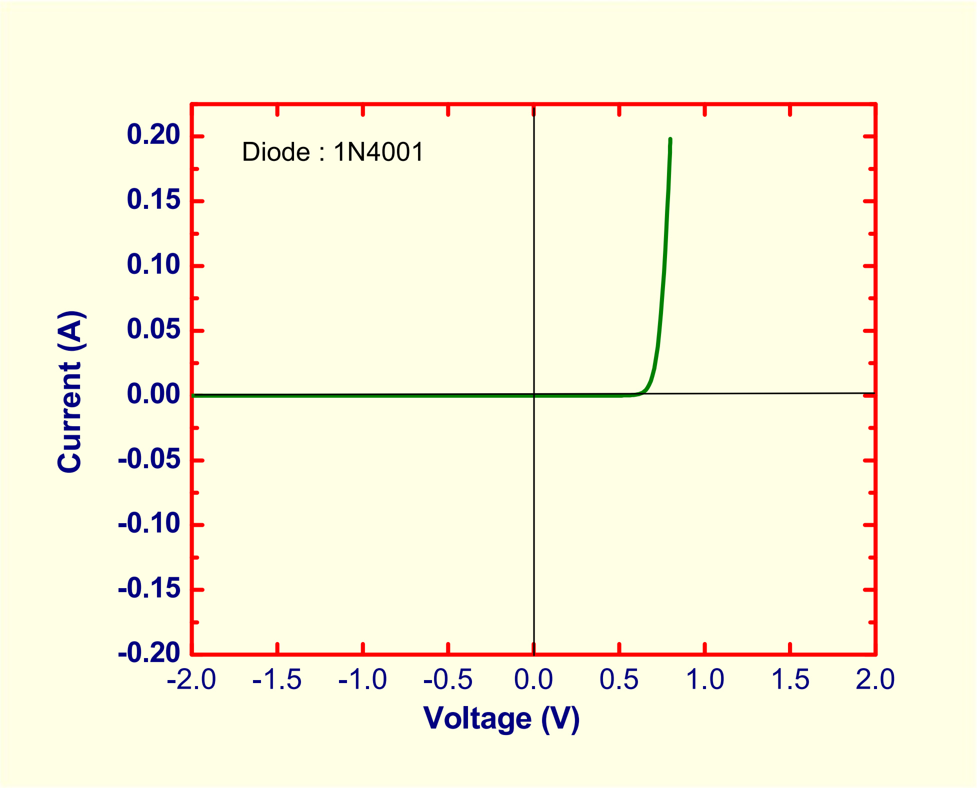


Reverse Bias

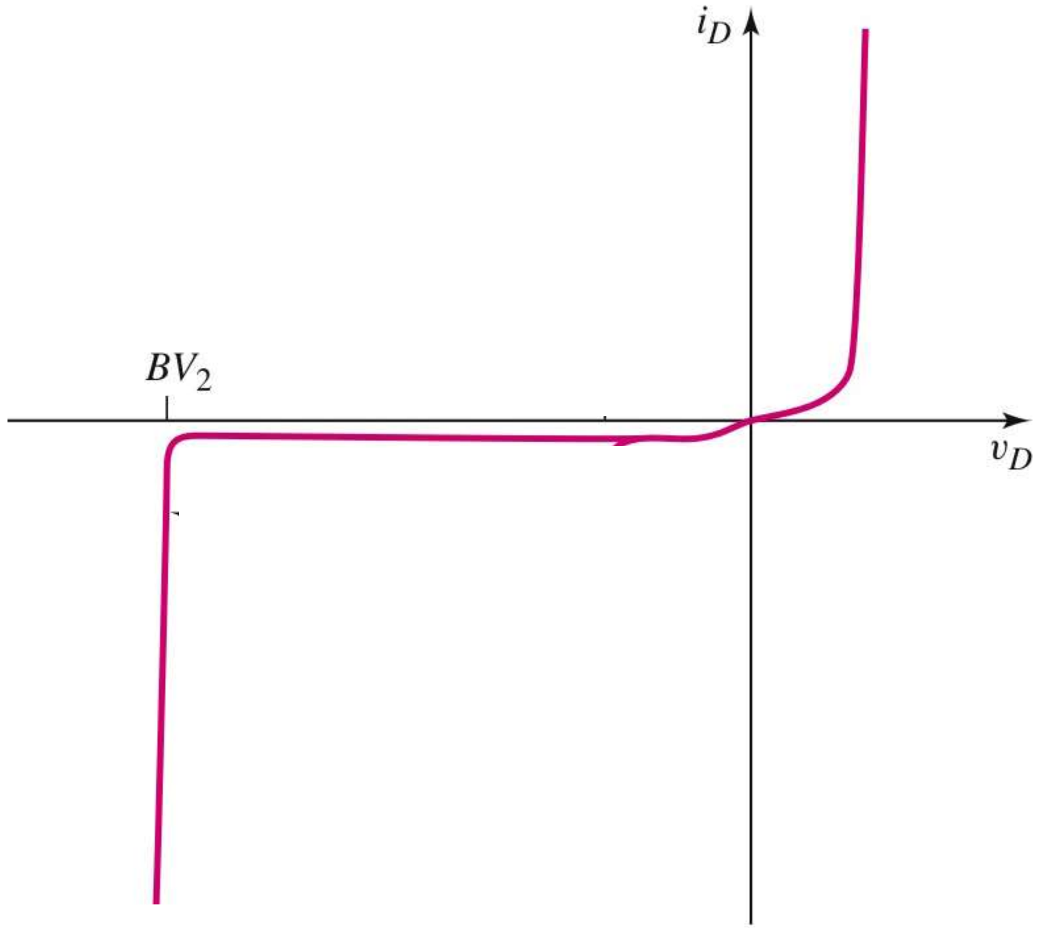
$$I = I_S \times \{\exp(\frac{v_d}{V_T}) - 1\}$$

$$v_d = -v_R$$

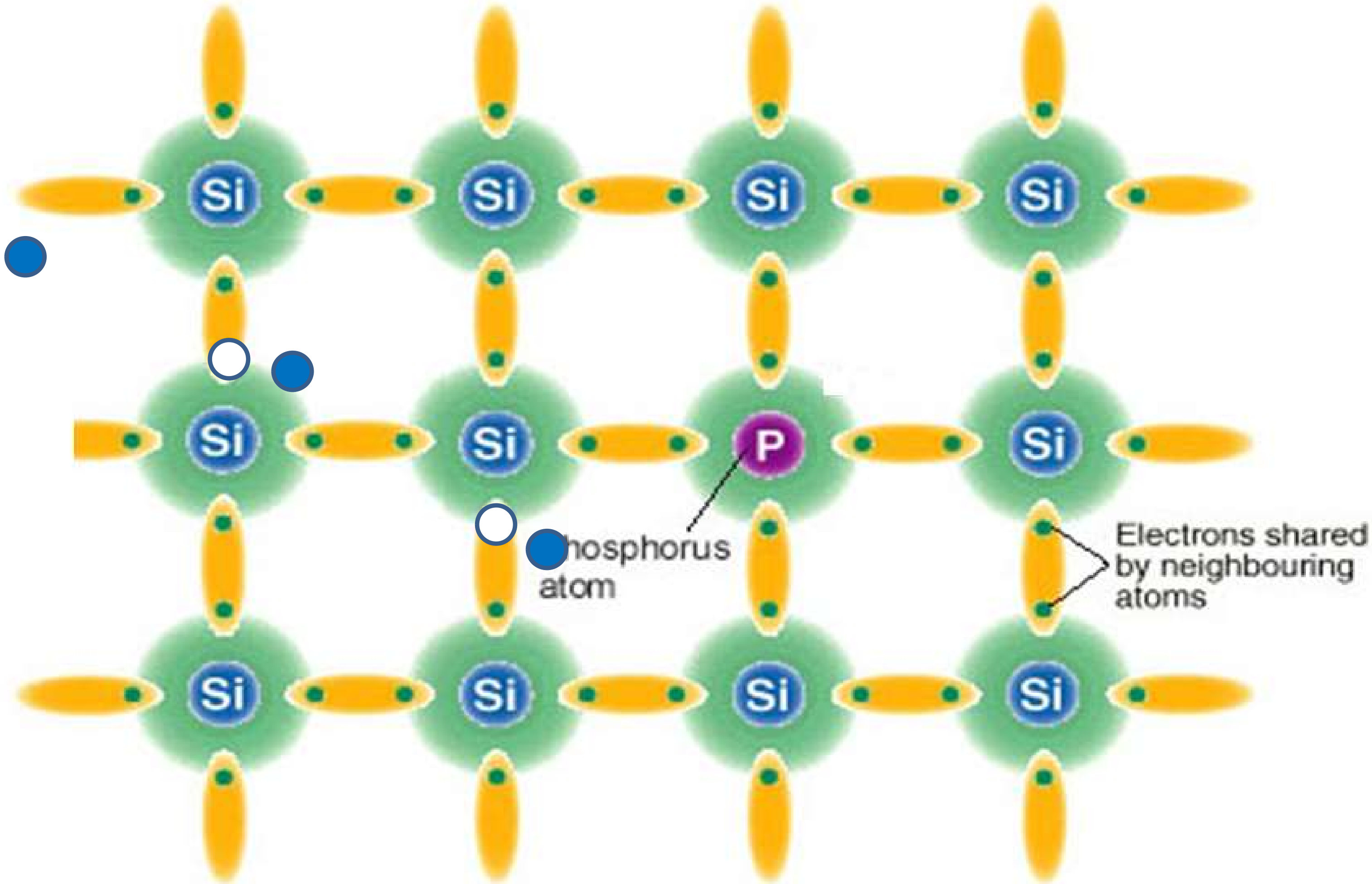
$$I = I_S \times \{\exp(-\frac{v_R}{V_T}) - 1\} \cong -I_S$$



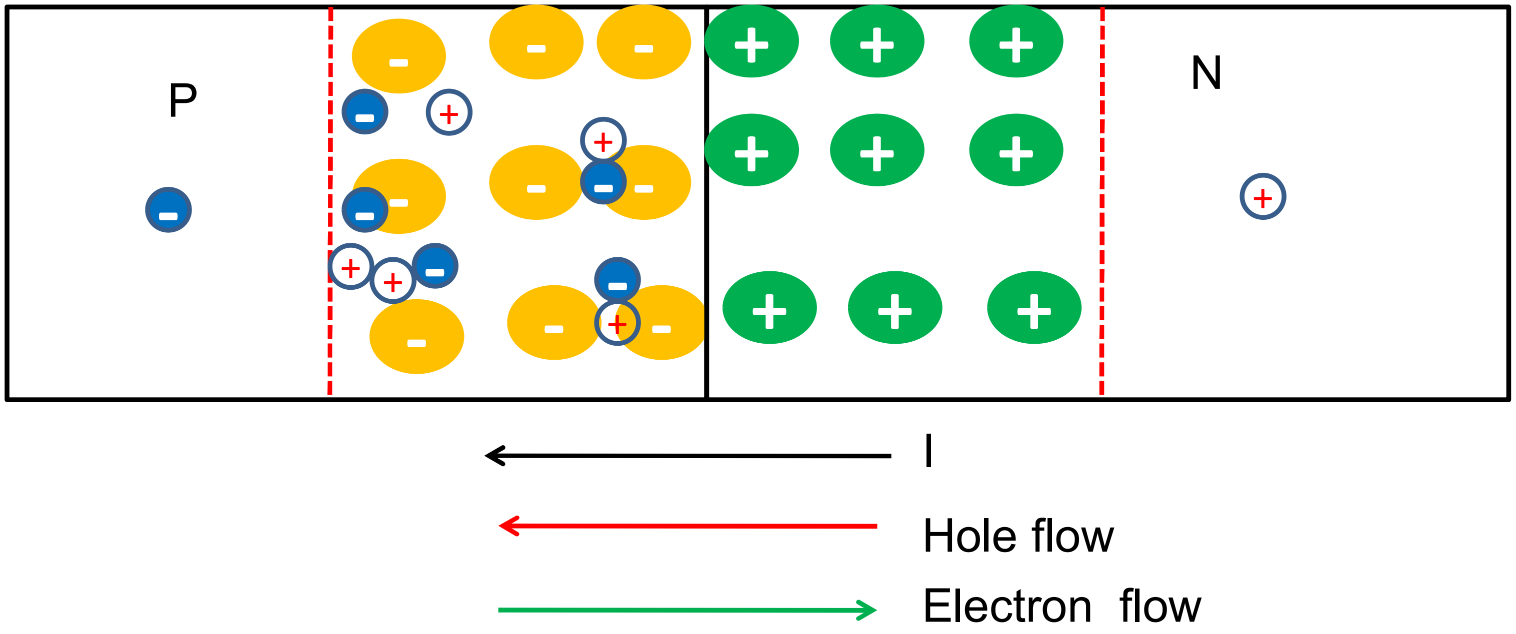
Breakdown



Impact Ionization



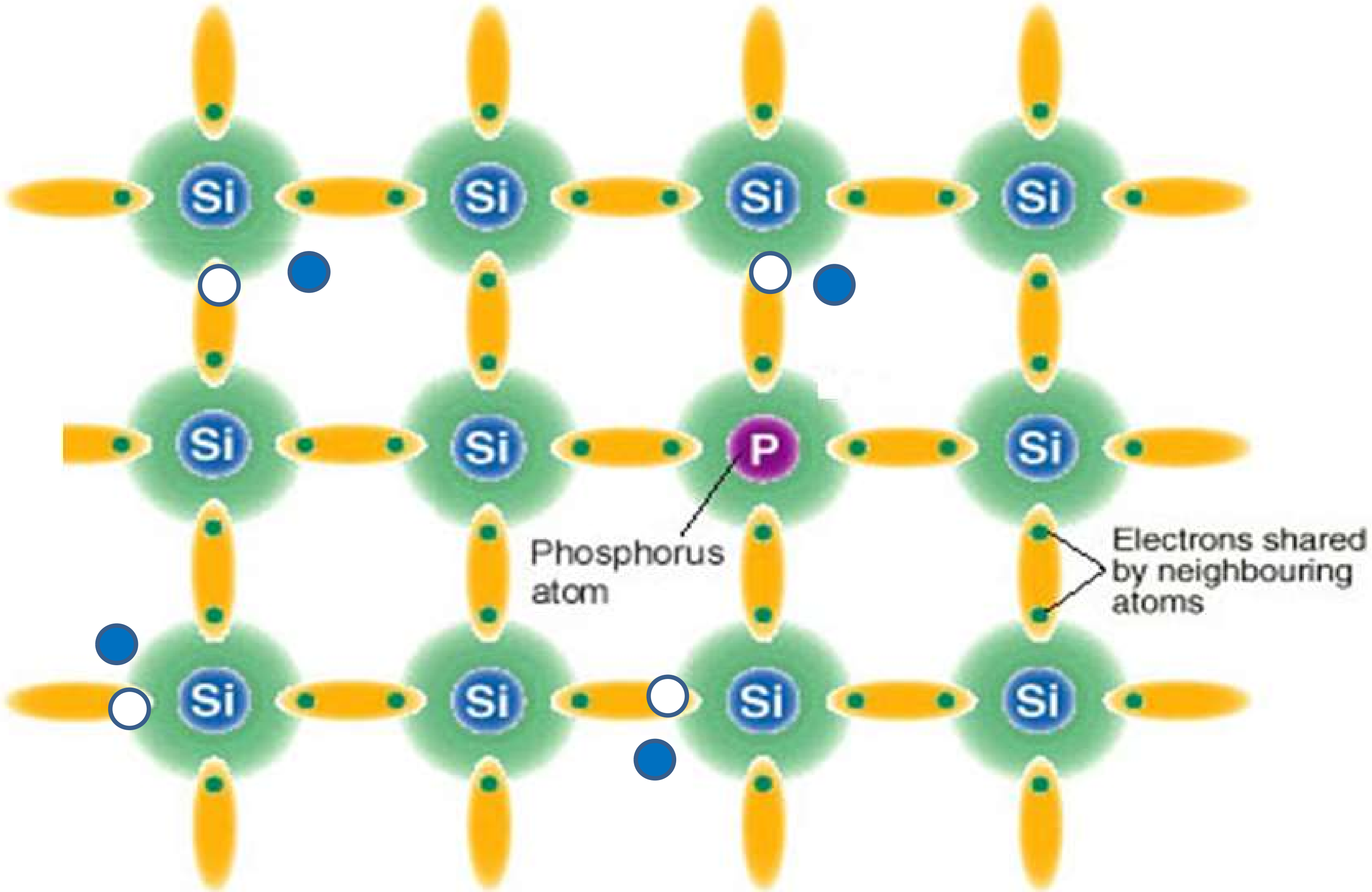
Breakdown Mechanism: Avalanche



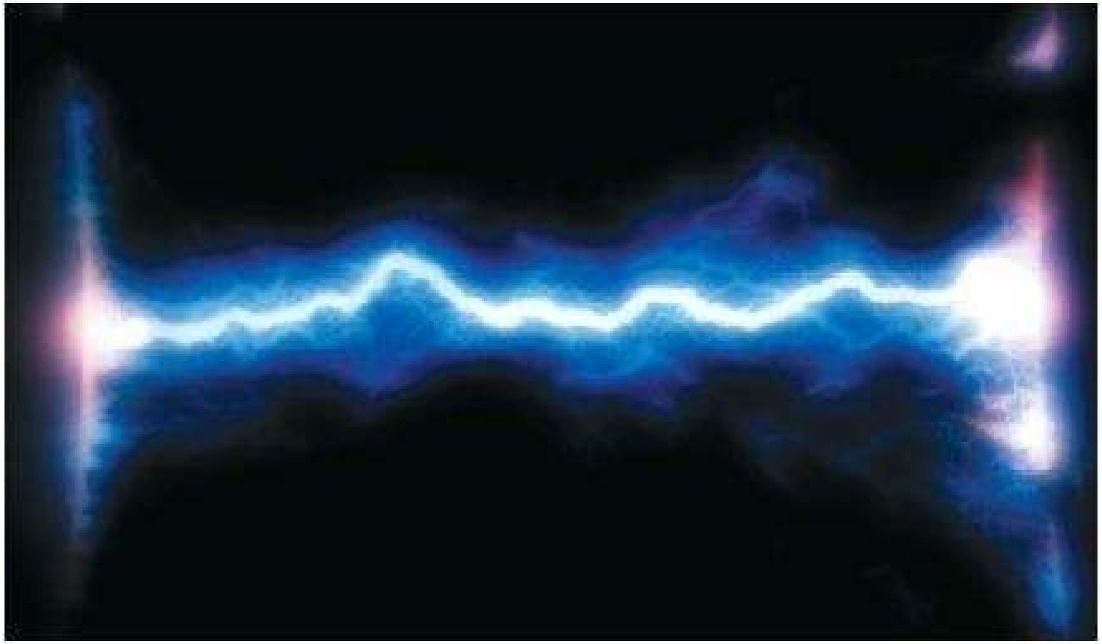
A multiplication of carriers takes place due to impact ionization in the depletion region, as a result of which large current begins to flow.

Avalanche

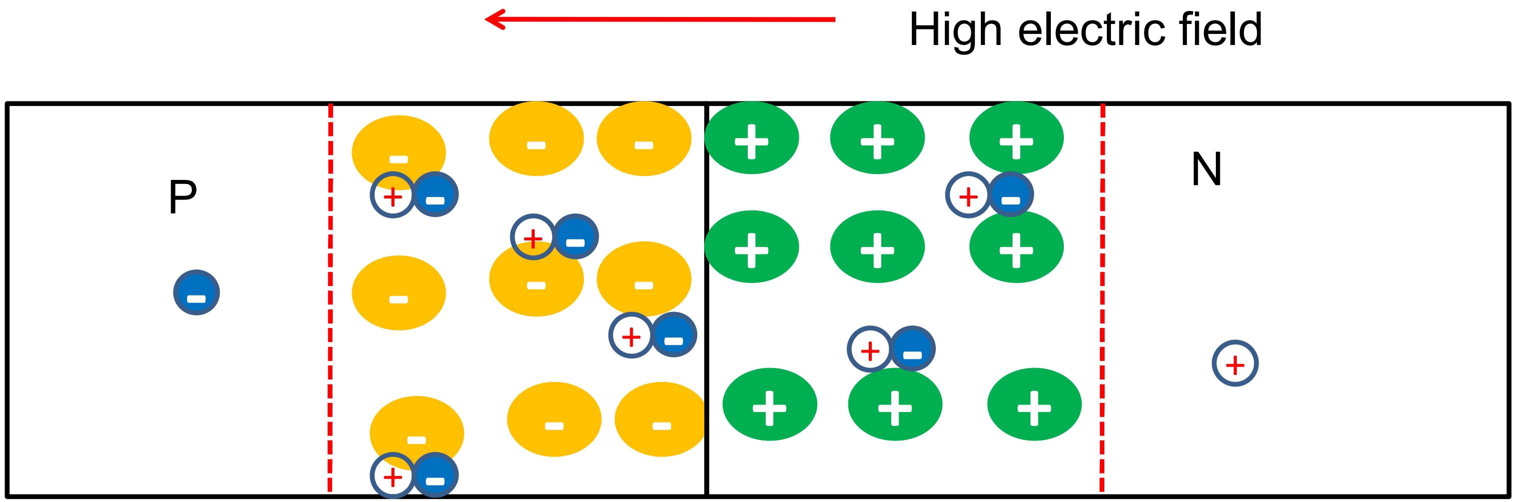
Ionization can also occur due to electric field



Electric Arc



Breakdown: Zener Heavily doped junctions



Electric field “**breaks the bond”** creating electron and hole pairs. These carriers move to give rise to large current.

Most of the common pn junction diodes breakdown due to avalanche mechanism. Even diodes which are called zener diodes have avalanche breakdown

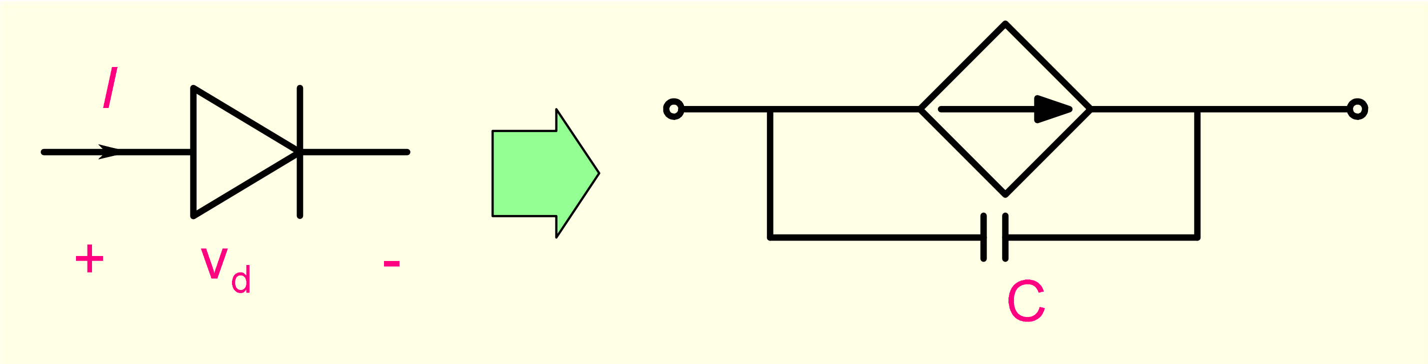
ESC201T : Introduction to Electronics

Lecture 21: Diode Model For Circuit Analysis

B. Mazhari
Dept. of EE, IIT Kanpur

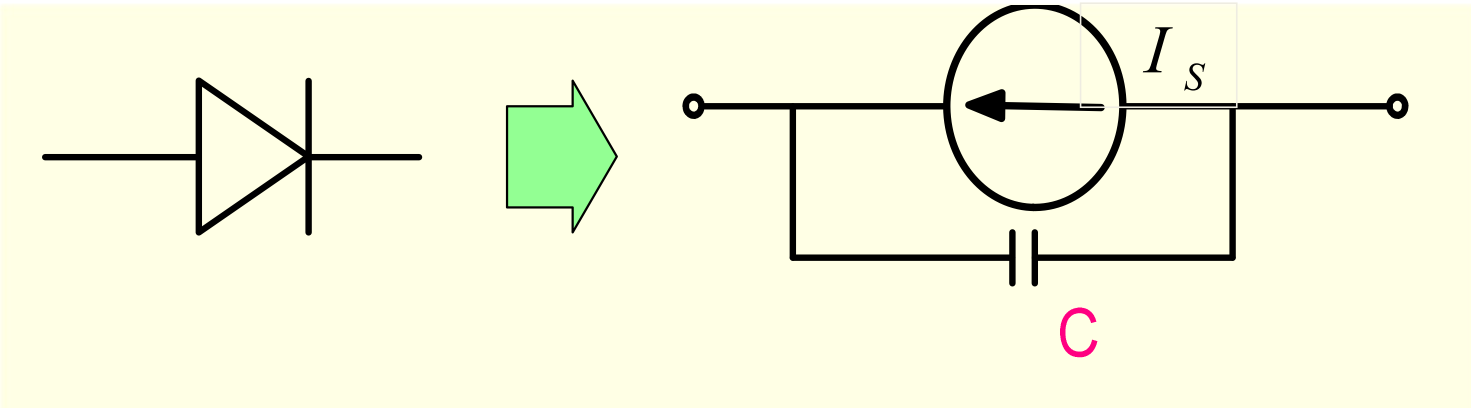
Diode Model: Forward Bias

$$I = I_S \times \{\exp(\frac{V_d}{nV_T}) - 1\}$$



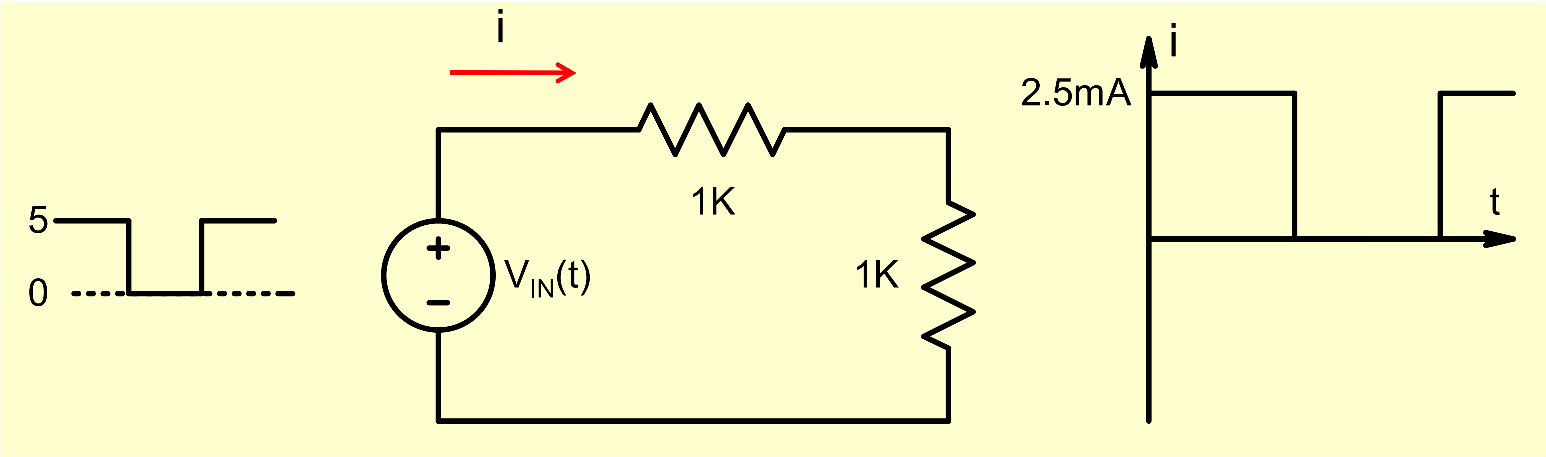
For dc and low frequency ac circuits, the effect of diode capacitance can be neglected

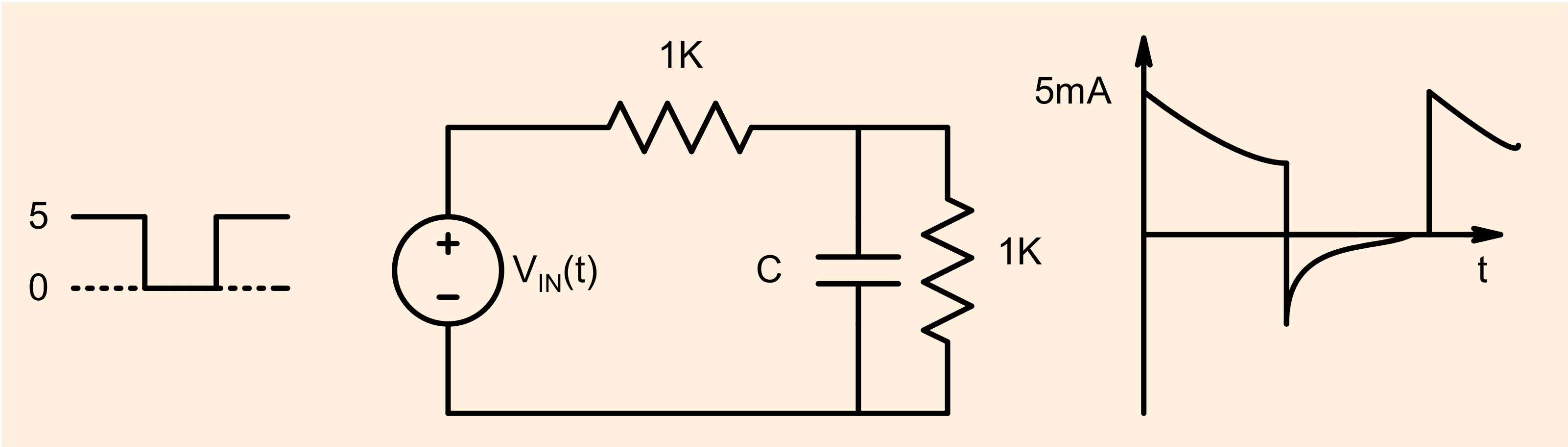
Diode Model: Reverse Bias

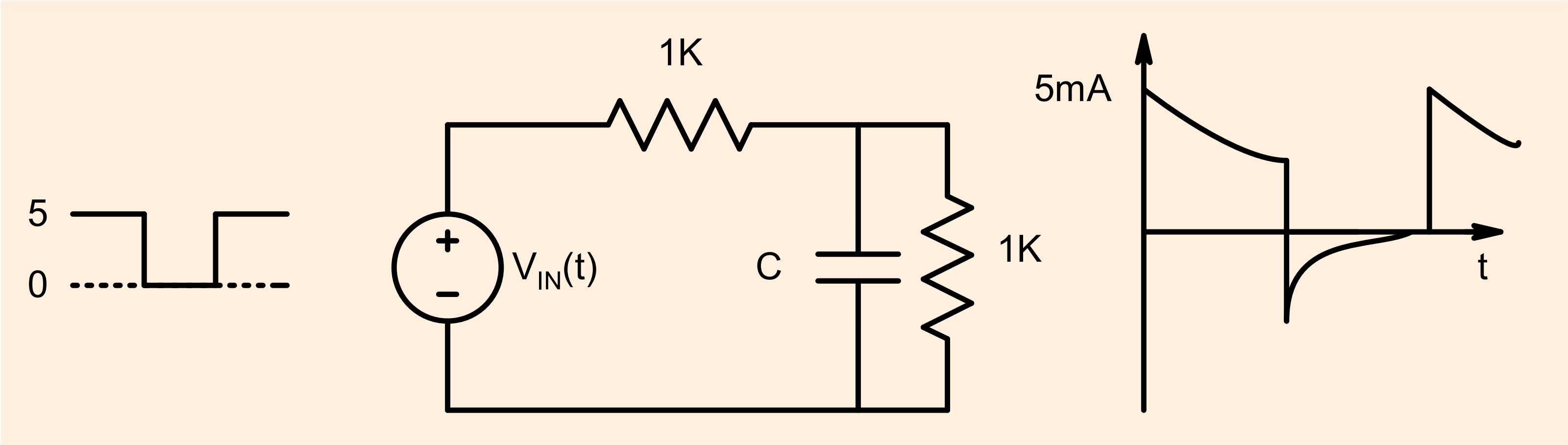


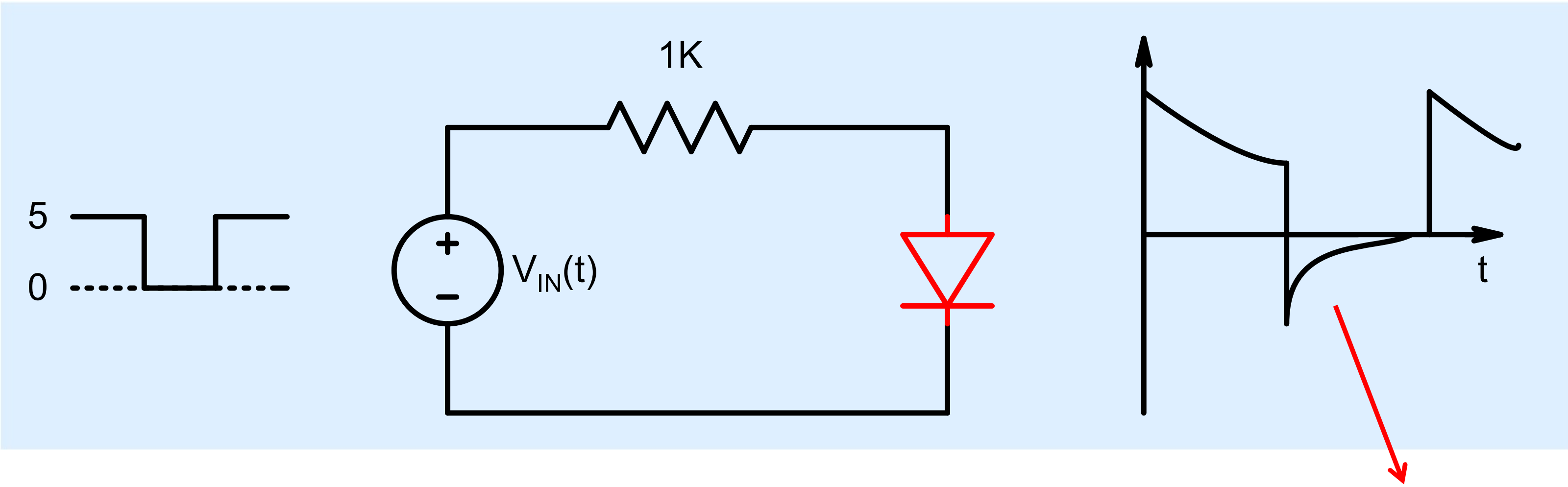
Because of capacitance, a diode even though reverse biased, can carry significant current momentarily

Example



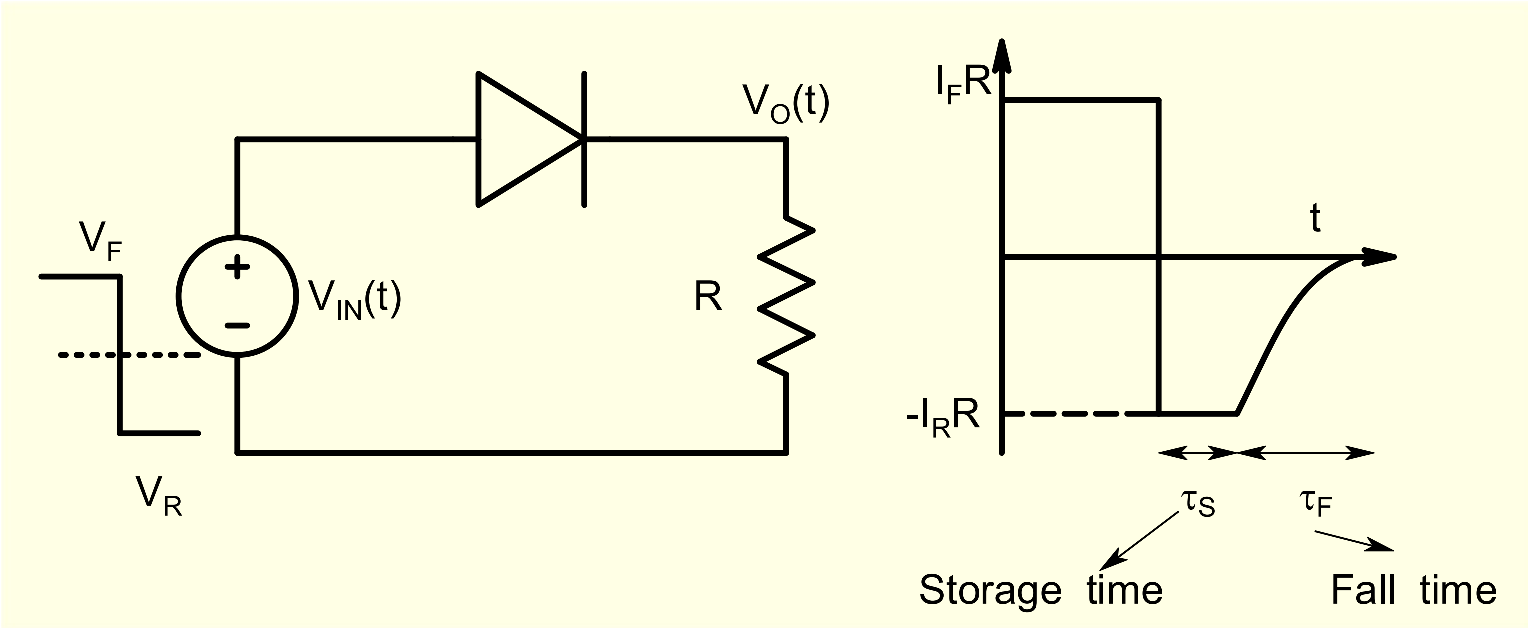






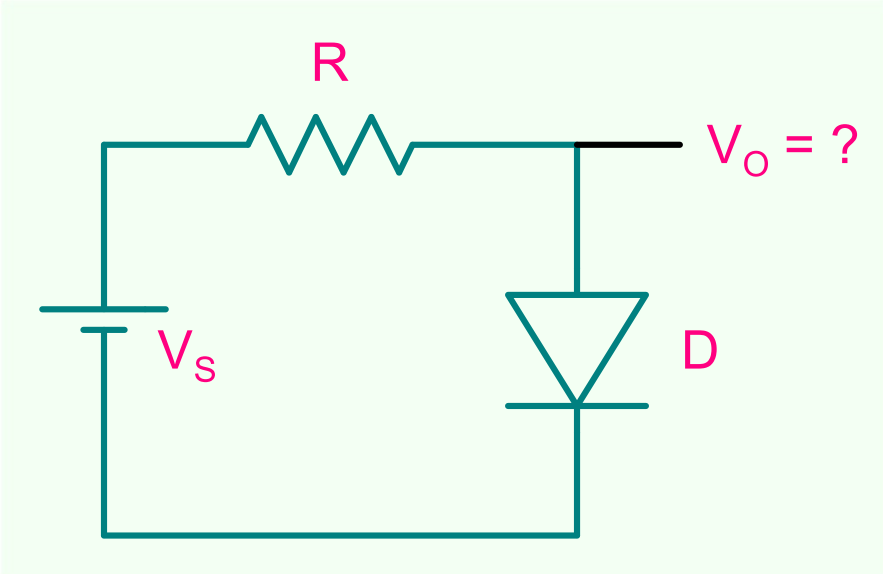
Current in reverse direction

Transient Response



Diode does not switch off instantly but remains conducting for a period called reverse recovery time which is sum of storage and fall delay times..

Analysis using non-linear diode model is not easy



$$V_S = IR + V_O \quad (1)$$

$$I = I_S \times \{\exp(\frac{V_O}{nV_T}) - 1\} \quad (2)$$

$$\Rightarrow \quad V_O = nV_T \times \ln(\frac{\mathrm{I}}{\mathrm{I_S}} + 1) \quad (3)$$

$$\Rightarrow \quad V_S = IR + nV_T \times \ln(\frac{\mathrm{I}}{\mathrm{I_S}} + 1) \quad (4)$$

Iterative Method:

$$V_S = IR + V_O \quad (1)$$

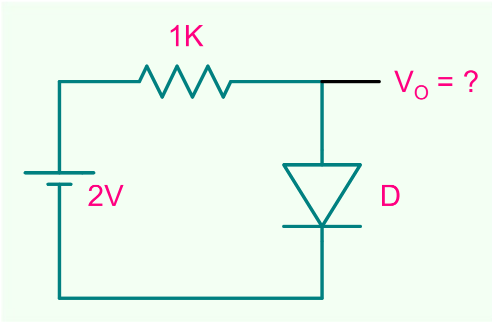
$$I = I_S \times \{\exp(\frac{V_O}{nV_T}) - 1\} \; (2)$$

Assume $V_O = 0.6\text{V}$

Calculate $I = \dfrac{V_S - V_O}{R}$

Re-calculate $V_O = nV_T \times \ln(\mathrm{I}/\mathrm{I_S} + 1)$

Convergence: $\dfrac{\Delta I}{I} \leq \varepsilon$



$$I = I_S \times \{\exp(\frac{V}{V_T}) - 1\}$$

$$I_S = 2 \times 10^{-15}\ A$$

$$V_T = kT / q \cong 26\ mV \text{ at } T = 300K$$

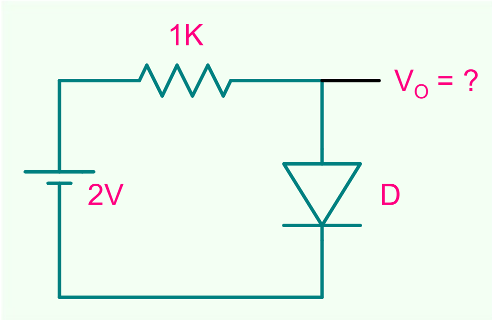
Assume V_O

$$I = \frac{V_S - V_O}{R}$$

$$V_O = nV_T \times \ln(I/I_S + 1)$$

$V_O = 0.5$	$V_O = 0.711$	$V_O = 0.707$
$I = 1.5 \times 10^{-3}$	$I = 1.289 \times 10^{-3}$	$I = 1.293 \times 10^{-3}$
$V_O = 0.711$	$V_O = 0.707$	$V_O = 0.707$

CONVERGENCE



$$I = I_S \times \{\exp(\frac{V}{V_T}) - 1\}$$

$$I_S = 2 \times 10^{-15}\ A$$

$$V_T = kT\ /\ q \cong\ 26\ mV \quad \text{at T} = 300\text{K}$$

Assume V_O

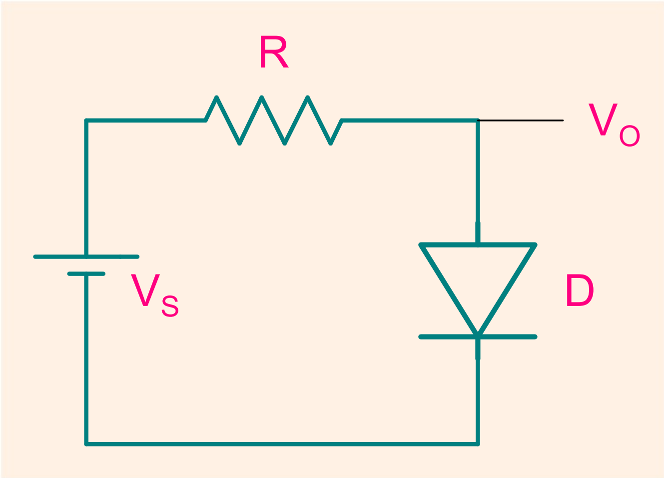
$$I = \frac{V_S - V_O}{R}$$

$$V_O = nV_T \times \ln(\mathrm{I}/\mathrm{I_S} + 1)$$

$V_O = 1.0$	$V_O = 0.7$	$V_O = 0.707$
$I = 1.0 \times 10^{-3}$	$I = 1.3 \times 10^{-3}$	$I = 1.293 \times 10^{-3}$
$V_O = 0.7$	$V_O = 0.707$	$V_O = 0.707$

CONVERGENCE to the same Result

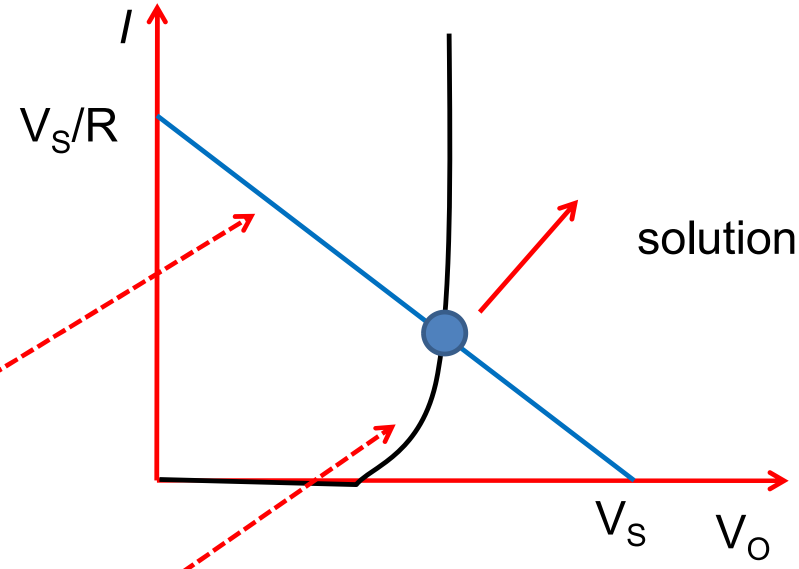
Graphical Method: Method of Load Line

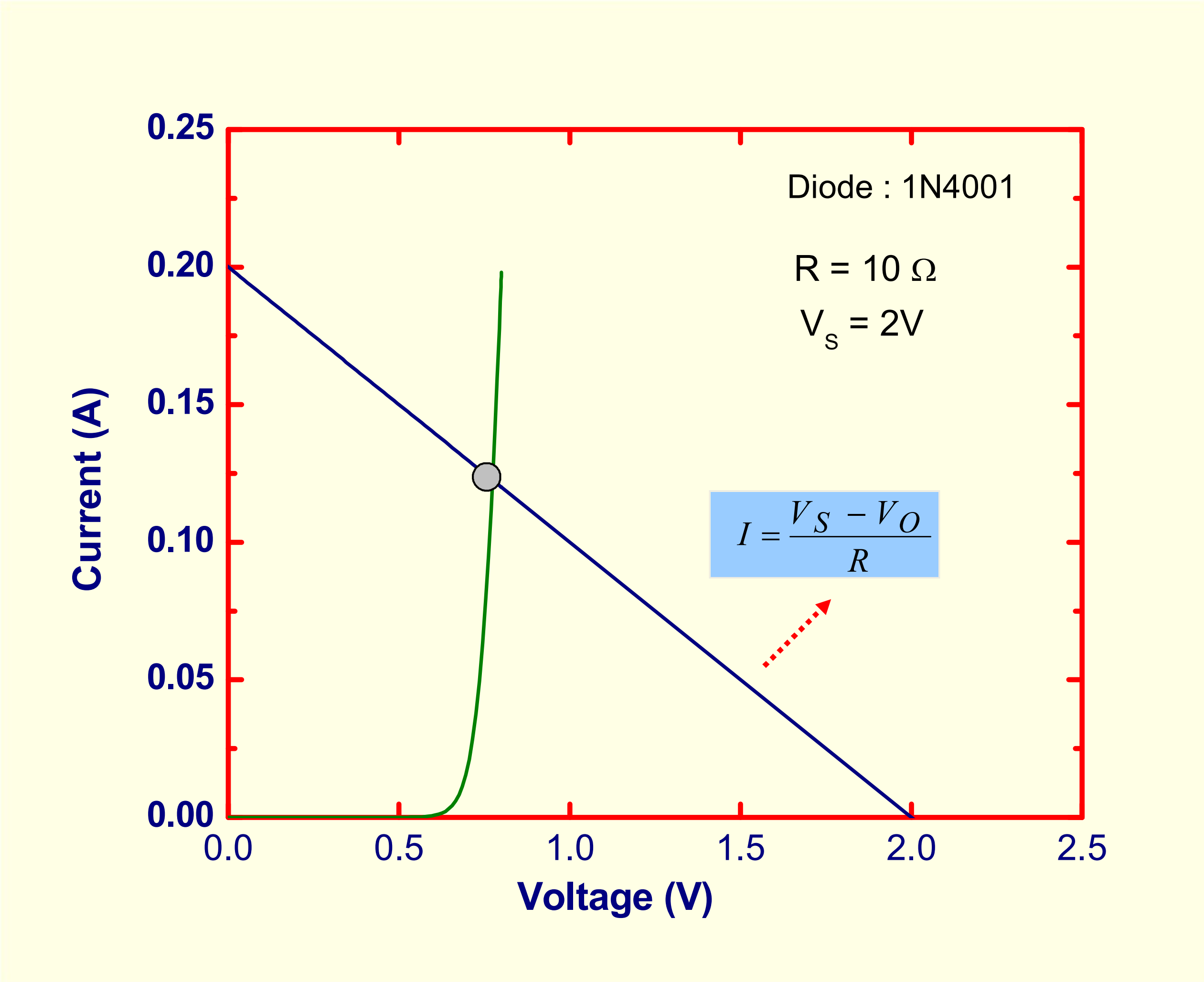


$$V_S = I \times R + V_O$$

$$I = \frac{V_S - V_O}{R}$$

$$I = I_S \times \{\exp(\frac{V_O}{nV_T}) - 1\}$$





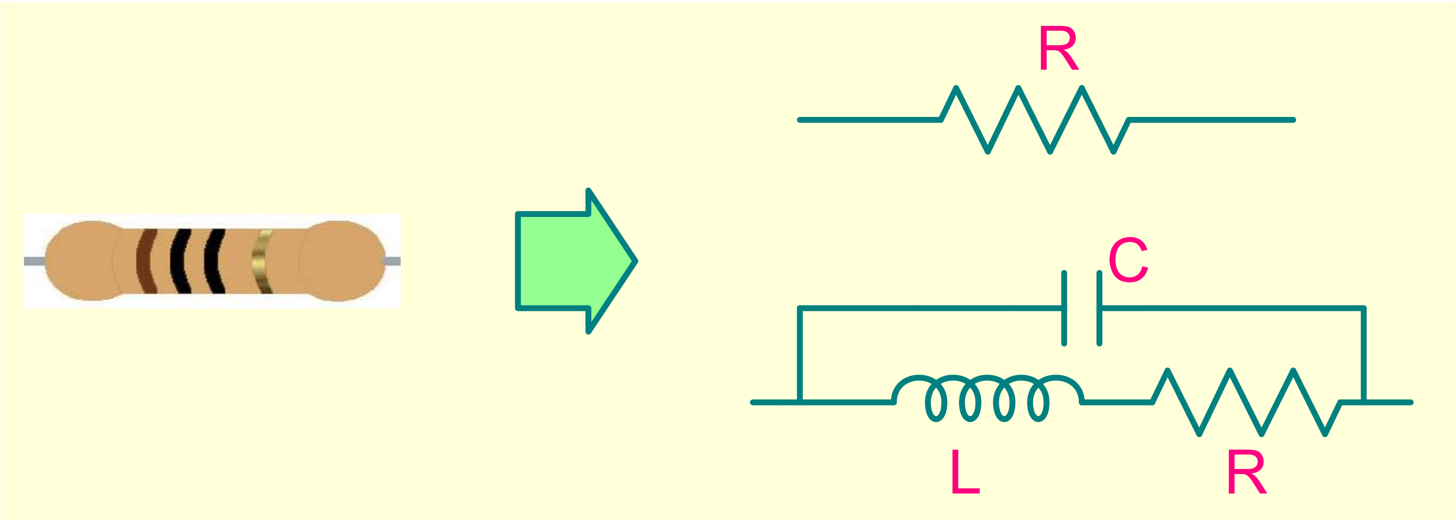
V_O = 0.77V; I = 0.12A

For hand analysis of circuits, we need simpler models!

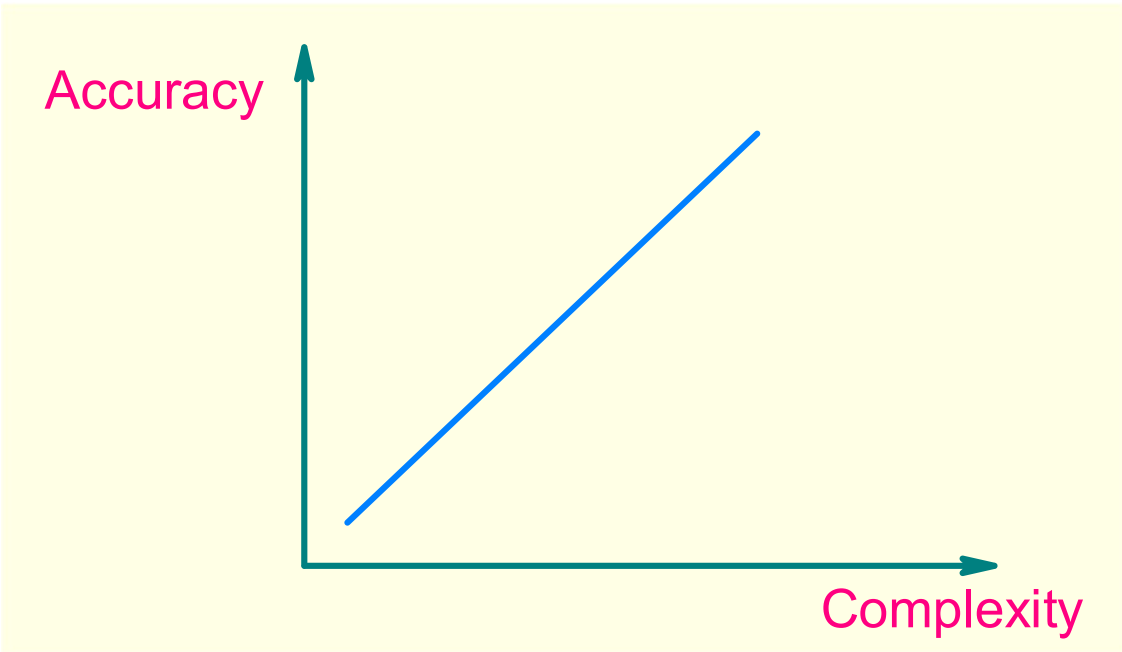
What is a model?

"A model is a representation for a PURPOSE"

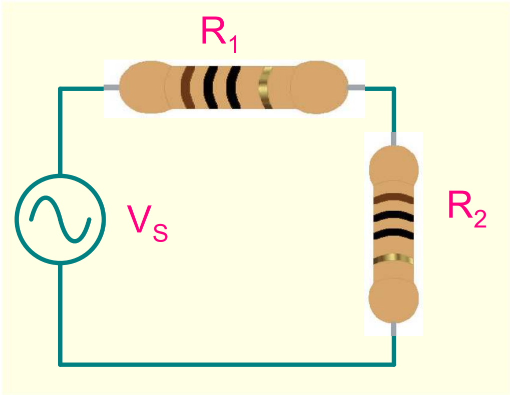
Depending on the purpose, an element can have several different models

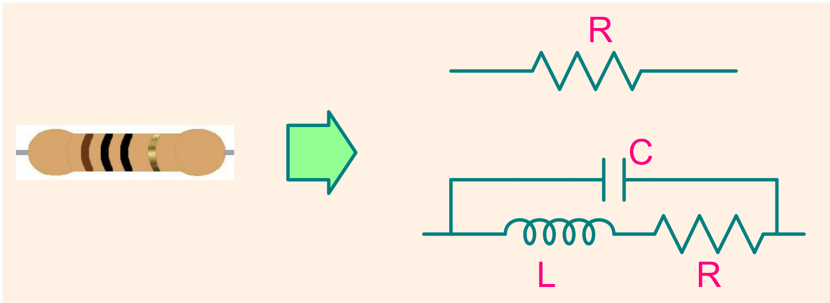


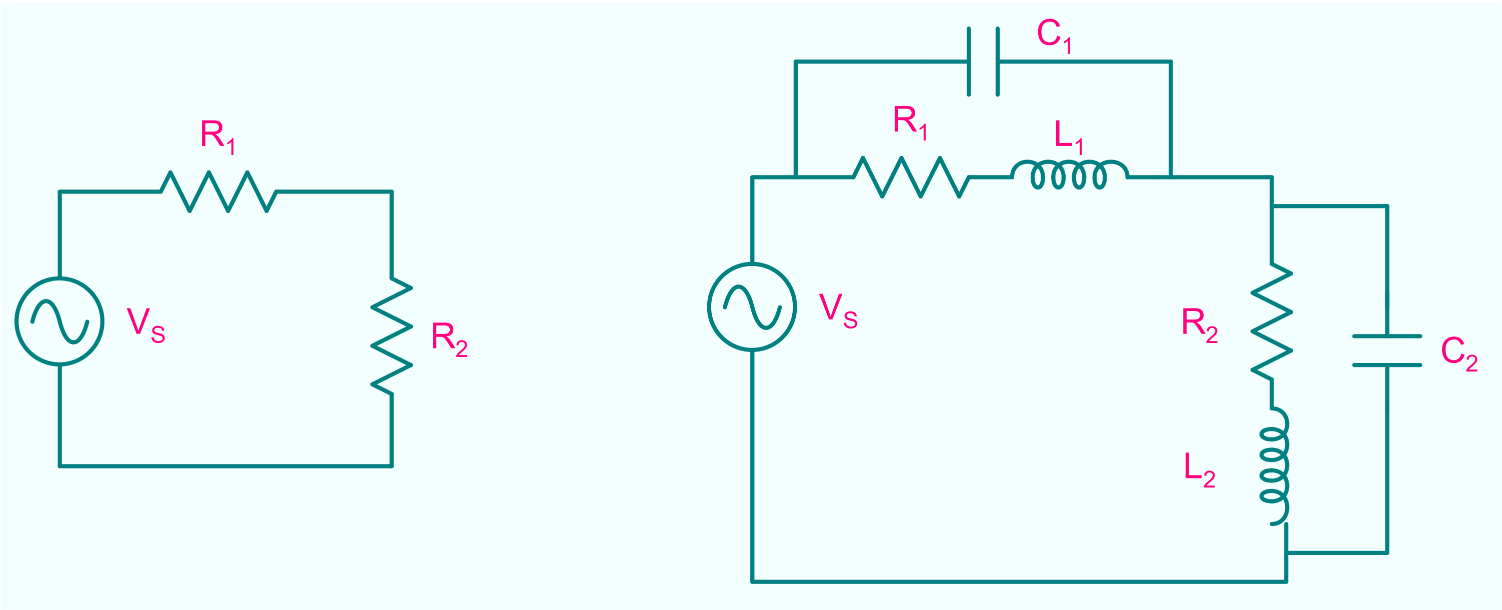
In general, there is a tradeoff between Accuracy and Complexity of model



What is the use of a less accurate model?

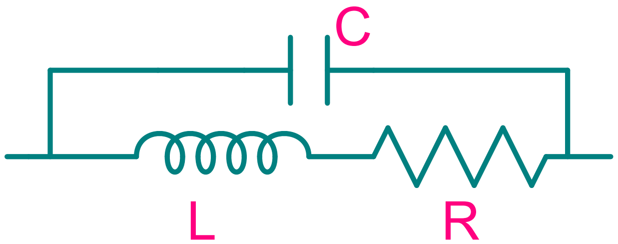






1. A simpler model makes analysis easier

$$\frac{V_2}{V_S} = \frac{R_2}{R_1 + R_2}$$



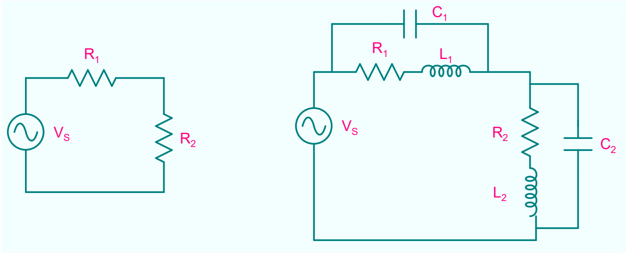
$$\frac{V_2}{V_S} = \frac{R_2 + j\omega L_2}{R_2 + j\omega L_2 + (R_1 + j\omega L_1)\dfrac{j\omega C_2 R_2 - \omega^2 L_2 C_2 + 1}{j\omega C_1 R_1 - \omega^2 L_1 C_1 + 1}}$$

The results of analysis are easier to understand

3. The results of analysis can be used easily to carry out the design

Design the circuit such that :

$$\frac{V_2}{V_S} = 0.2 \quad \text{at 1kHz frequency}$$

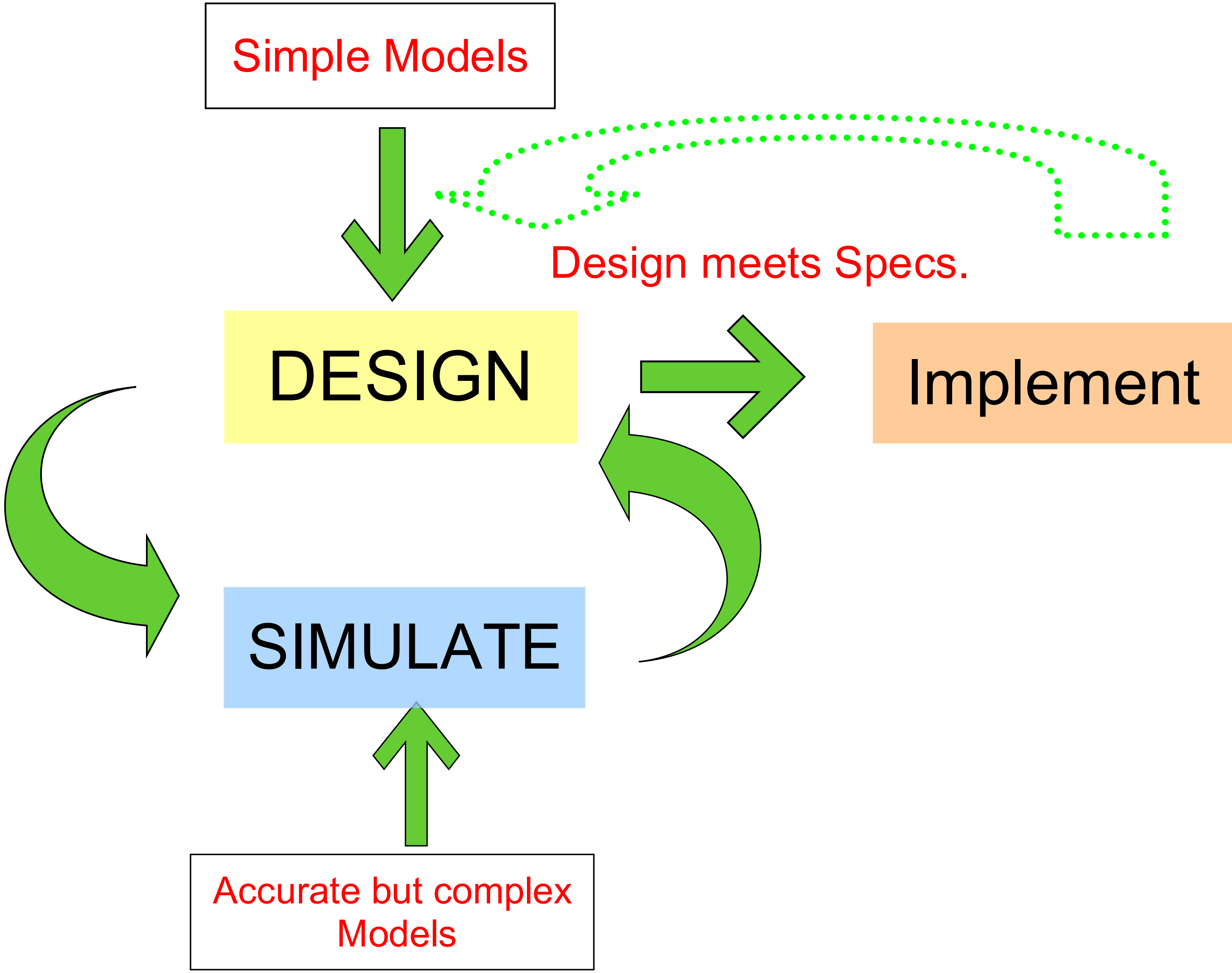


$$\frac{R_2}{R_1 + R_2} = 0.2 \quad \Rightarrow \quad \frac{R_1}{R_2} = 4$$

Try doing the design with this expression:

$$\frac{V_2}{V_S} = \frac{R_2 + j\omega L_2}{R_2 + j\omega L_2 + (R_1 + j\omega L_1)\dfrac{j\omega C_2 R_2 - \omega^2 L_2 C_2 + 1}{j\omega C_1 R_1 - \omega^2 L_1 C_1 + 1}}$$

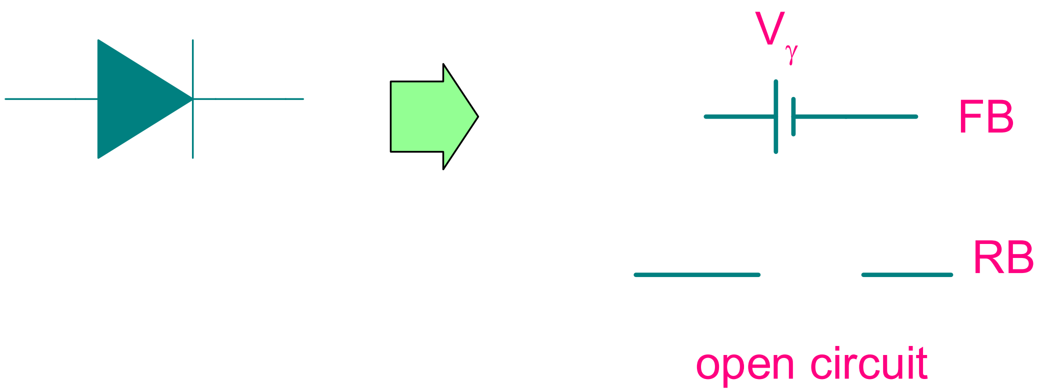
Role of simple model in design cycle



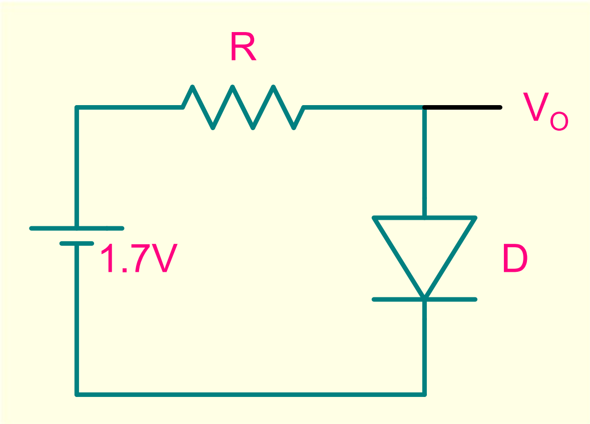
•Analysis using a non-linear diode model is relatively difficult and time consuming.

•It also does not give a symbolic expression that can provide insight and help in the design of the circuit.

Need SIMPLER and LINEAR Device Models



What should we take as diode drop?.....0.7V?



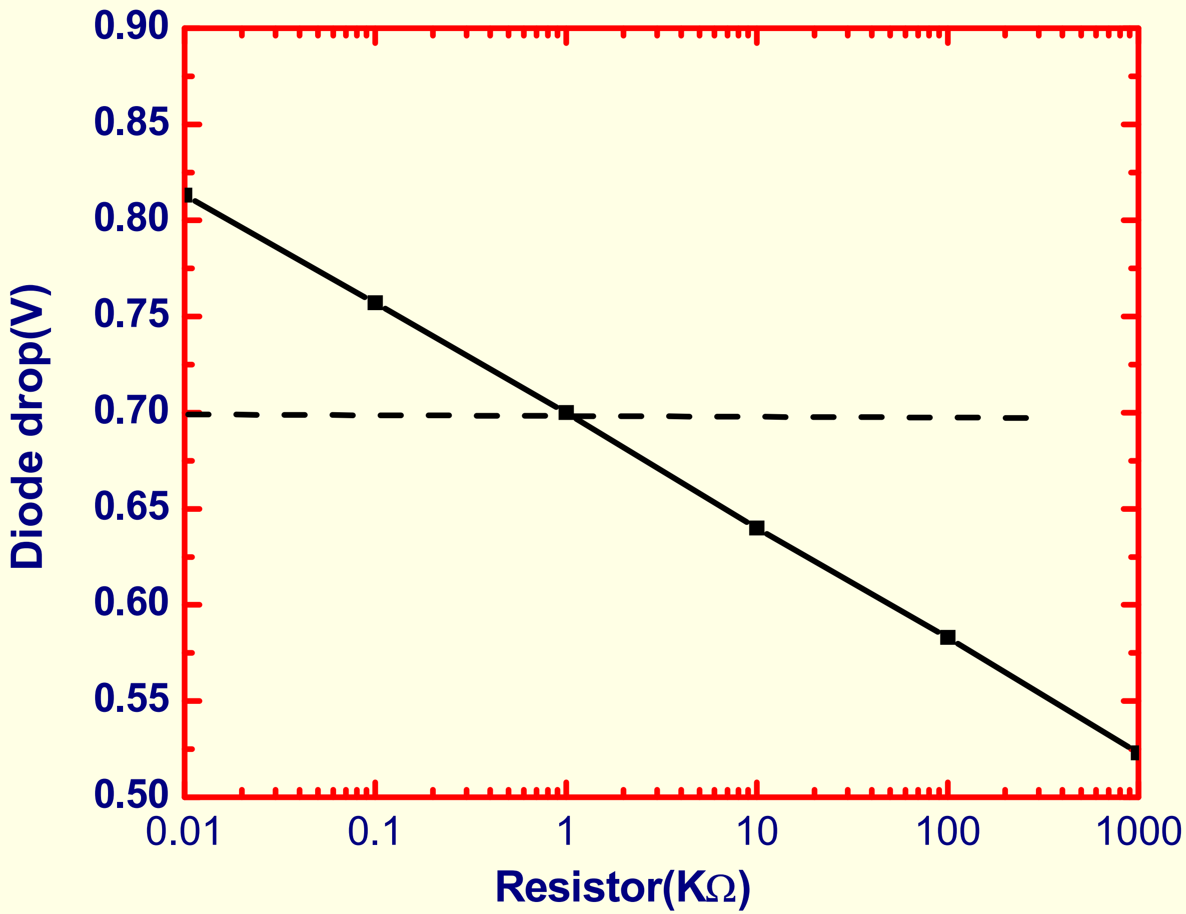
$$I = I_S \times \{\exp(\frac{V}{V_T}) - 1\}$$

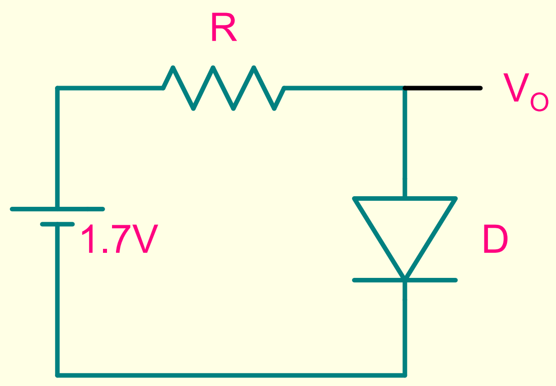
$$I_S = 2 \times 10^{-15}\ A$$

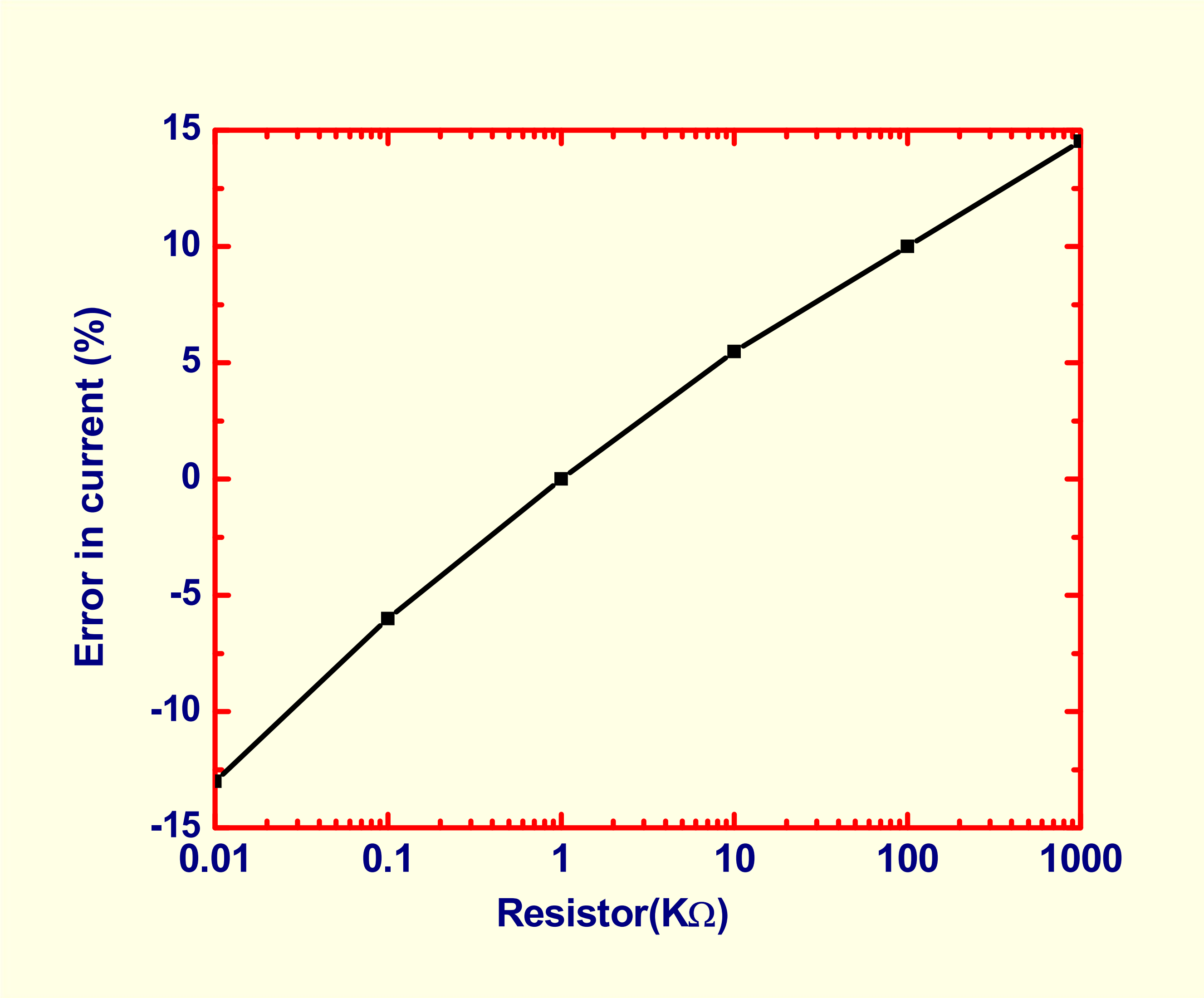
$$V_T = kT / q \cong 26\ mV \quad \text{at T} = 300\text{K}$$

$$R:\ 10\Omega \rightarrow 1M\Omega$$

Simple 0.7V model would predict: $I = \frac{1}{R}$


0.90
0.85
0.80
0.75
0.70
0.65
0.60
0.55
0.50
Diode drop(V)
0.01
0.1
1
10
100
1000
Resistor(KΩ)

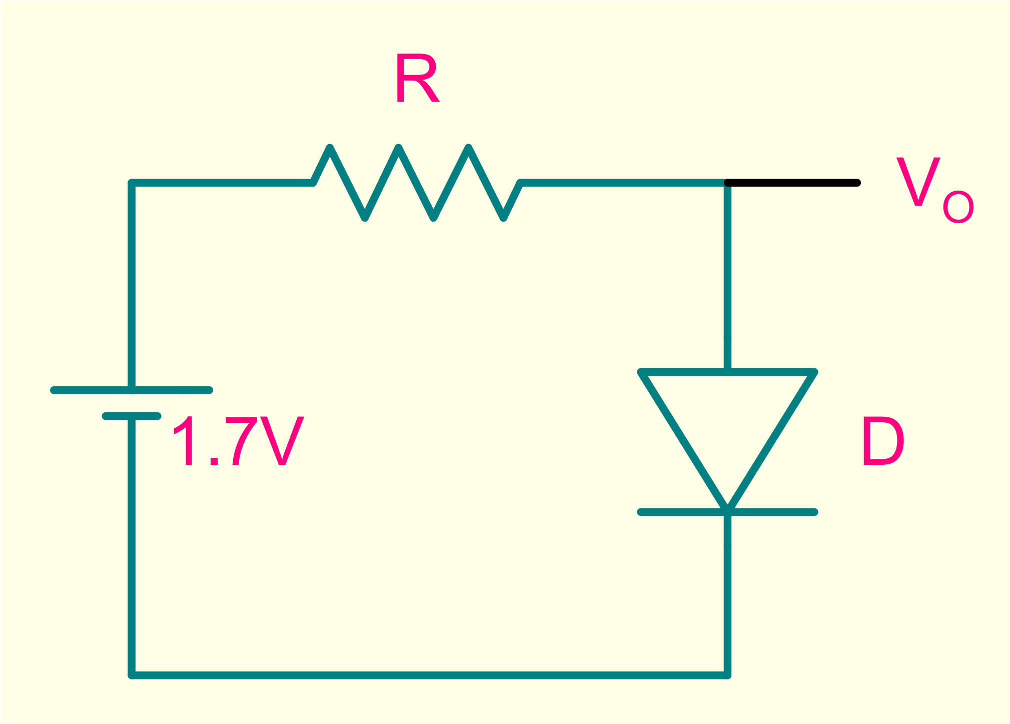

R
VO
1.7V
D



15
10
5
0
-5
-10
-15
Error in current (%)
0.01
0.1
1
10
100
1000
Resistor(KΩ)

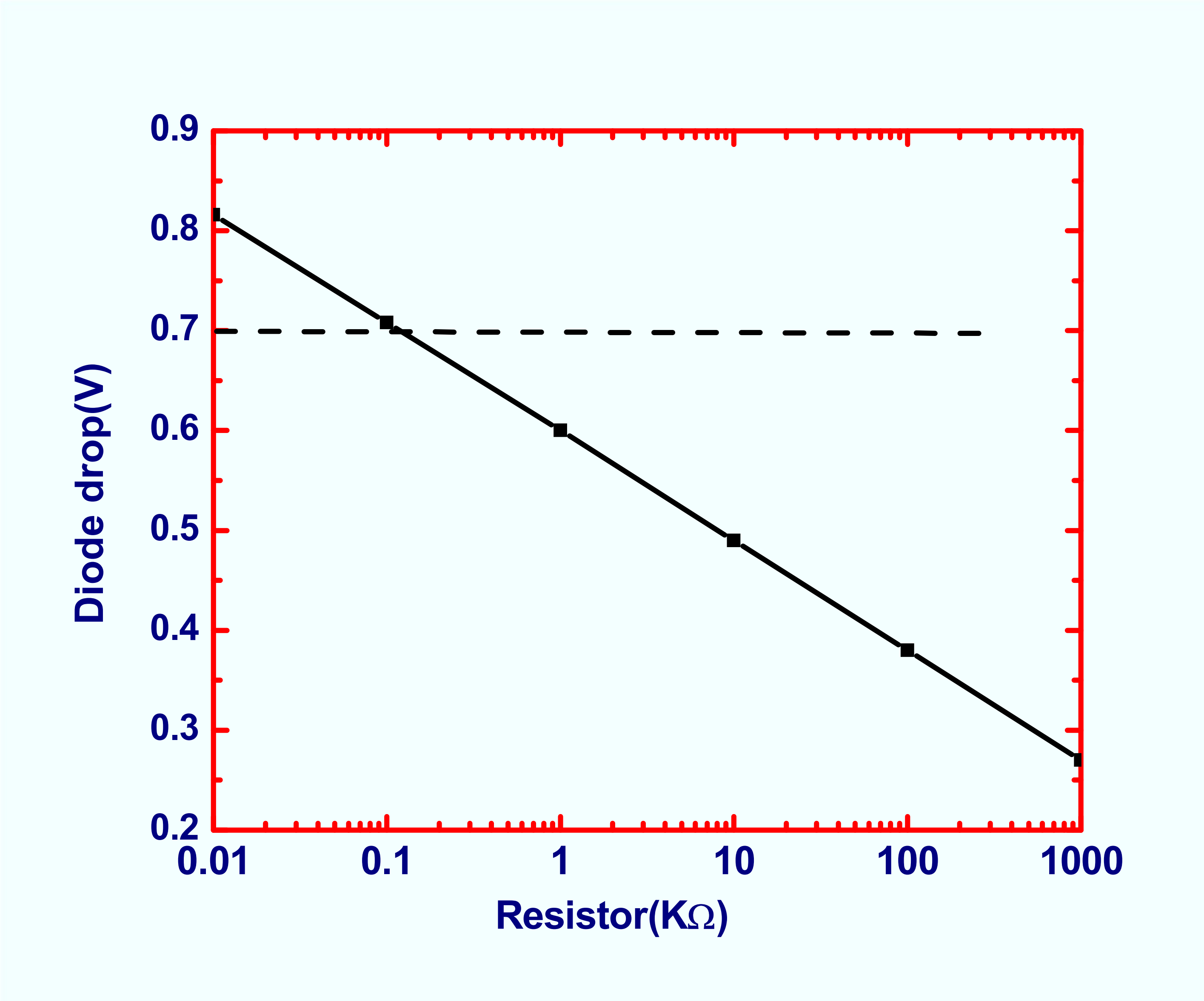
(100mA - 1μA)

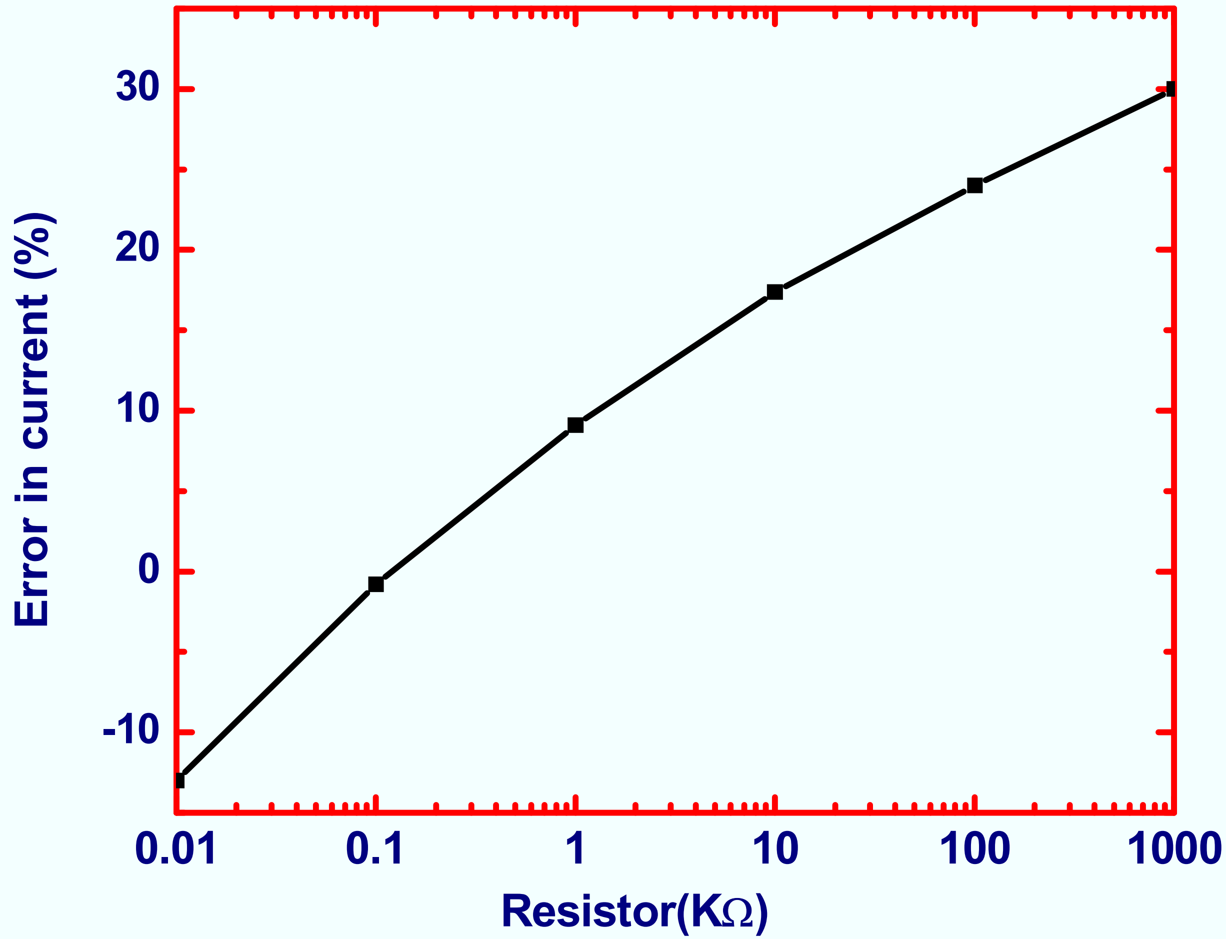
Different Diode: ~1N4148



$$I = I_S \times \{\exp(\frac{V}{nV_T}) - 1\}$$

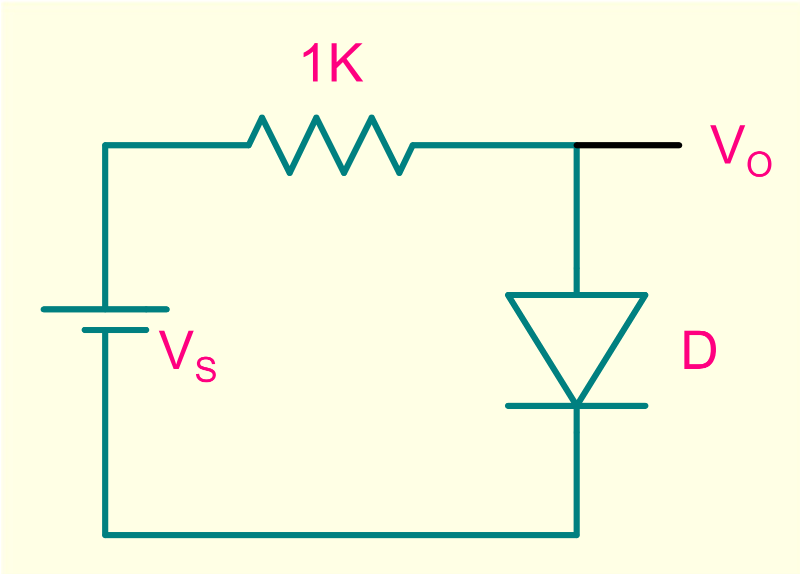
$$I_S = 5.9 \times 10^{-9} A \; ; \; n = 1.91$$


0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
Diode drop(V)
0.01
0.1
1
10
100
1000
Resistor(KΩ)



Error in current (%)
30
20
10
0
-10
0.01
0.1
1
10
100
1000
Resistor(KΩ)

Constant diode voltage approximation becomes worse as applied voltage approaches the diode drop !



$$I = \frac{V_S - V_D}{R}$$

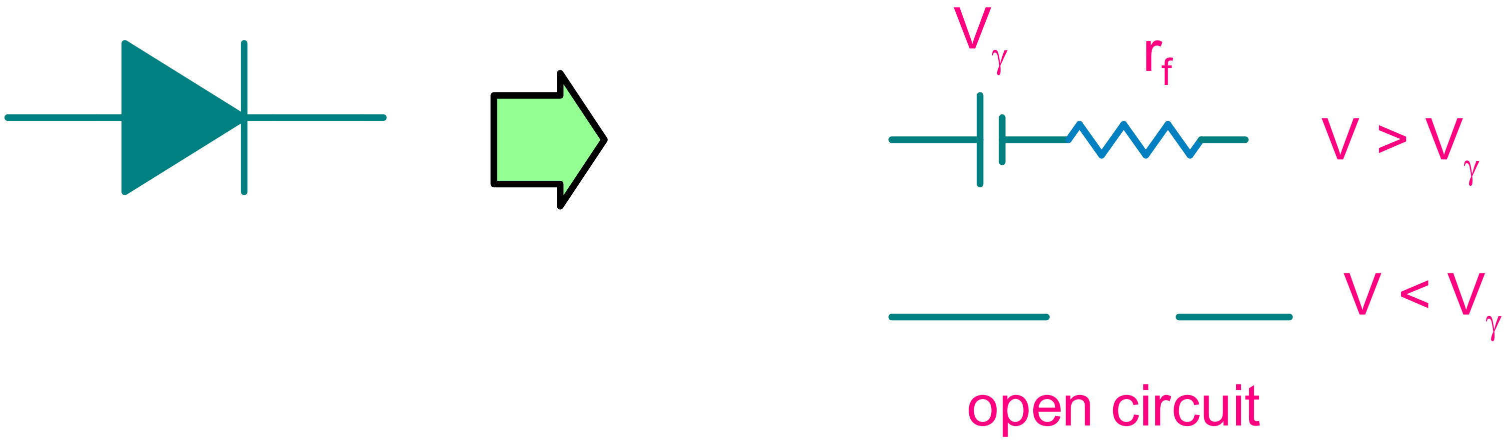
$$\Delta I = -\frac{\Delta V_D}{R}$$

$$\frac{\Delta I}{I} = -\left(\frac{\Delta V_D}{V_S - V_D}\right)$$

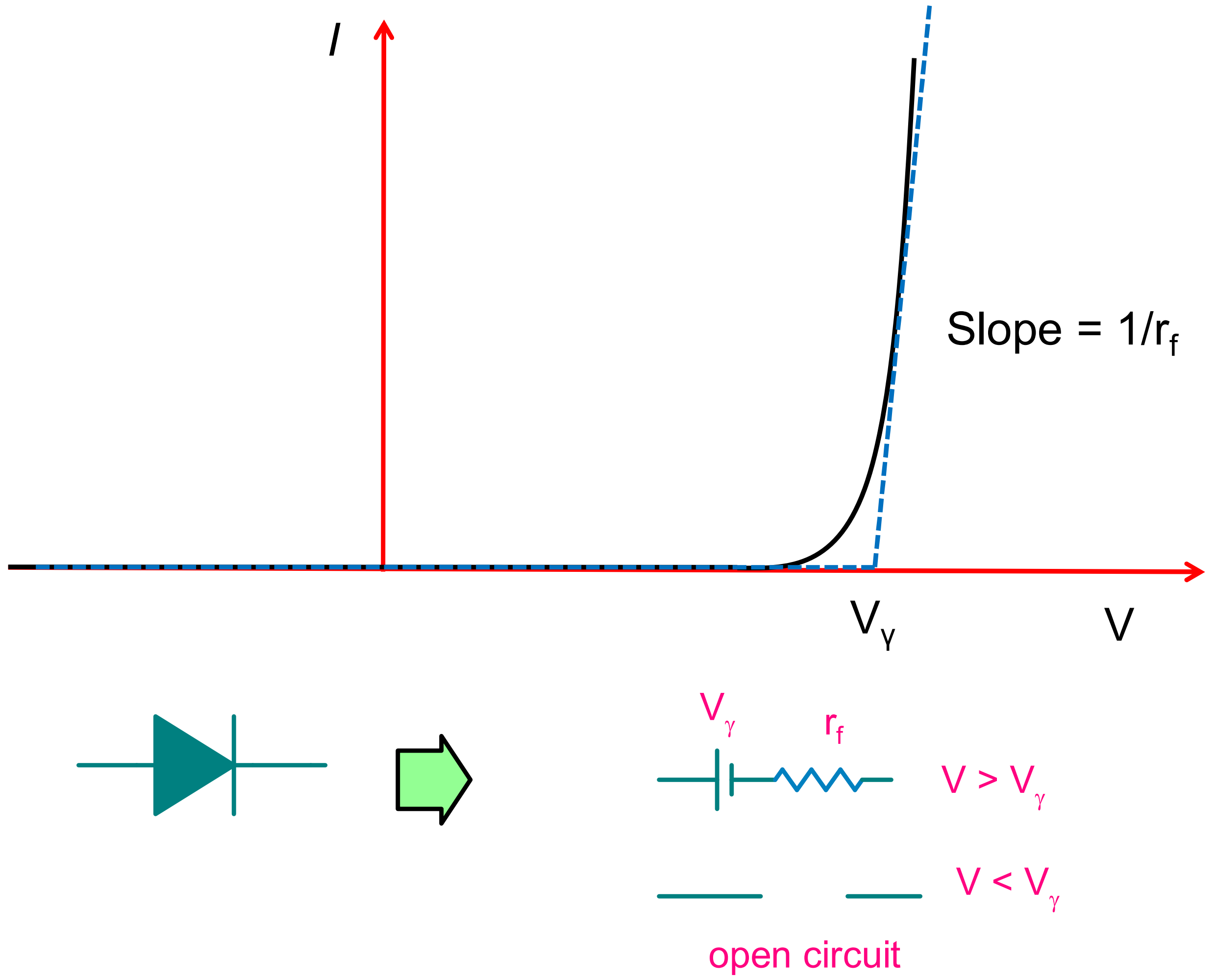
As $\mathbf{V}_s$ approaches $\mathrm{V_D} \rightarrow \left(\frac{\Delta I}{I}\right)$ increases

Error was ~9% with 1.7 V but 63% with 0.8V supply

A better Diode Model



Piece-Wise Linear Model

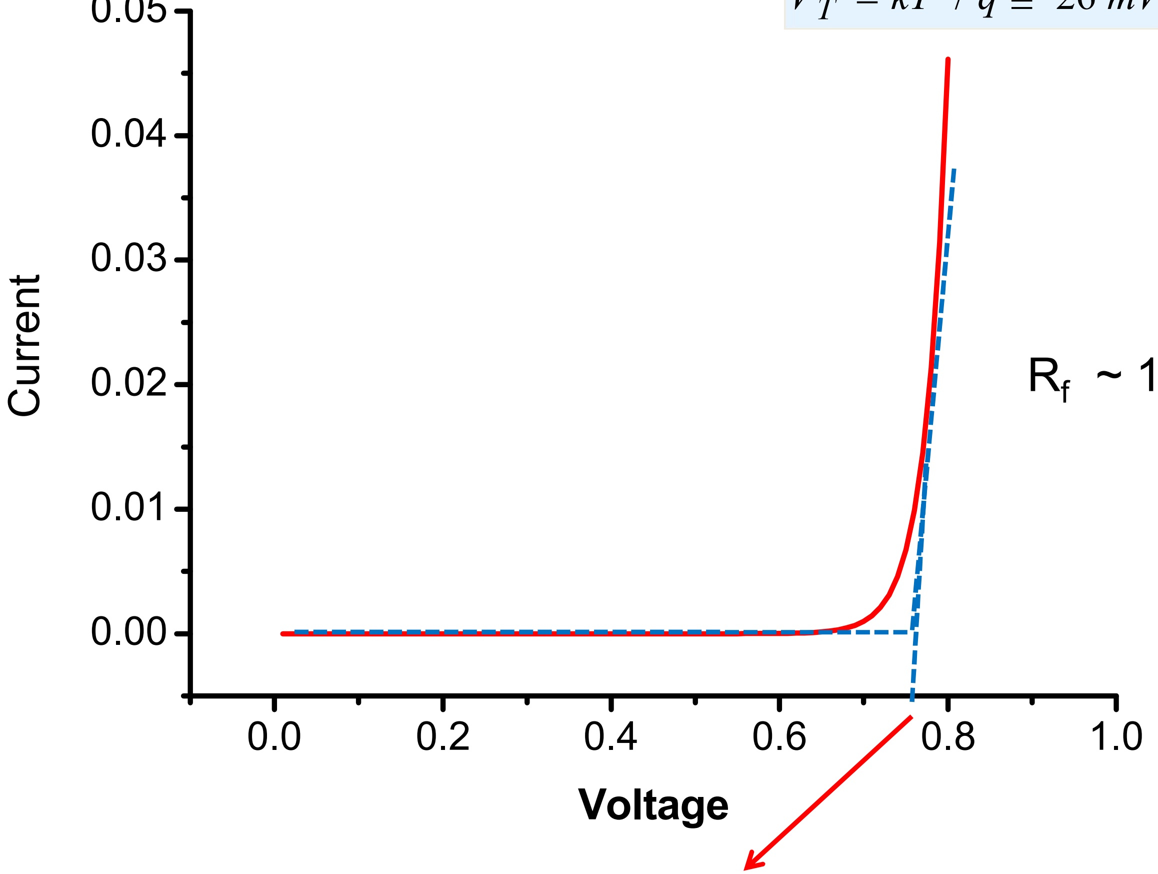


V_γ is called cut-in or turn-on voltage and depends on nature of diode and range of current considered

$$I = I_S \times \{\exp(\frac{V}{V_T}) - 1\}$$

$$I_S = 2 \times 10^{-15}\ A$$

$$V_T = kT\ /\ q \cong\ 26\ mV\ \text{ at } \mathrm{T} = 300\mathrm{K}$$



R_f ~ 1.4Ω

V_γ = 0.75V

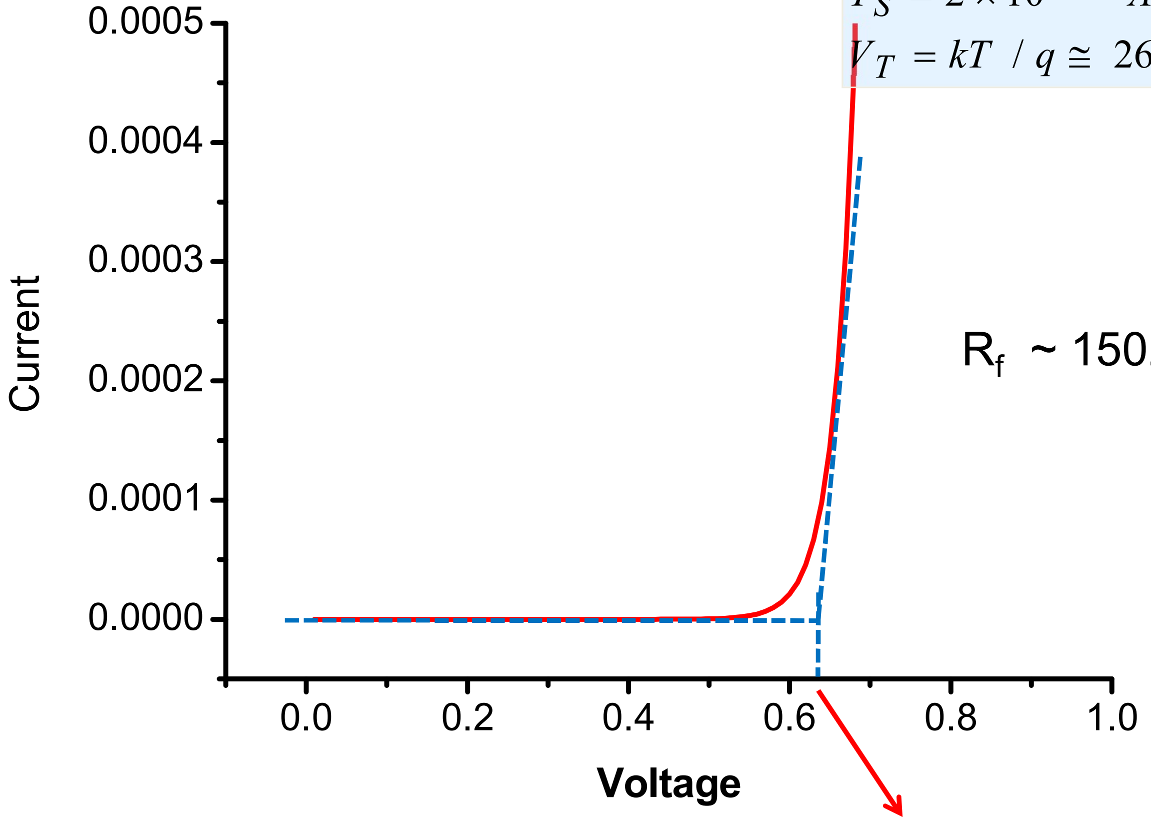
Current ~ 25mA

Current ~ 0.25mA

$$I = I_S \times \{\exp(\frac{V}{V_T}) - 1\}$$

$$I_S = 2 \times 10^{-15}\ A$$

$$V_T = kT / q \cong 26\ mV \text{ at } T = 300K$$

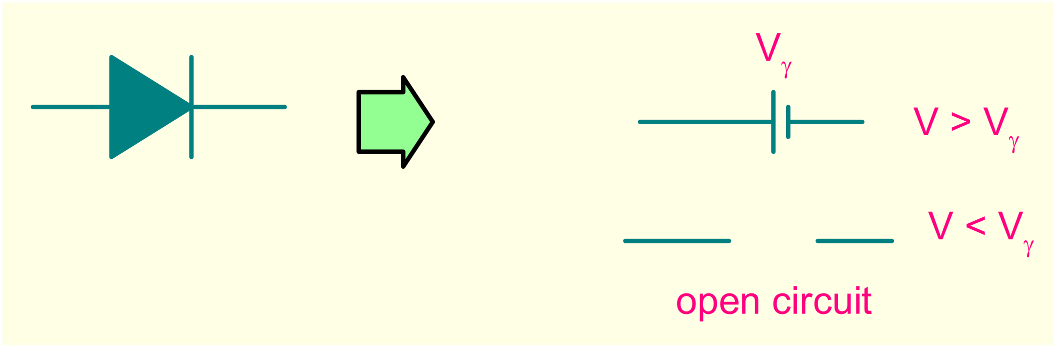


R_f ~ 150Ω

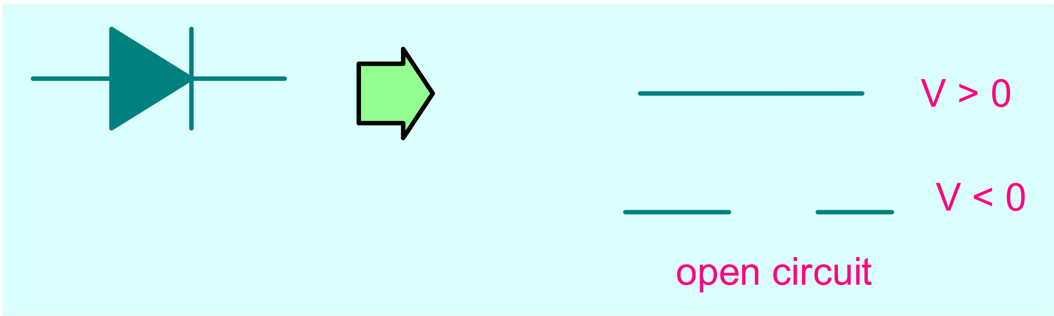
V_γ = 0.63V

For most of our analysis, we will take V_γ = 0.7V and r_f ~10Ω

Even Simpler Diode Models

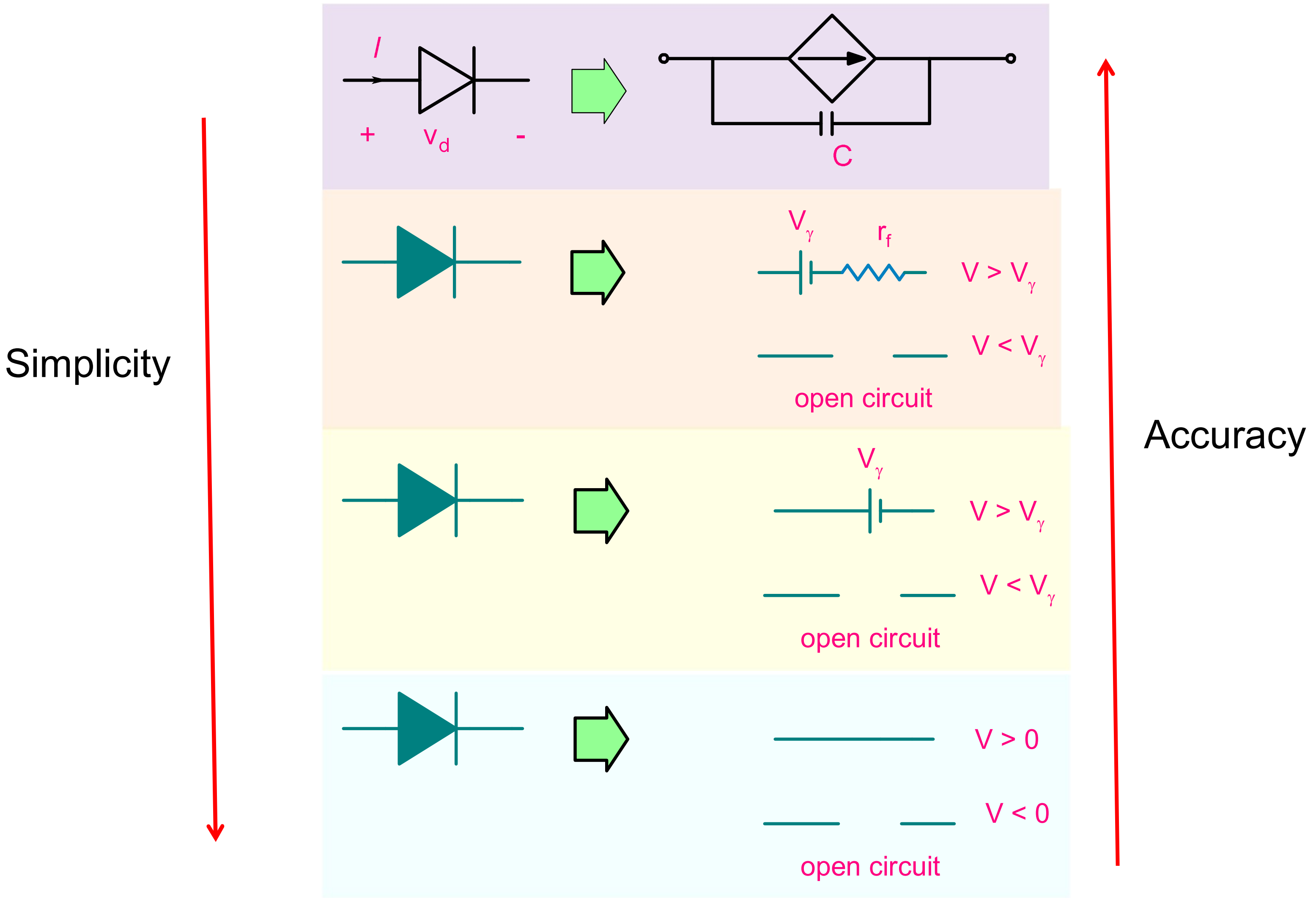


Ideal diode model

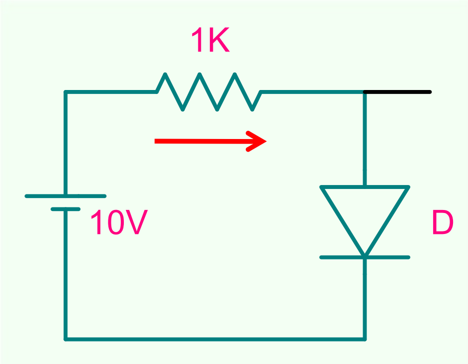


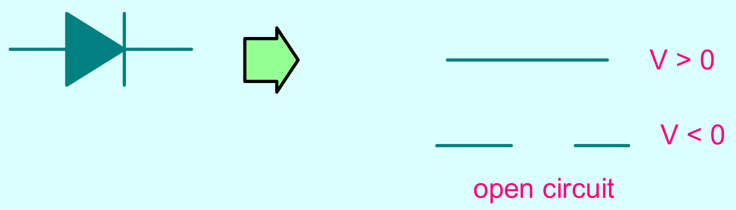
Diode Models

$$I = I_S \times \{\exp(\frac{v_d}{V_T}) - 1\}$$



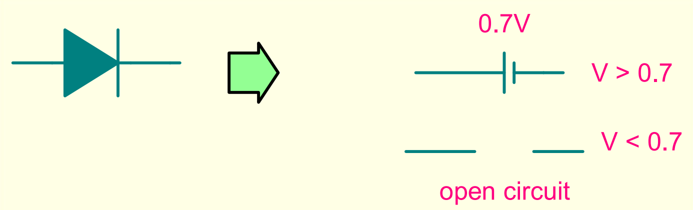
Use the simplest model that will yield results with desired accuracy





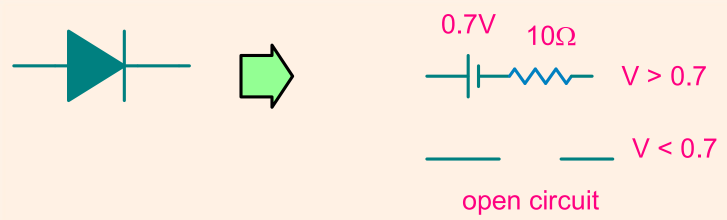
$$I = 10/10^3 = 10\,mA$$

8.2%



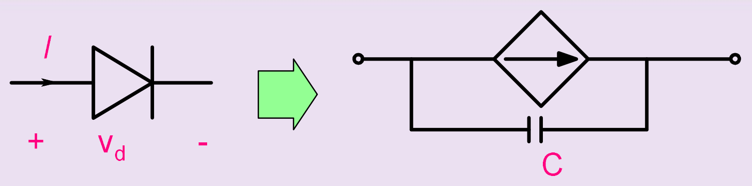
$$I = (10 - 0.7)/10^3 = 9.3\,mA$$

0.65%



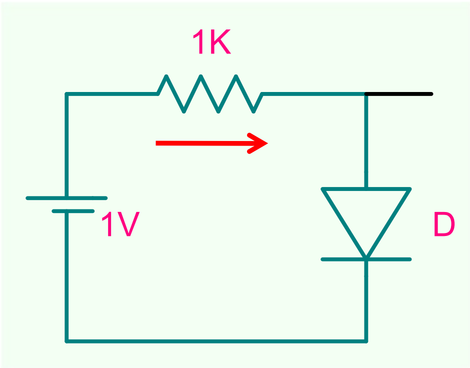
$$I = (10 - 0.7)/(10^3 + 10) = 9.208\,mA$$

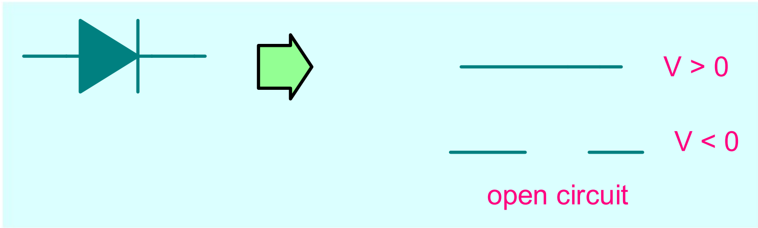
-0.34%



$$I = 9.24\,mA$$

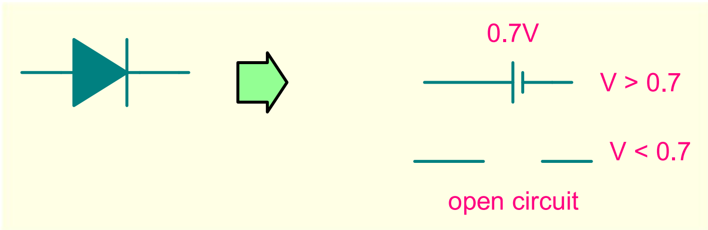
Use the simplest model that will yield results with desired accuracy





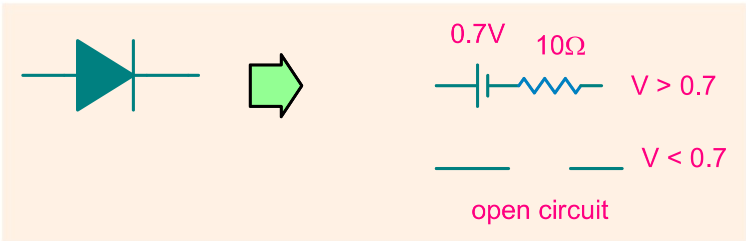
$$I = 1/10^3 = 1mA$$

~200%



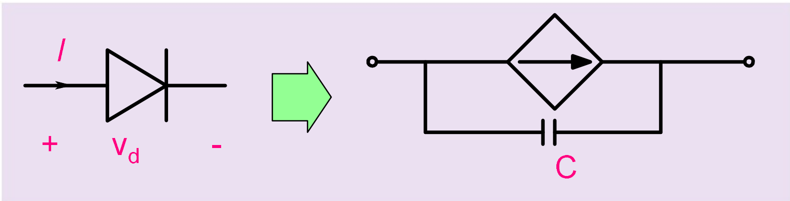
$$I = (1-0.7)/10^3 = 0.3mA$$

-8.8%



$$I = (1-0.7)/(10^3+10) = 0.297mA$$

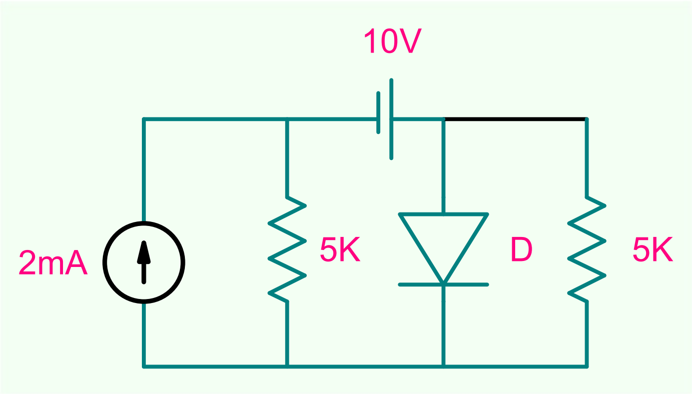
-9.7%



$$I = 0.329mA$$

Example

Find the current through the diode using ideal diode model



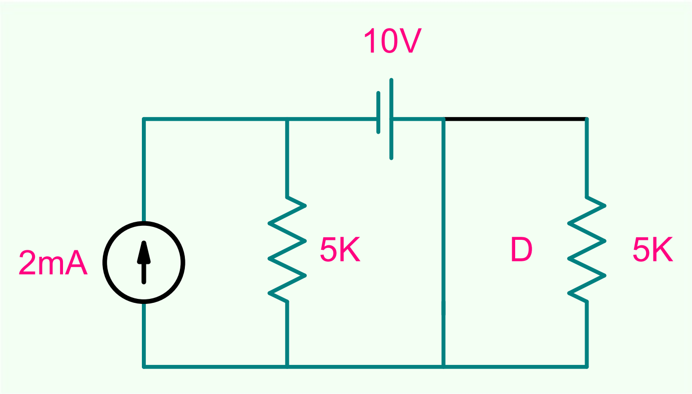
If it is not evident whether diode is forward or reverse biased then we can assume that it is forward biased, carry out analysis and then check if current through the diode is in appropriate direction. If not, diode is reverse biased and we carry out analysis again.

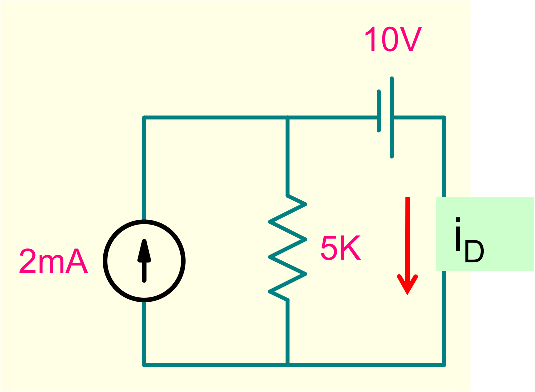
$$-2mA + \frac{-10}{5K} + i_D = 0$$

Assume forward bias

$$i_D = 4mA$$

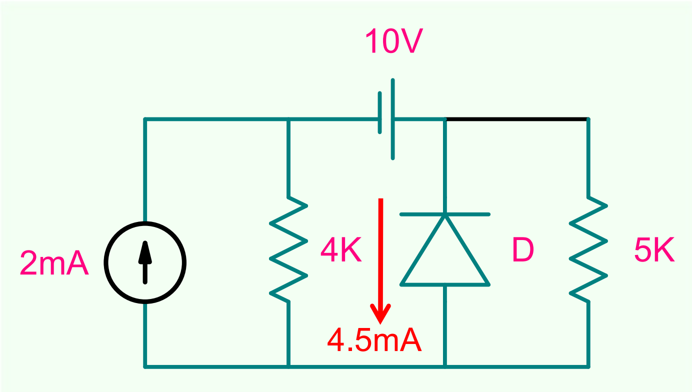
Current is positive, so our assumption is correct





Example

Find the current through the 5K resistor using ideal diode model

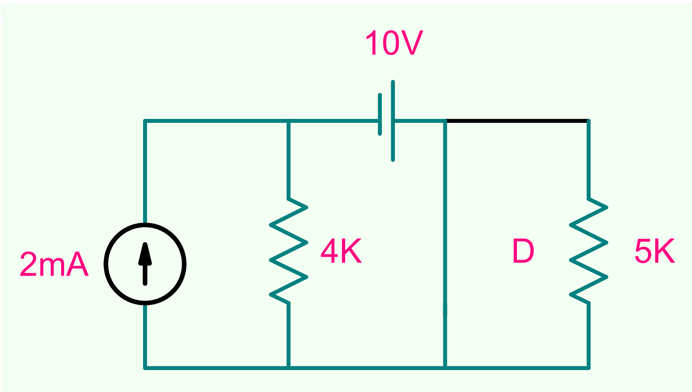


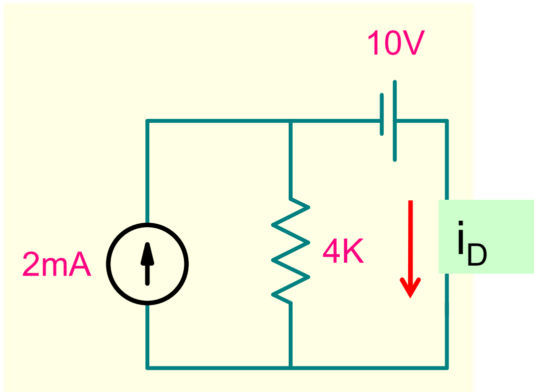
$$-2mA + \frac{-10}{4K} + i_D = 0$$

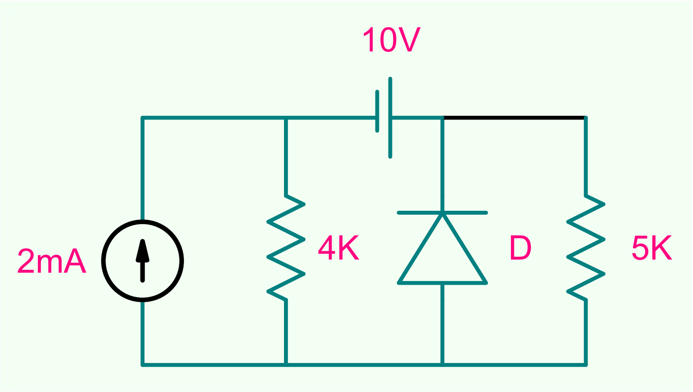
$$i_D = 4.5mA$$

Assume forward bias

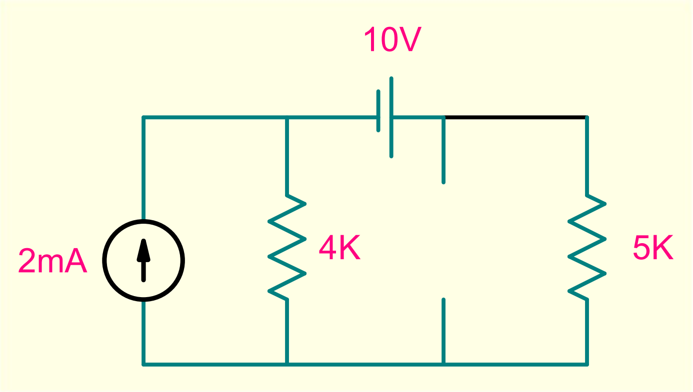
But this cannot be, so our assumption is incorrect



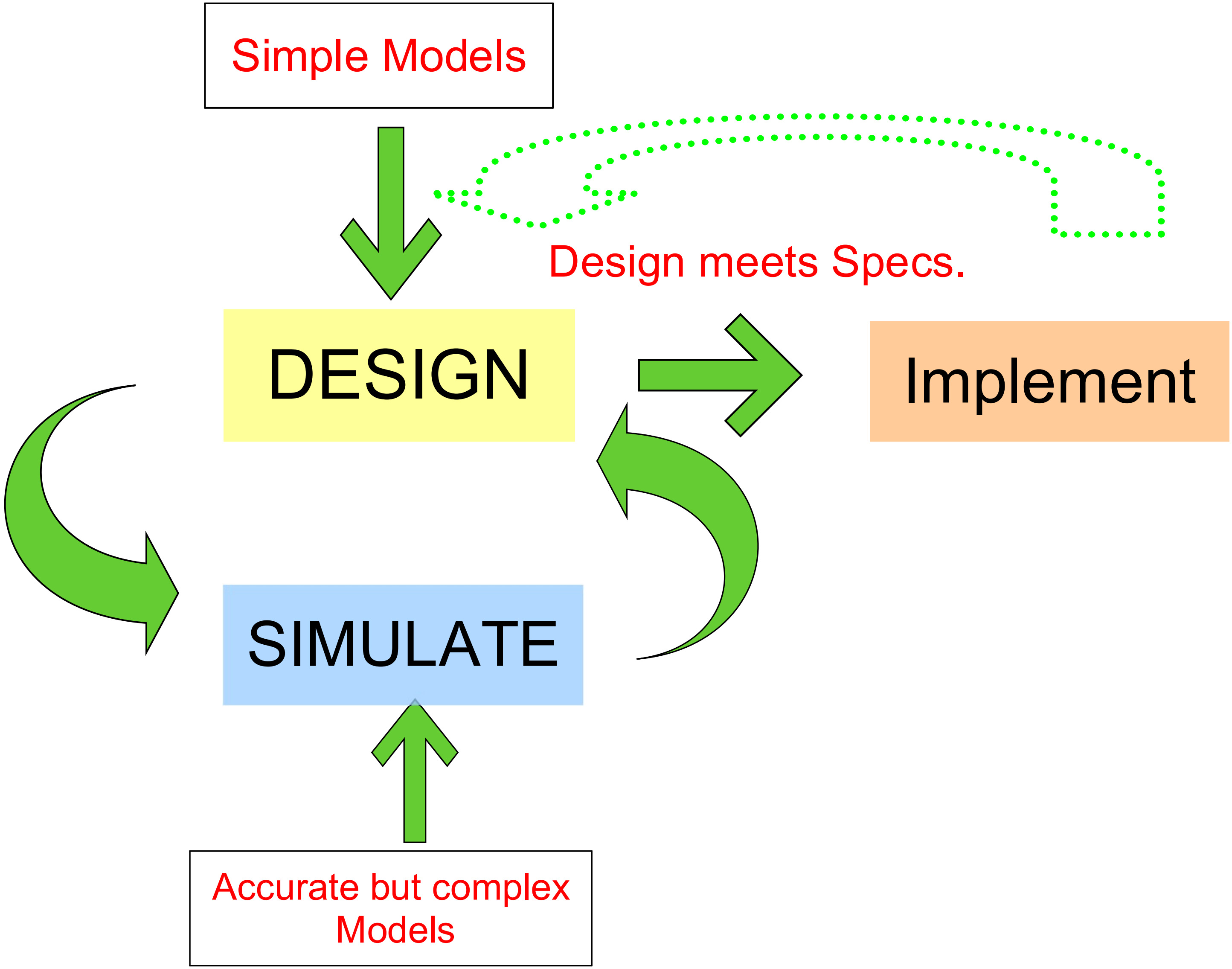




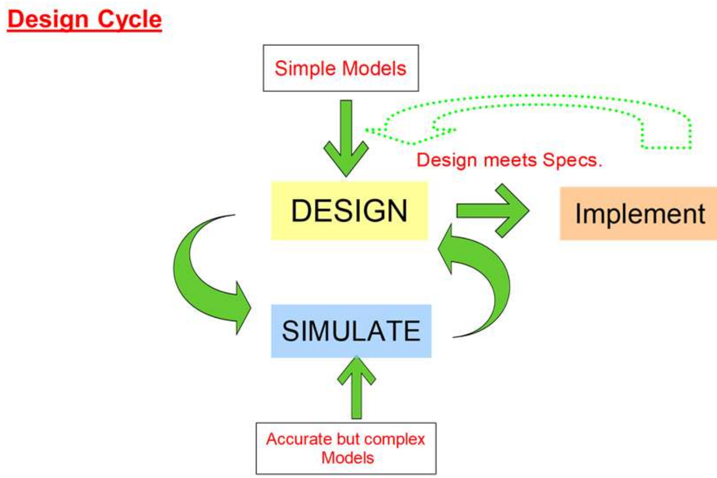
Assume reverse bias

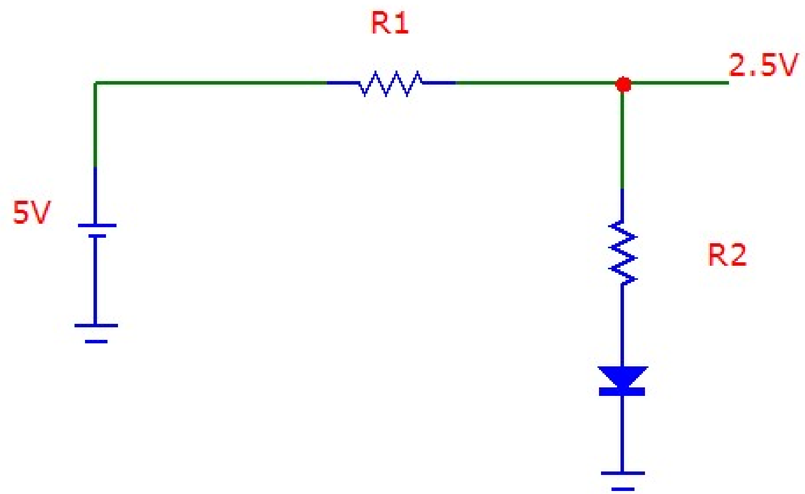


Design Cycle

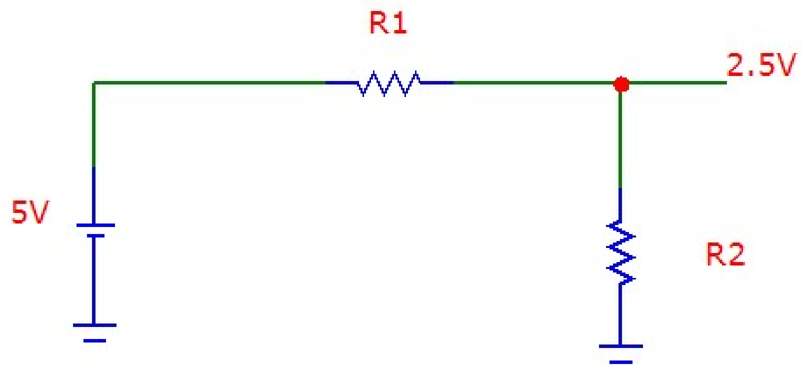


Design the following circuit





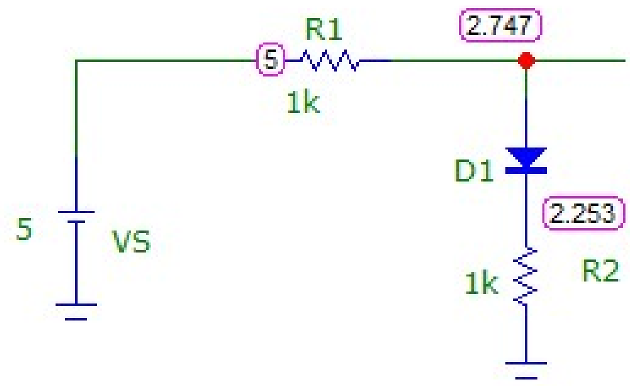
Assuming ideal diode model



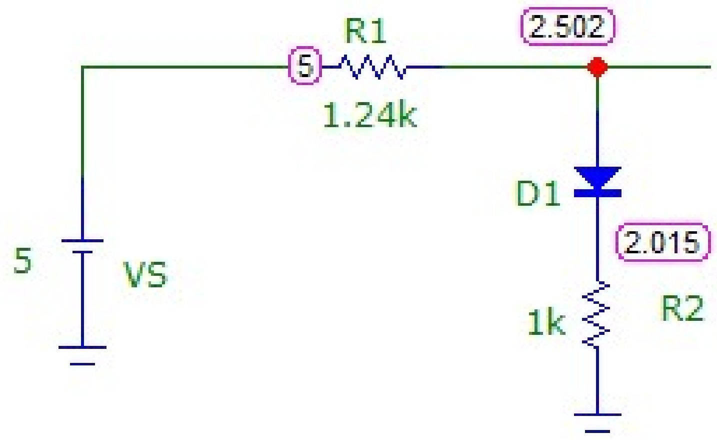
$R_1 = R_2 = 1K$

Carry out simulations to fine tune the design

Initial design



Final Design



ESC201T : Introduction to Electronics

Lecture 22: Diode Circuits

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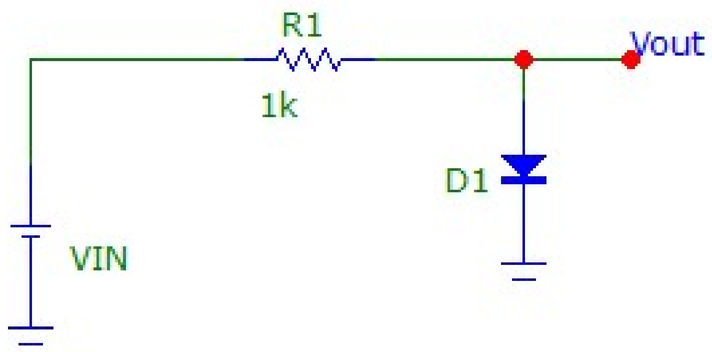
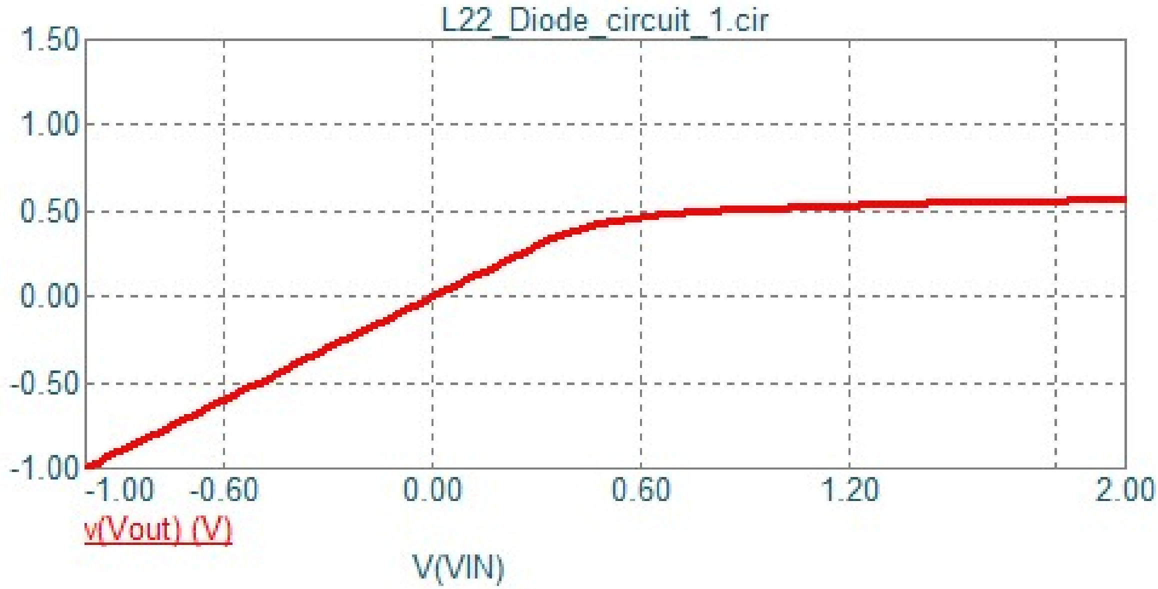
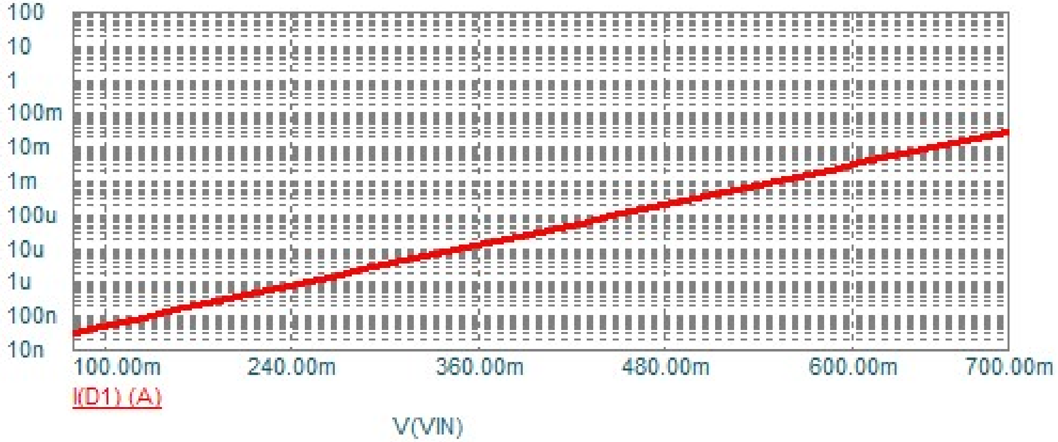
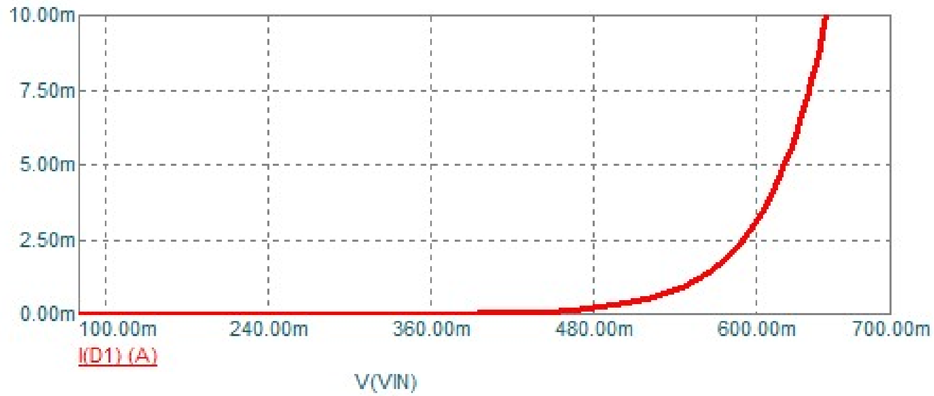
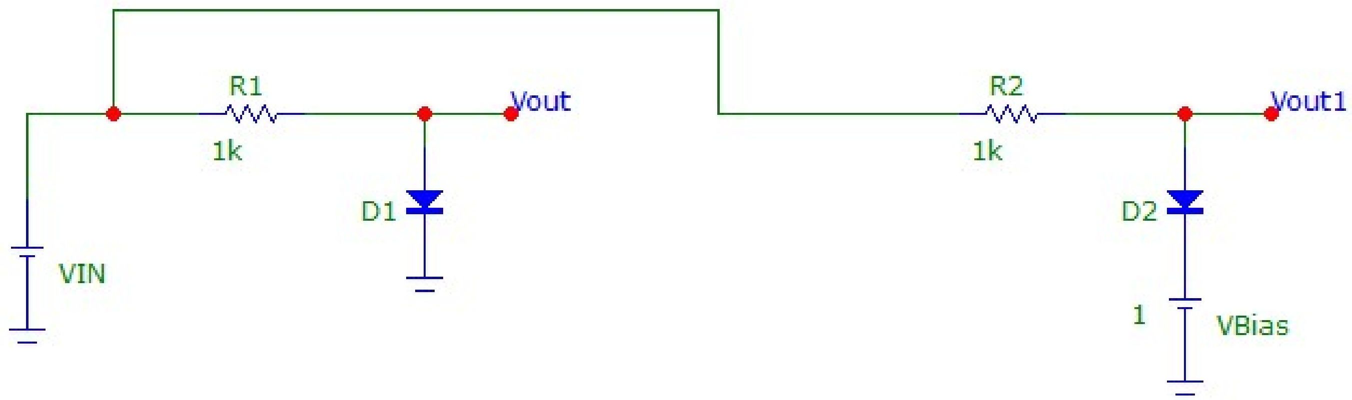
Dept. of EE, IIT Kanpur

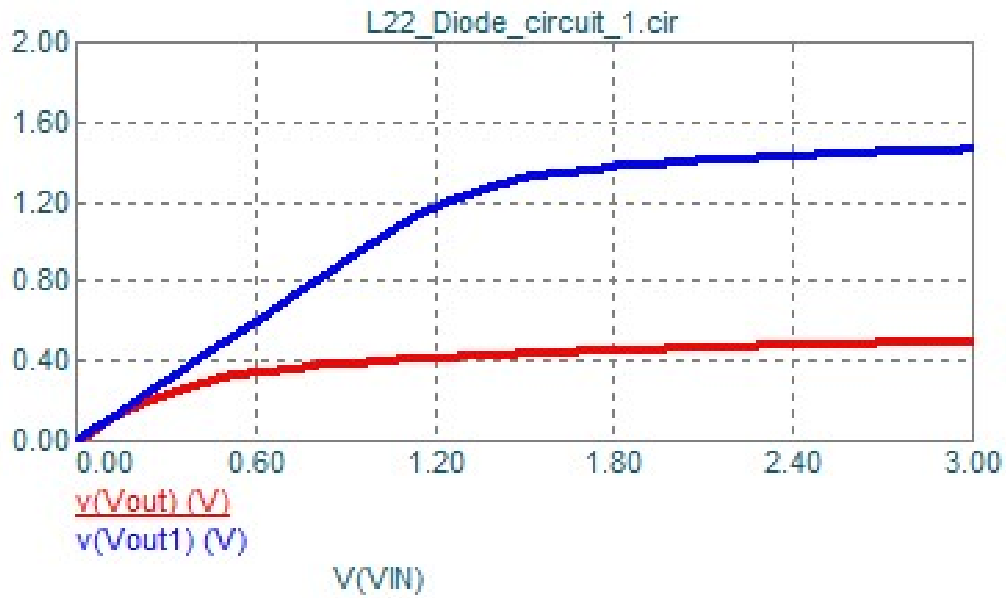

R1
1k
Vout
D1
VIN

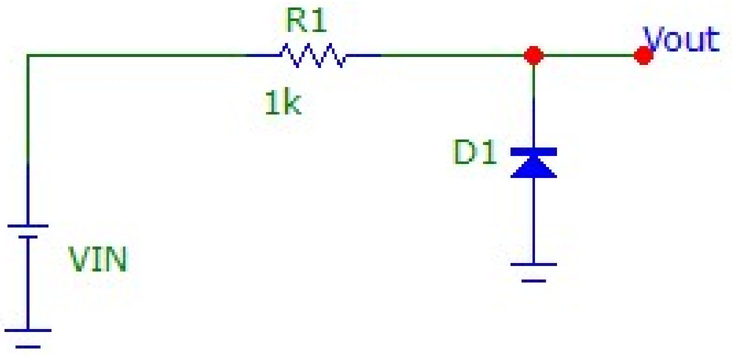

L22_Diode_circuit_1.cir
1.50
1.00
0.50
0.00
-0.50
-1.00
-1.00
-0.60
0.00
0.60
1.20
2.00
v(Vout) (V)
V(VIN)

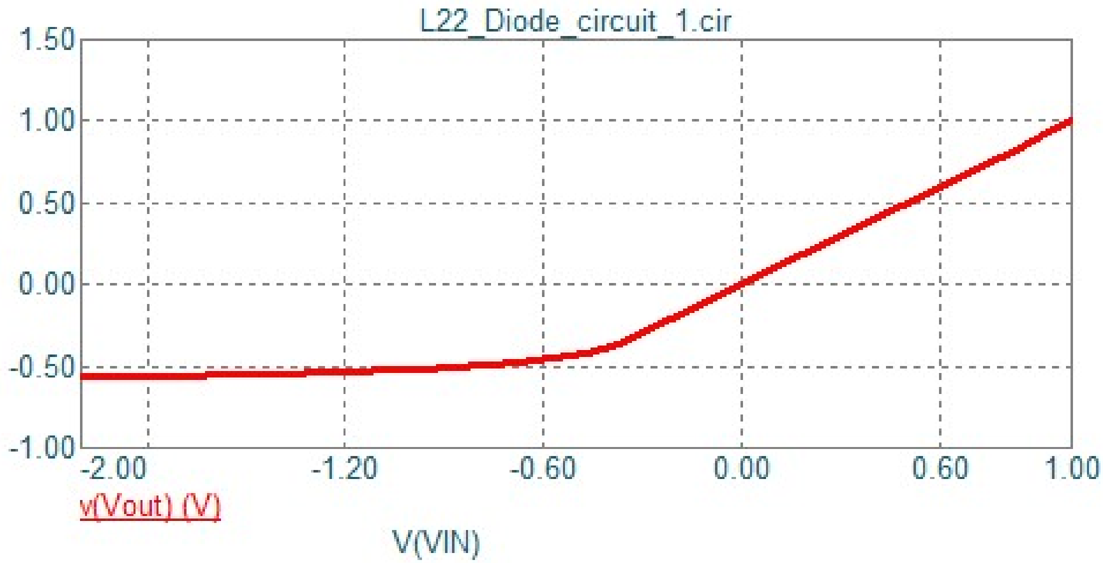

100
10
1
100m
10m
1m
100u
10u
1u
100n
10n
100.00m
240.00m
360.00m
480.00m
600.00m
700.00m
I(D1) (A)
V(VIN)


10.00m
7.50m
5.00m
2.50m
0.00m
100.00m
240.00m
360.00m
480.00m
600.00m
700.00m
I(D1) (A)
V(VIN)

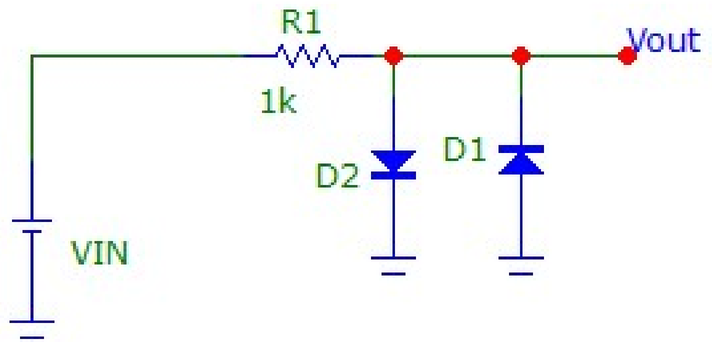

R1
1k
Vout
D1
VIN
R2
1k
Vout1
D2
1
VBias

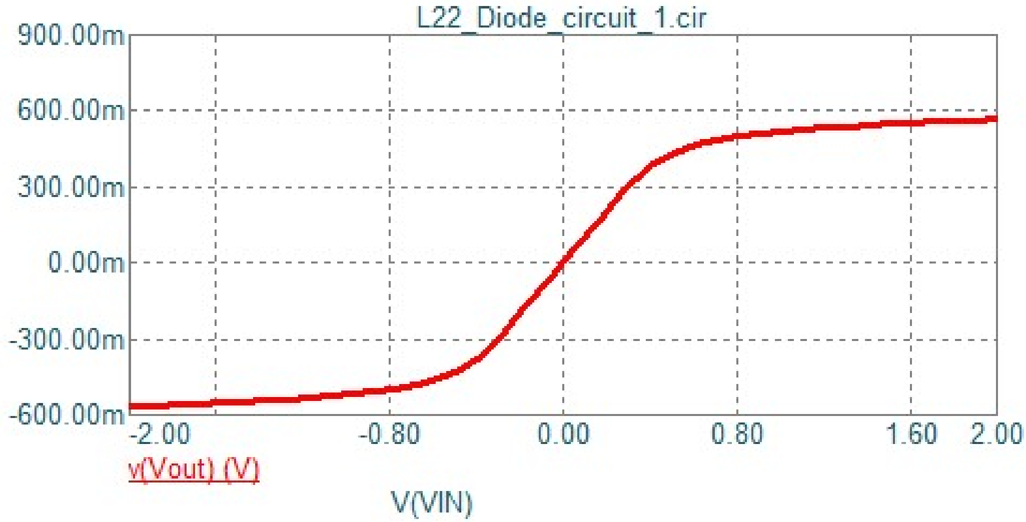

L22_Diode_circuit_1.cir
2.00
1.60
1.20
0.80
0.40
0.00
0.00
0.60
1.20
1.80
2.40
3.00
v(Vout) (V)
v(Vout1) (V)
V(VIN)

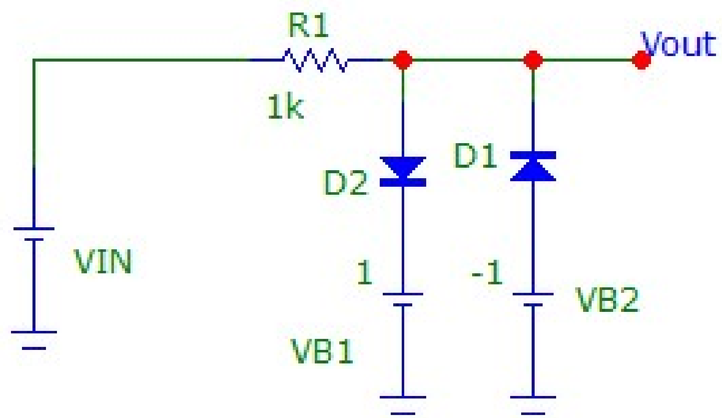

R1
1k
Vout
D1
VIN

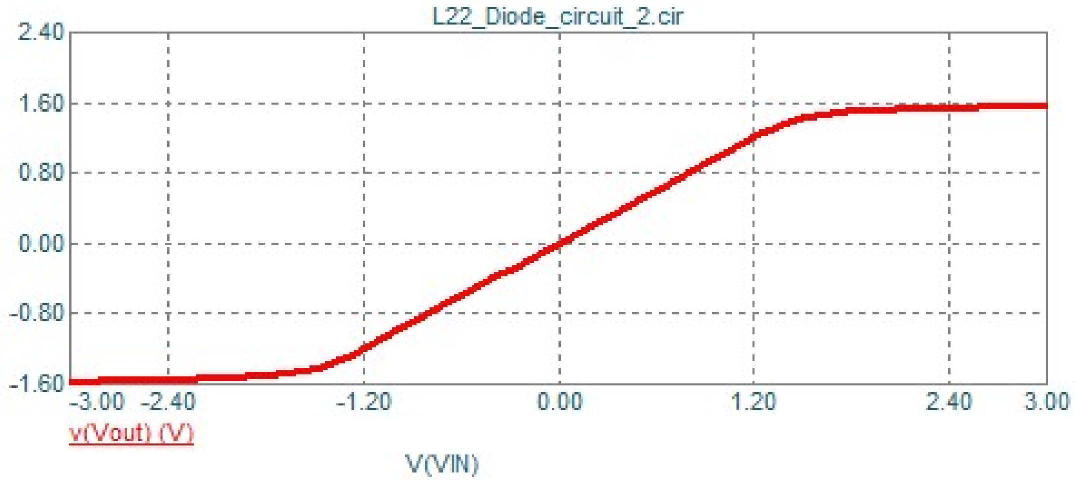

L22_Diode_circuit_1.cir
1.50
1.00
0.50
0.00
-0.50
-1.00
-2.00
-1.20
-0.60
0.00
0.60
1.00
v(Vout) (V)
V(VIN)

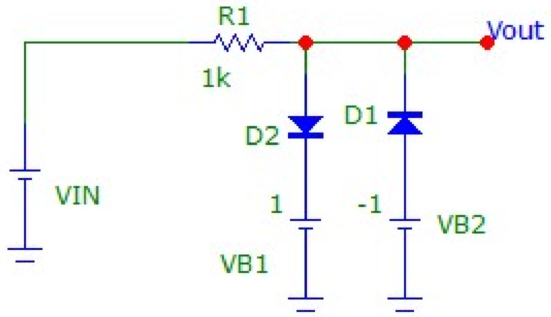
Clipper Circuit

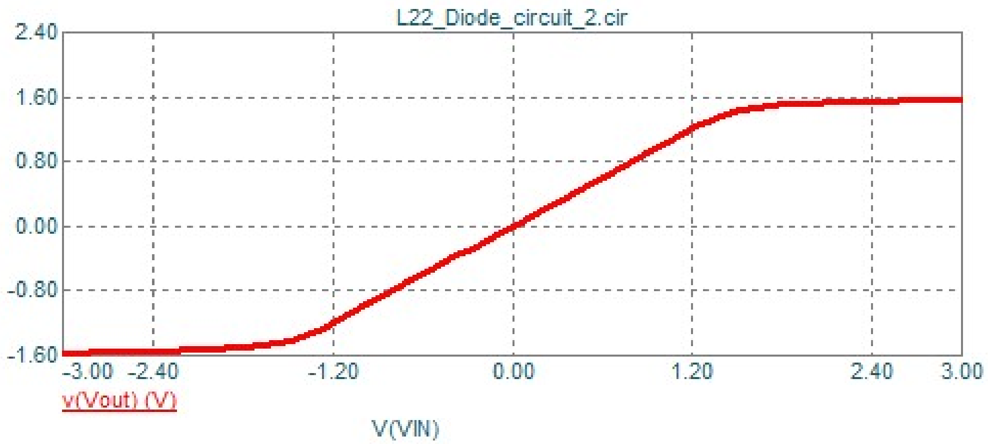


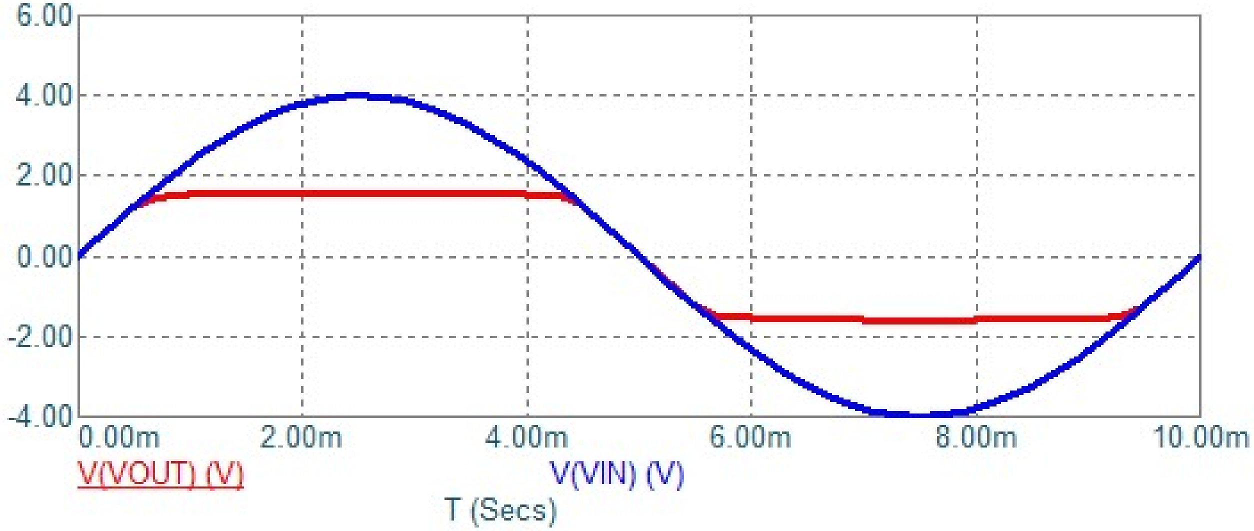






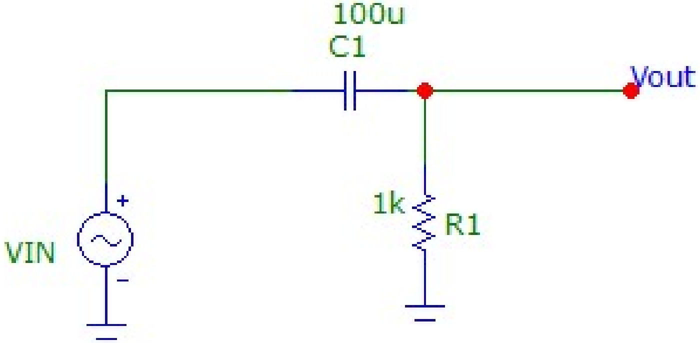

R1
1k
Vout
D2
D1
VIN
1
-1
VB2
VB1

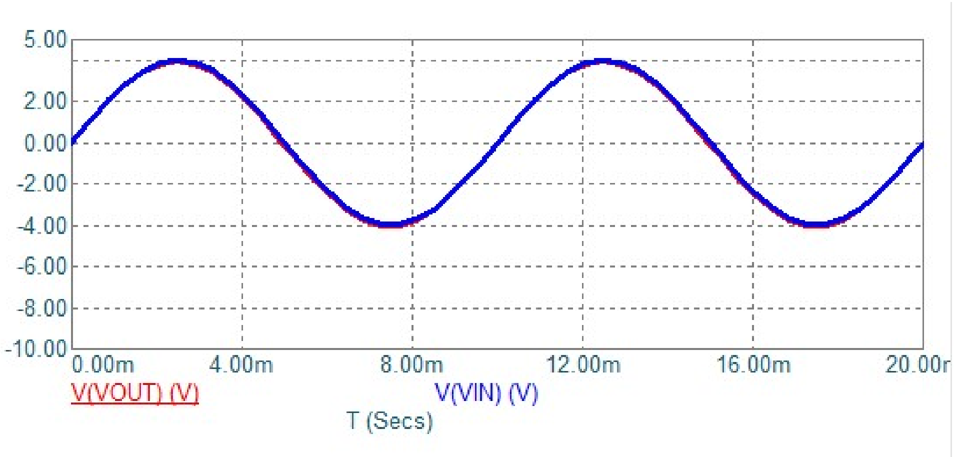

L22_Diode_circuit_2.cir
2.40
1.60
0.80
0.00
-0.80
-1.60
-3.00 -2.40
-1.20
0.00
1.20
2.40
3.00
v(Vout) (V)
V(VIN)


6.00
4.00
2.00
0.00
-2.00
-4.00
0.00m
2.00m
4.00m
6.00m
8.00m
10.00m
V(VOUT) (V)
V(VIN) (V)
T (Secs)

Negative Clamper

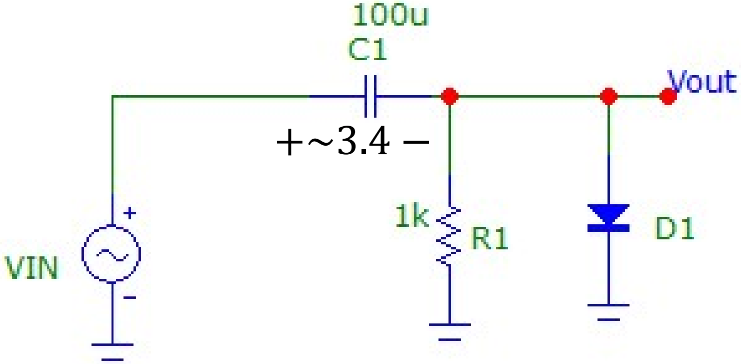
$\tau = 0.1s$

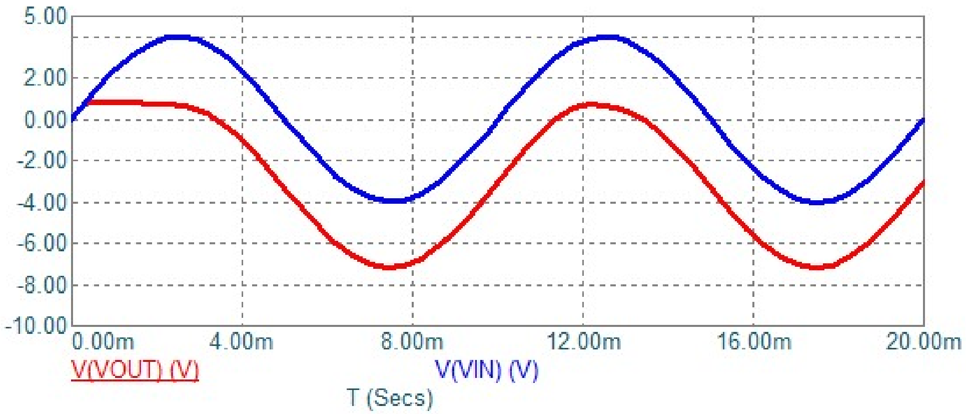




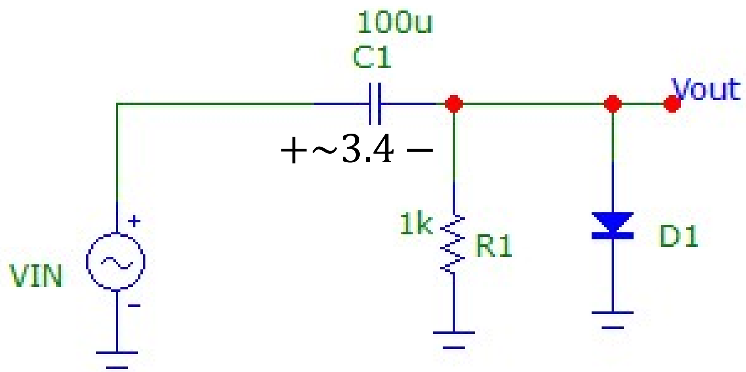
$4Vsin(\omega t)$

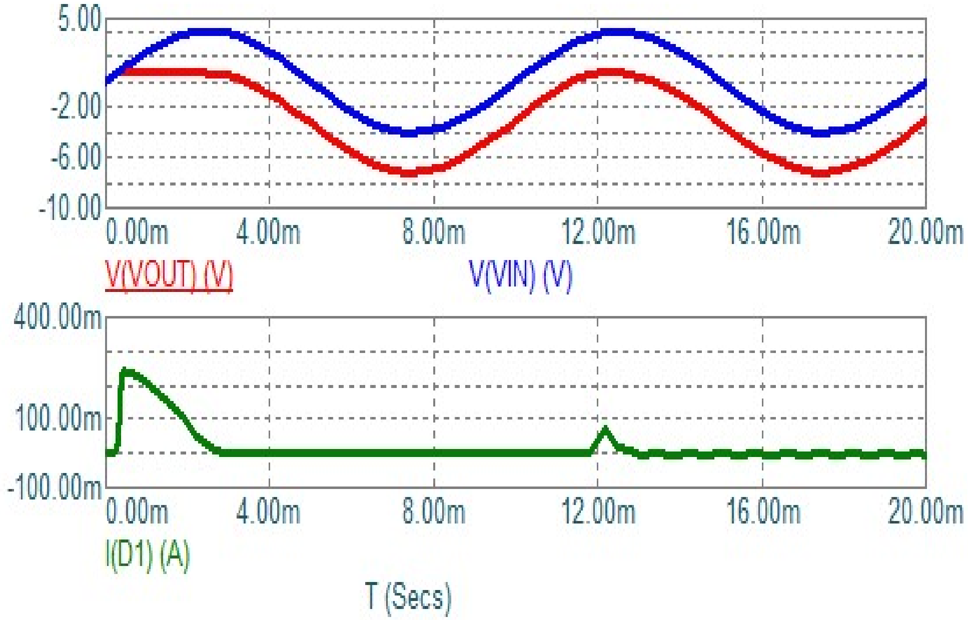
$f = 100Hz$





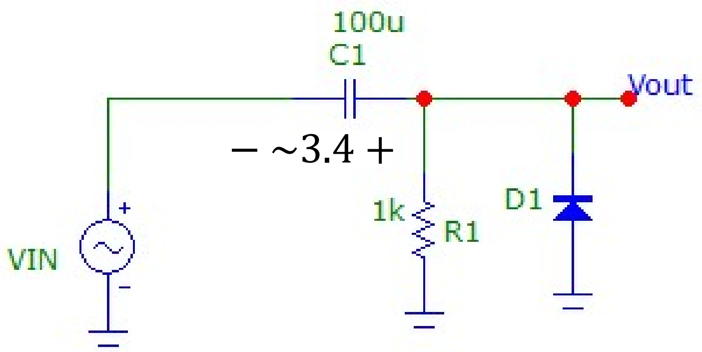
$$V_{IN} - V_{OUT} \sim 3.4 \Rightarrow V_{OUT} = V_{IN} - 3.4$$


100u
C1
Vout
+~3.4 −
1k
R1
D1
VIN


5.00
-2.00
-6.00
-10.00
0.00m
4.00m
8.00m
12.00m
16.00m
20.00m
V(VOUT) (V)
V(VIN) (V)
400.00m
100.00m
-100.00m
I(D1) (A)
T (Secs)

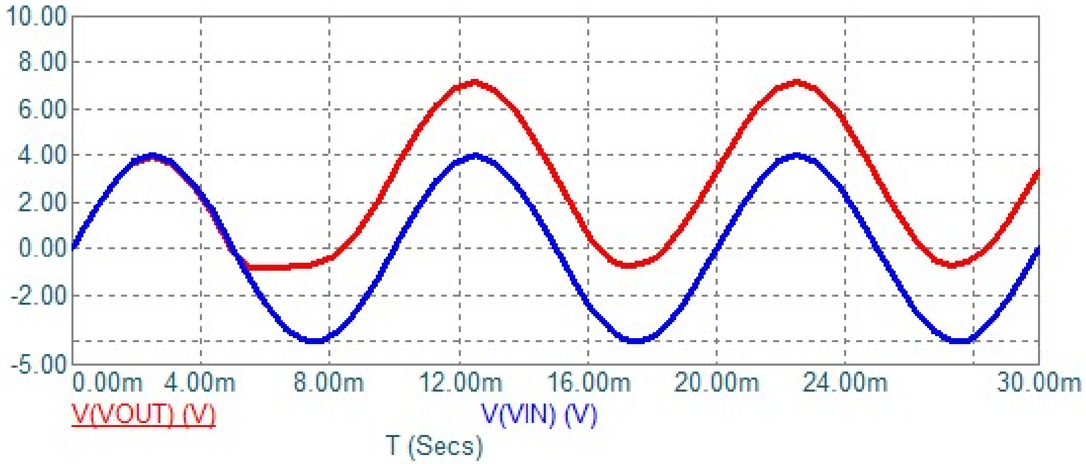
Positive Clamper

$\tau = 0.1s$



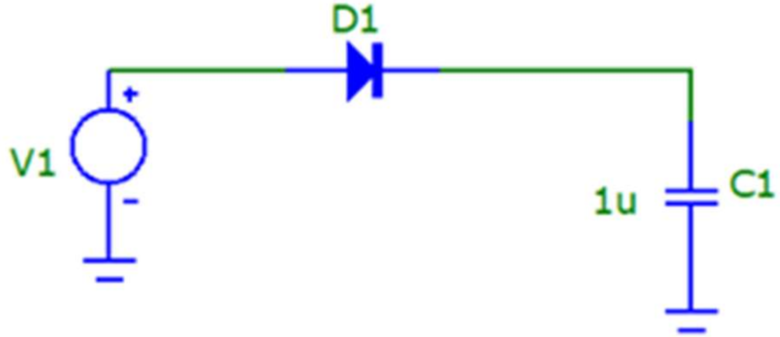
$4V sin(\omega t)$

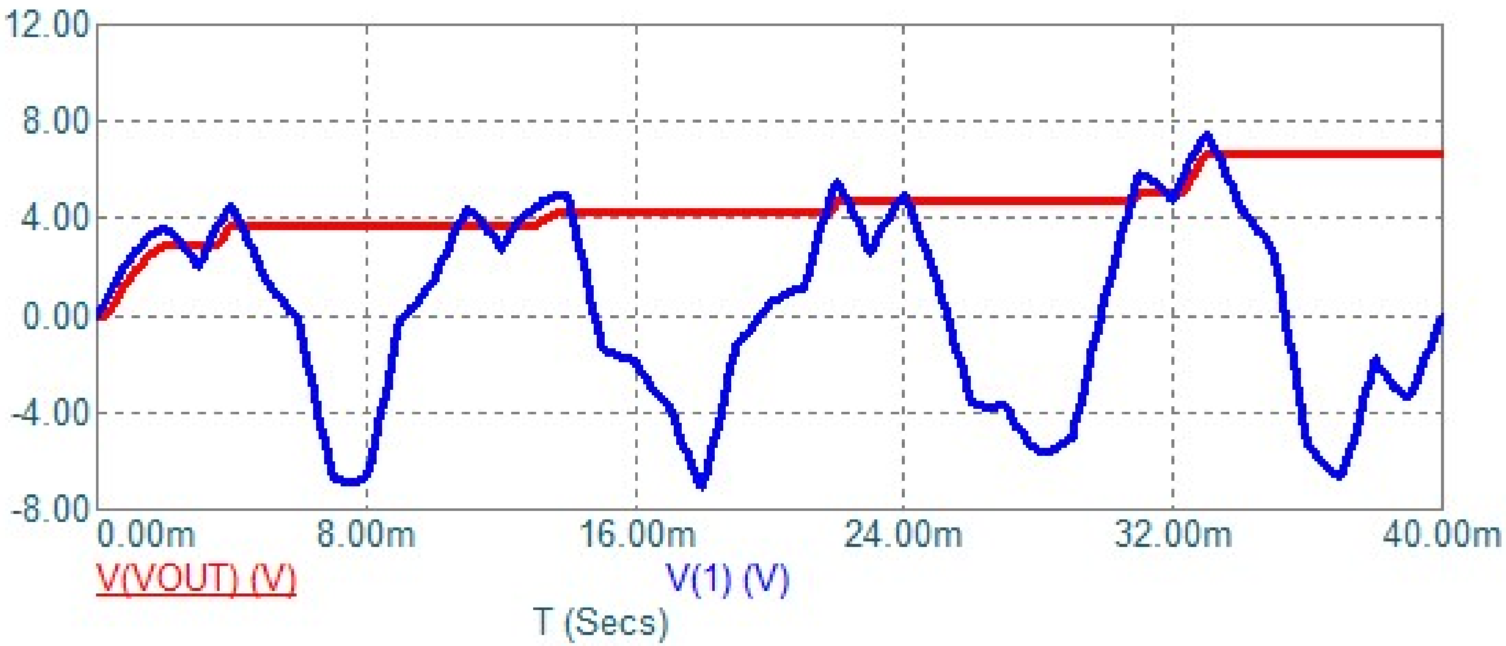
$f = 100Hz$



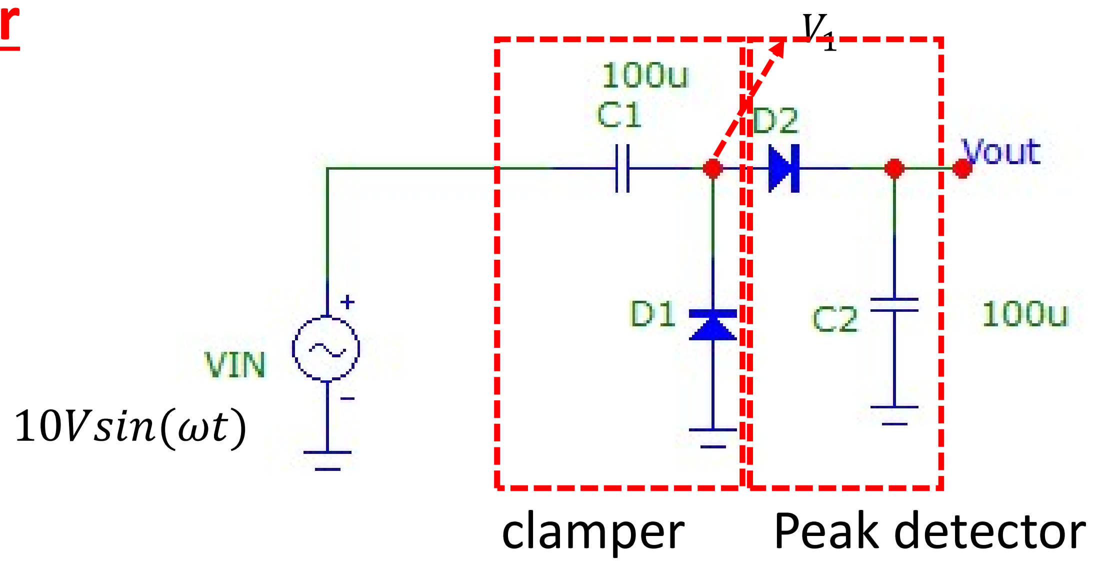
$$V_{IN} - V_{OUT} \sim -3.4 \Rightarrow V_{OUT} = V_{IN} + 3.4$$

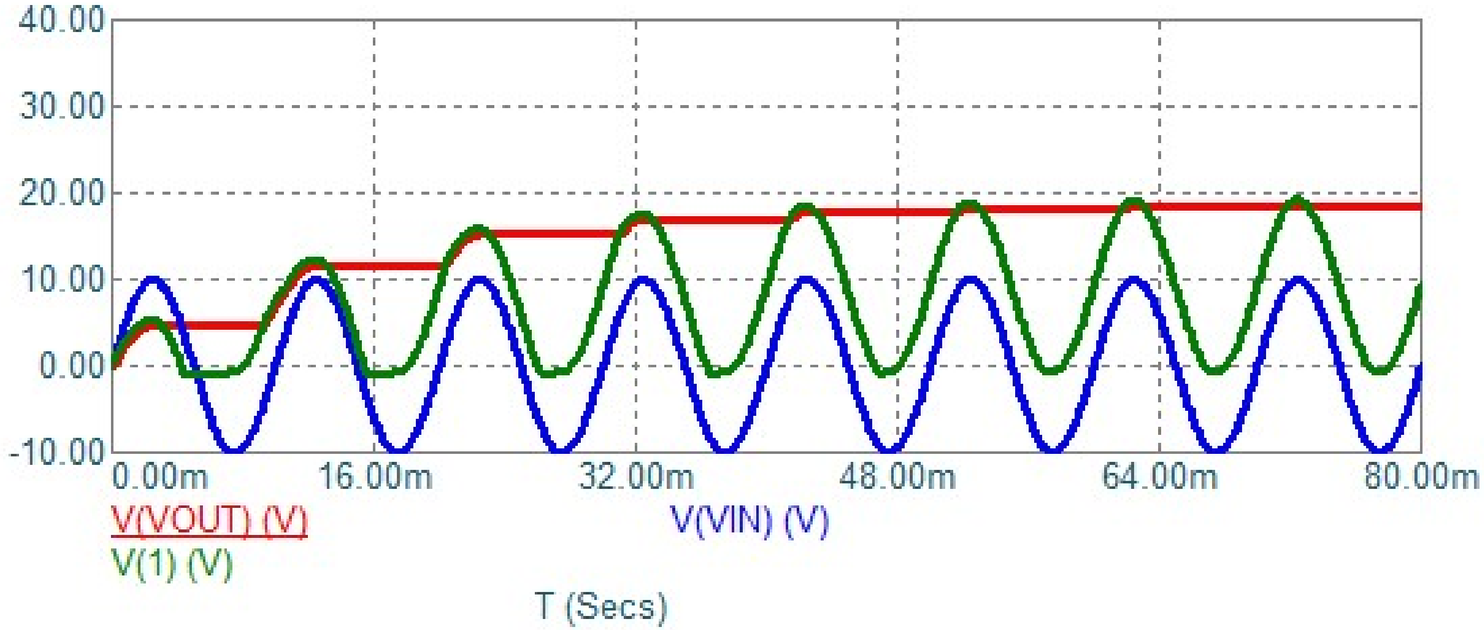
Peak Detector





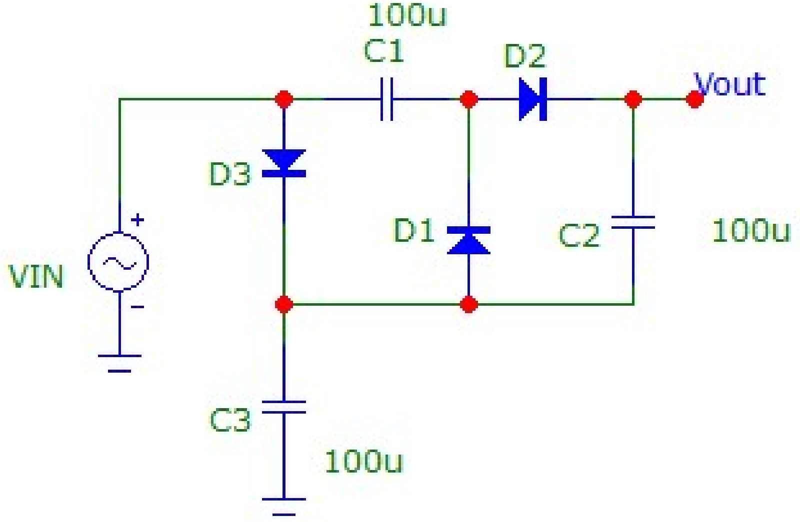
Voltage Doubler

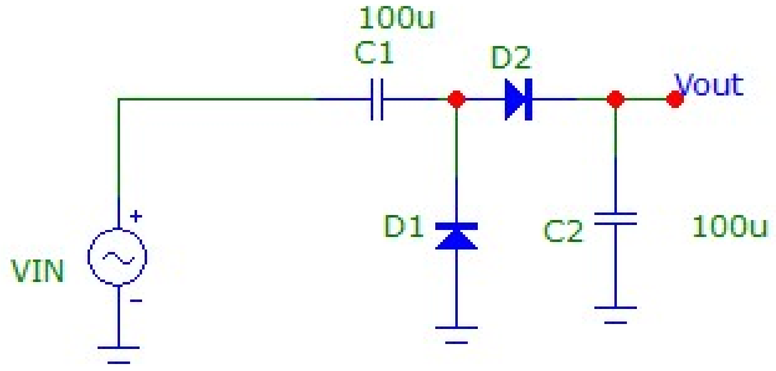


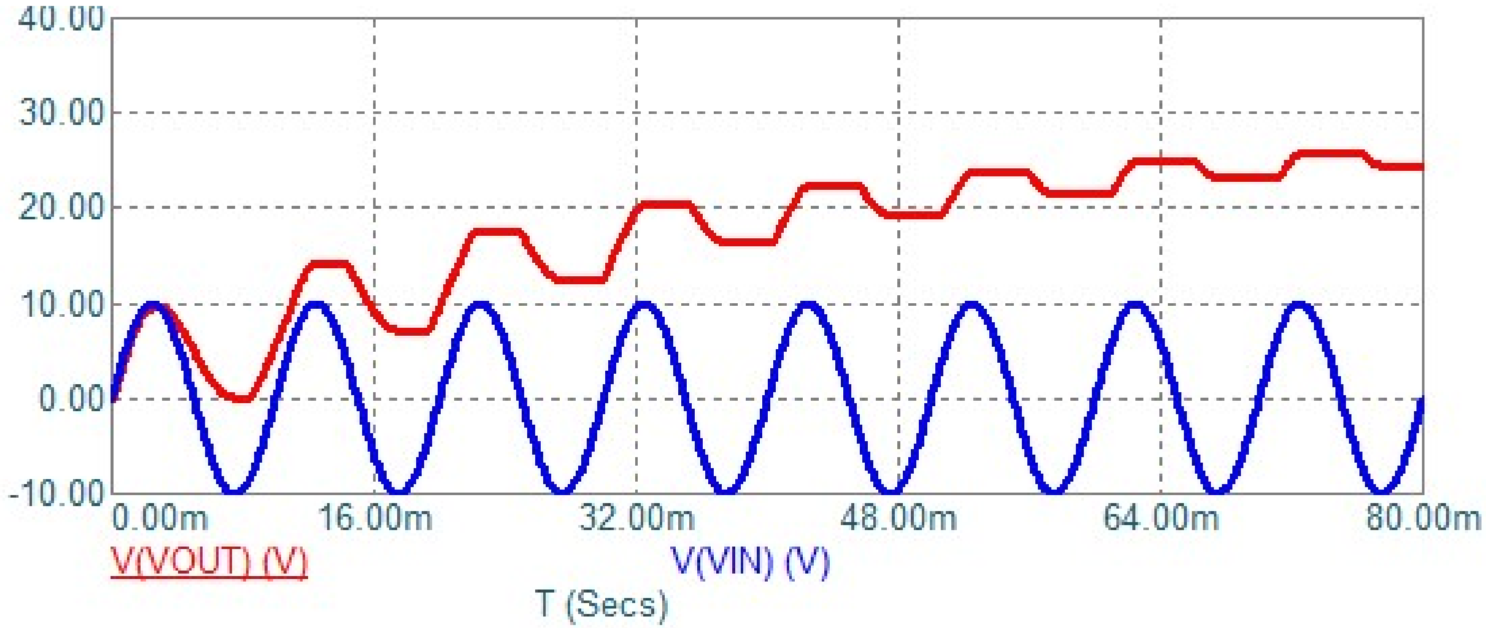


<u>Voltage Tripler</u>

$10V sin(\omega t)$







Temperature dependence of diode characteristics

$$I_D = I_S \times \{\exp(\frac{V_d}{V_T}) - 1\}$$

$$V_T = \frac{kT}{Q}$$

$$I_S \propto n_i^2 \propto e^{-\frac{E_g}{kT}}$$

Reverse saturation current increases with temperature. For forward bias, even though V_T increases, current still increases because of greater influence of I_S

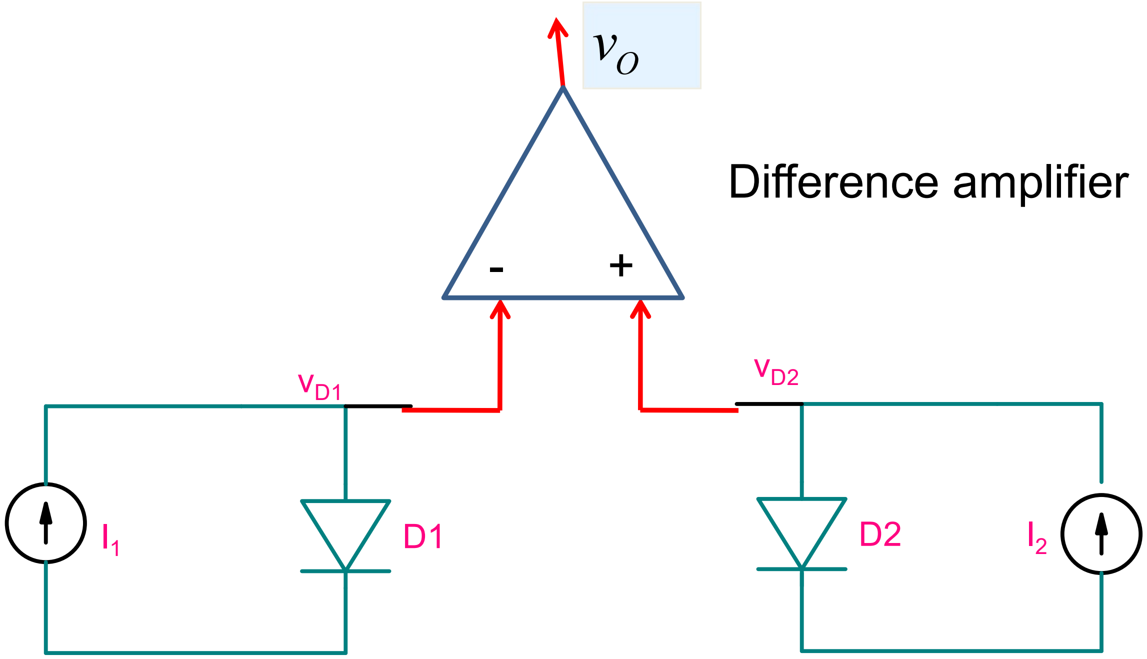
For a diode in forward bias at a fixed current I_O : $v_D = V_T \times \ln(I_O / I_S + 1)$

For Silicon diodes, v_D decreases at the rate of ~ -2mV/°C

If the diode voltage is 0.7 at 27°C, then at 100°C it would be only :

$$0.7 - 2 \times 10^{-3} \times (100 - 27) = 0.554V$$

Measurement of temperature using a pn junction diode



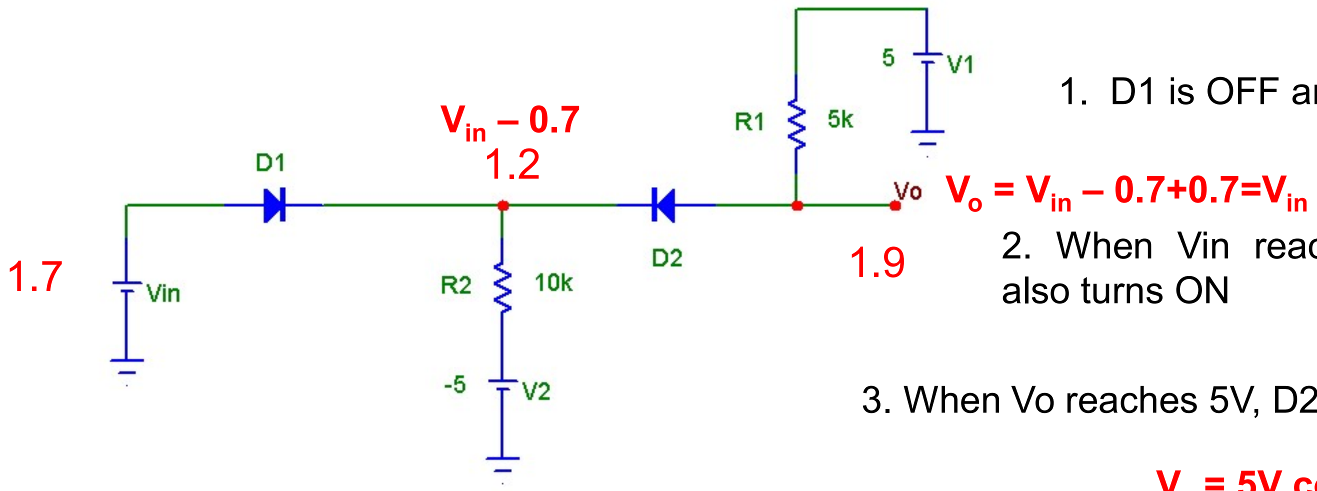
$$v_{D1} = V_T \times \ln(I_1/I_S + 1)$$

$$v_{D2} = V_T \times \ln(I_2/I_S + 1)$$

$$v_O = C \times (v_{D2} - v_{D1})$$

$$v_O = (C \times \frac{k}{q} \times \ln(\frac{I_2}{I_1})) \times T$$

Multiple-diode Circuits

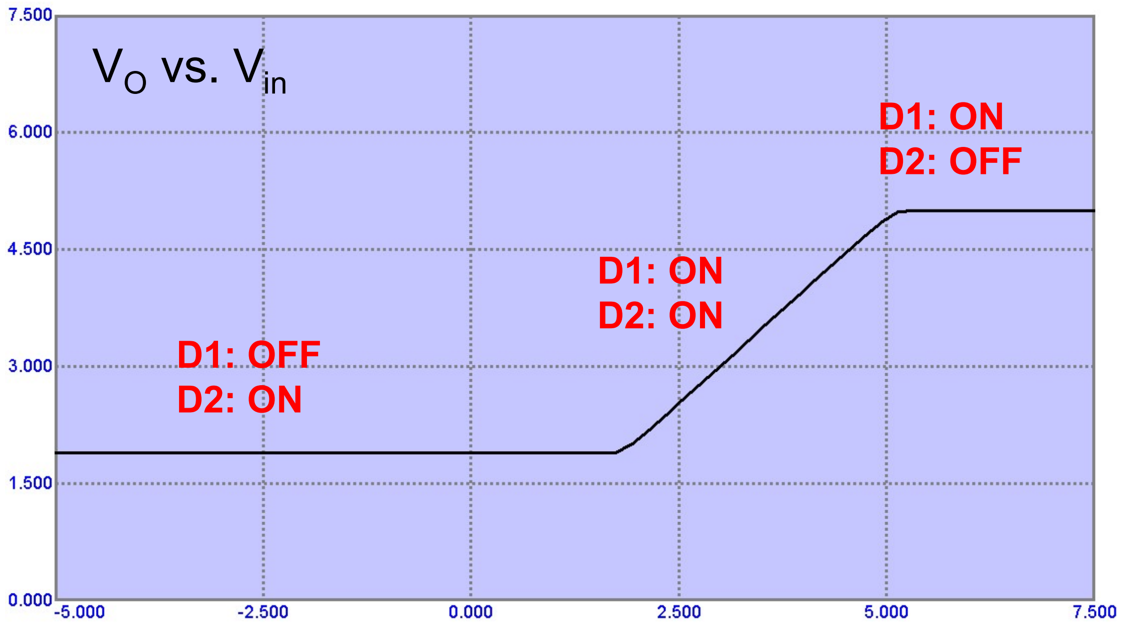


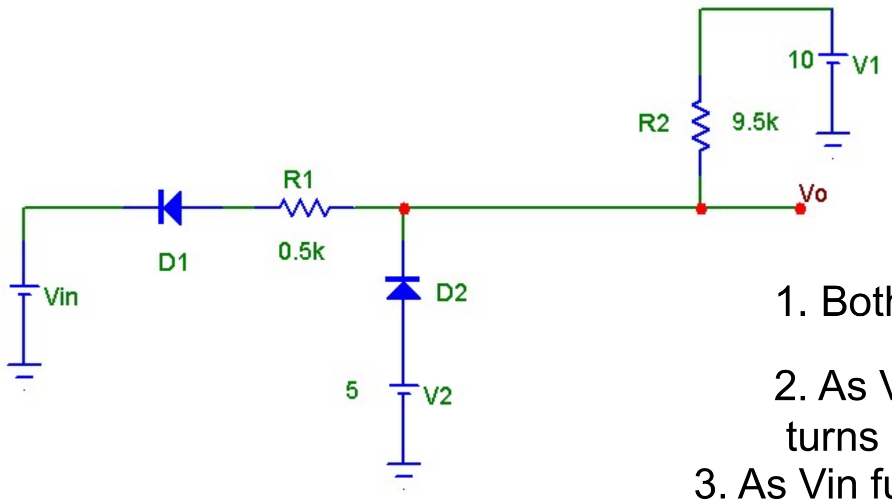
1. D1 is OFF and D2 is ON

2. When Vin reaches 1.7, D1 also turns ON

3. When Vo reaches 5V, D2 turns OFF

V_o = 5V constant

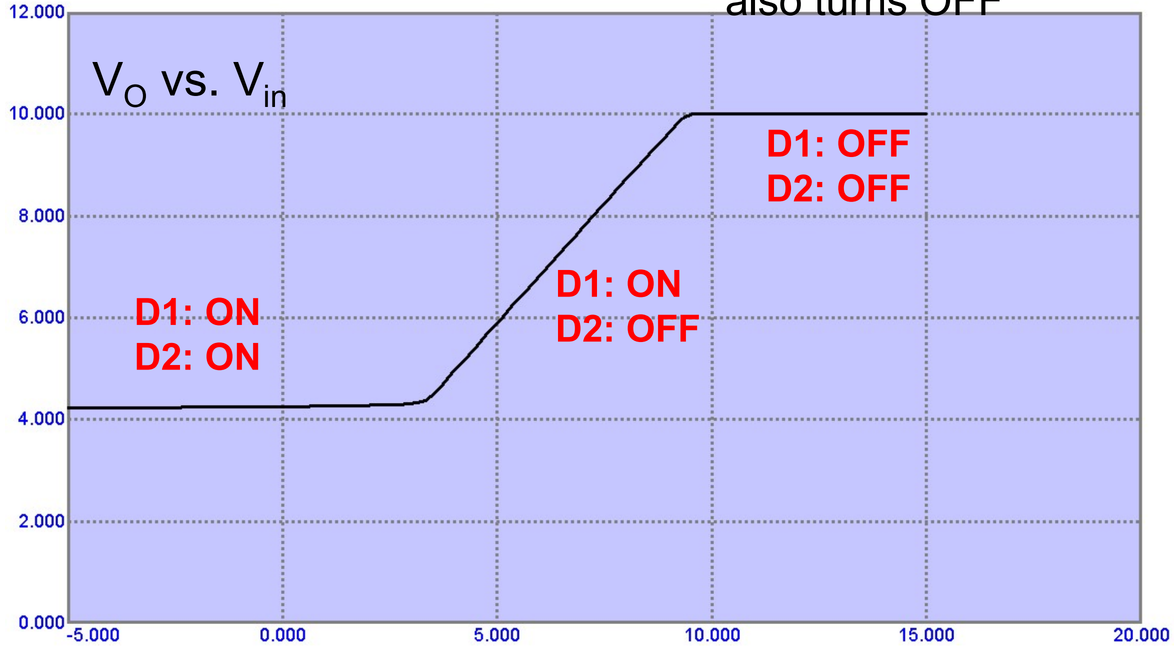




1. Both diodes are initially ON

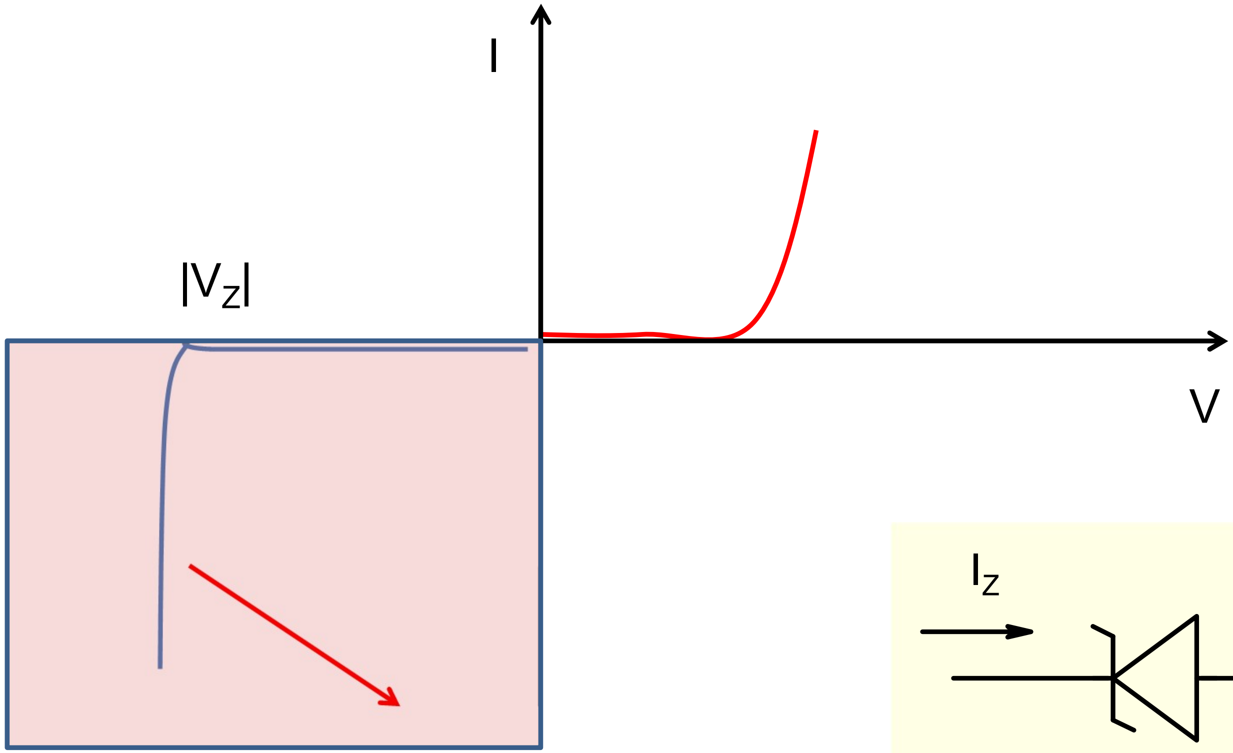
2. As Vin increases, eventually D2 turns OFF

3. As Vin further increases, eventually D1 also turns OFF

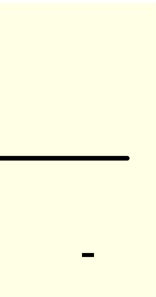


Zener Diode

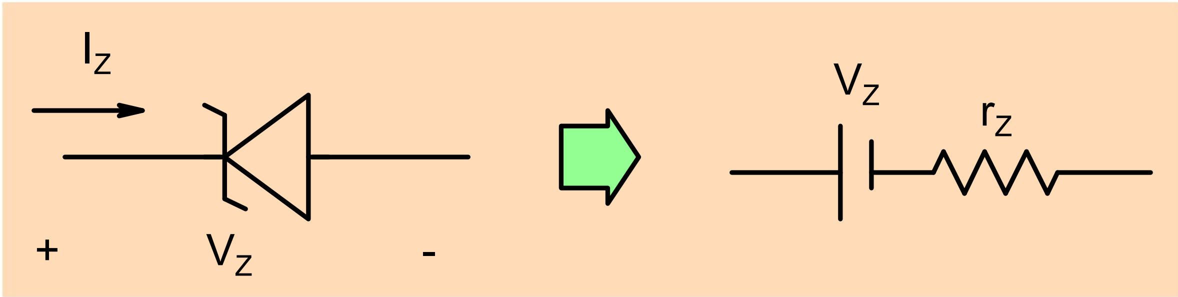
A diode specially designed to operate in reverse bias in 'breakdown' region



$$Slope = r_Z^{-1}$$



Model



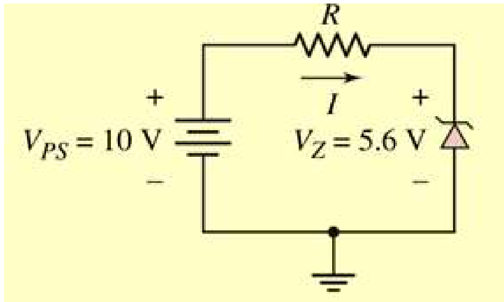
Often we will assume that r_z is negligible

Example

Given $V_Z = 5.6V$

$r_Z = 0\Omega$

Find a value for R such that the current through the diode is limited to 3mA



$$I = \frac{V_{PS} - V_Z}{R} \qquad R = \frac{V_{PS} - V_Z}{I} = \frac{10V - 5.6V}{3mA} = 1.47k\Omega$$

$$P_Z = I_Z V_Z = 3mA \cdot 5.6V = 1.68mW$$

Datasheet

Zeners
1N4728A - 1N4752A

Absolute Maximum Ratings*

T_A = 25°C unless otherwise noted

Symbol	Parameter	Value	Units
P_D	Power Dissipation Derate above 50°C	1.0 6.67	W mW/°C
T_{STG}	Storage Temperature Range	-65 to +200	°C
T_J	Operating Junction Temperature	+ 200	°C
$R_{\theta JL}$	Thermal resistance Junction to Lead	53.5	°C/W
$R_{\theta JA}$	Thermal resistance Junction to Ambient	100	°C/W
	Lead Temperature (1/16" from case for 10 seconds)	+ 230	°C
	Surge Power**	10	W

*These ratings are limiting values above which the serviceability of the diode may be impaired.
**Non-recurrent square wave PW = 8.3 ms, TA = 55 degrees C.

NOTES:
1) These ratings are based on a maximum junction temperature of 200 degrees C.
2) These are steady state limits. The factory should be consulted on applications involving pulsed or low duty cycle operations.

Tolerance: A = 5%

DO-41

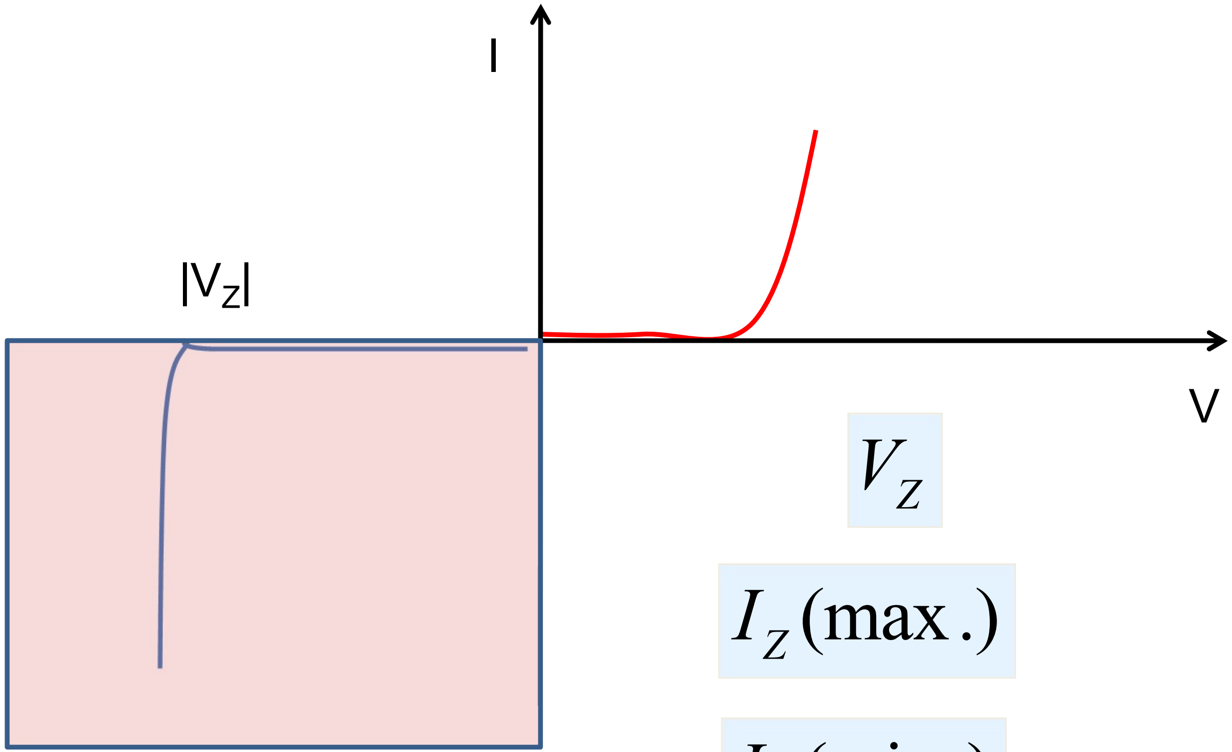
COLOR BAND DENOTES CATHODE

Electrical Characteristics

T_A = 25°C unless otherwise noted

Device	V_Z (V)	Z_Z (Ω) @	I_{ZT} (mA)	Z_{ZK} (Ω) @	I_{ZK} (mA)	V_R (V) @	I_R (μA)	I_{SURGE} (mA)	I_{ZM} (mA)
1N4728A	3.3	10	76	400	1.0	1.0	100	1380	276
1N4729A	3.6	10	69	400	1.0	1.0	100	1260	252
1N4730A	3.9	9.0	64	400	1.0	1.0	50	1190	234
1N4731A	4.3	9.0	58	400	1.0	1.0	10	1070	217
1N4732A	4.7	8.0	53	500	1.0	1.0	10	970	193
1N4733A	5.1	7.0	49	550	1.0	1.0	10	890	178
1N4734A	5.6	5.0	45	600	1.0	2.0	10	810	162
1N4735A	6.2	2.0	41	700	1.0	3.0	10	730	146
1N4736A	6.8	3.5	37	700	1.0	4.0	10	660	133
1N4737A	7.5	4.0	34	700	0.5	5.0	10	605	121
1N4738A	8.2	4.5	31	700	0.5	6.0	10	550	110
1N4739A	9.1	5.0	28	700	0.5	7.0	10	500	100
1N4740A	10	7.0	25	700	0.25	7.6	10	454	91
1N4741A	11	8.0	23	700	0.25	8.4	5.0	414	83
1N4742A	12	9.0	21	700	0.25	9.1	5.0	380	76
1N4743A	13	10	19	700	0.25	9.9	5.0	344	69
1N4744A	15	14	17	700	0.25	11.4	5.0	304	61
1N4745A	16	16	15.5	700	0.25	12.2	5.0	285	57
1N4746A	18	20	14	750	0.25	13.7	5.0	250	50
1N4747A	20	22	12.5	750	0.25	15.2	5.0	225	45
1N4748A	22	23	11.5	750	0.25	16.7	5.0	205	41
1N4749A	24	25	10.5	750	0.25	18.2	5.0	190	38
1N4750A	27	35	9.5	750	0.25	20.6	5.0	170	34
1N4751A	30	40	8.5	1000	0.25	22.8	5.0	150	30

Zener diode: Important Characteristics

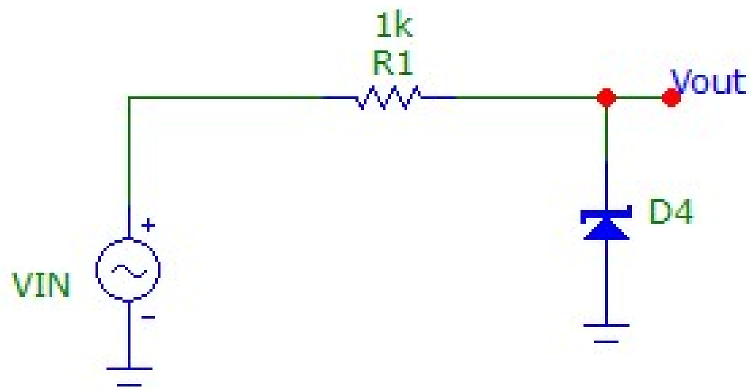


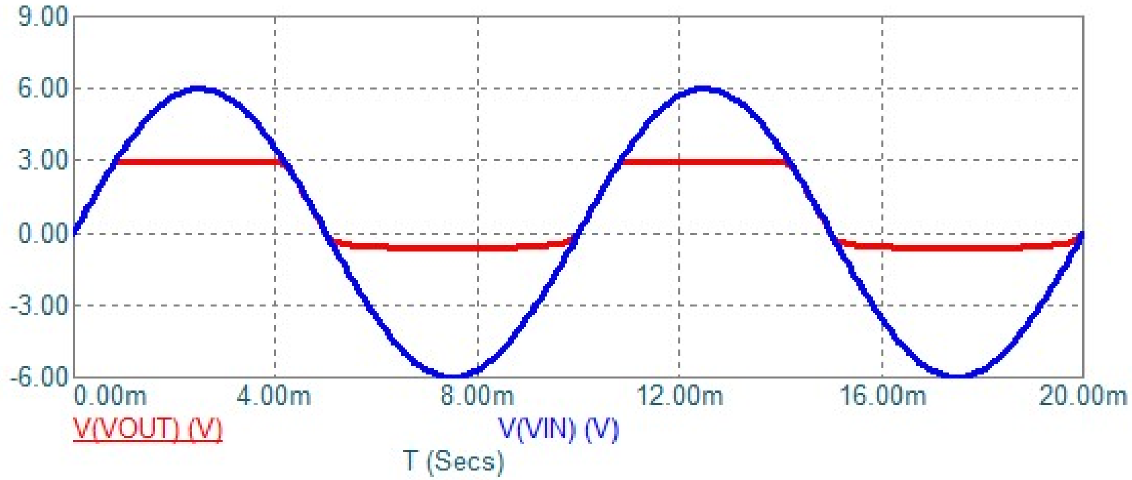
$$V_Z$$

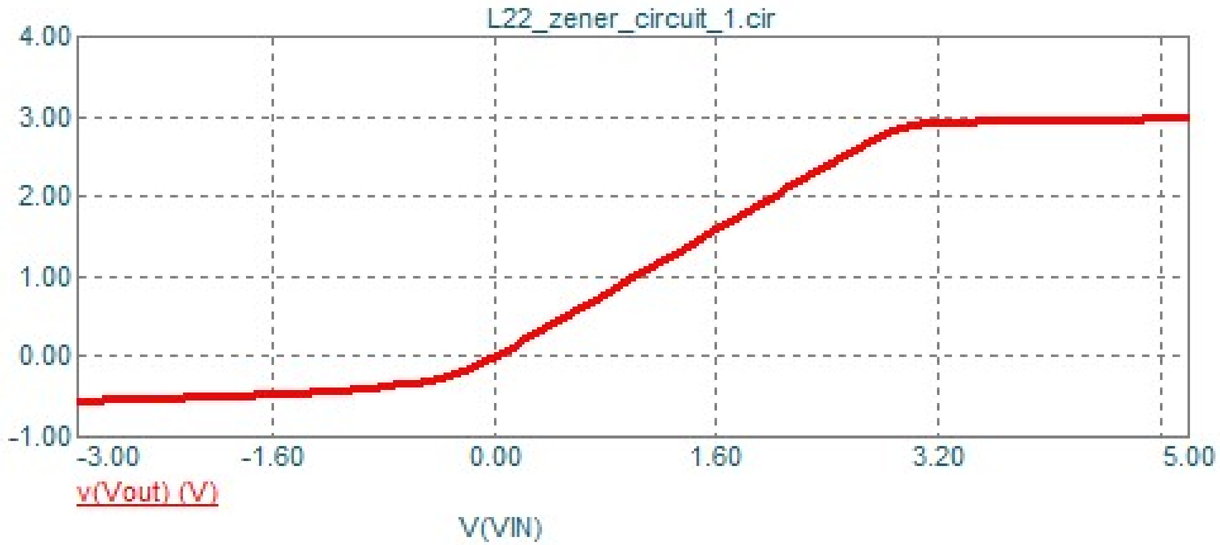
$$I_Z(\max.)$$

$$I_Z(\min.)$$

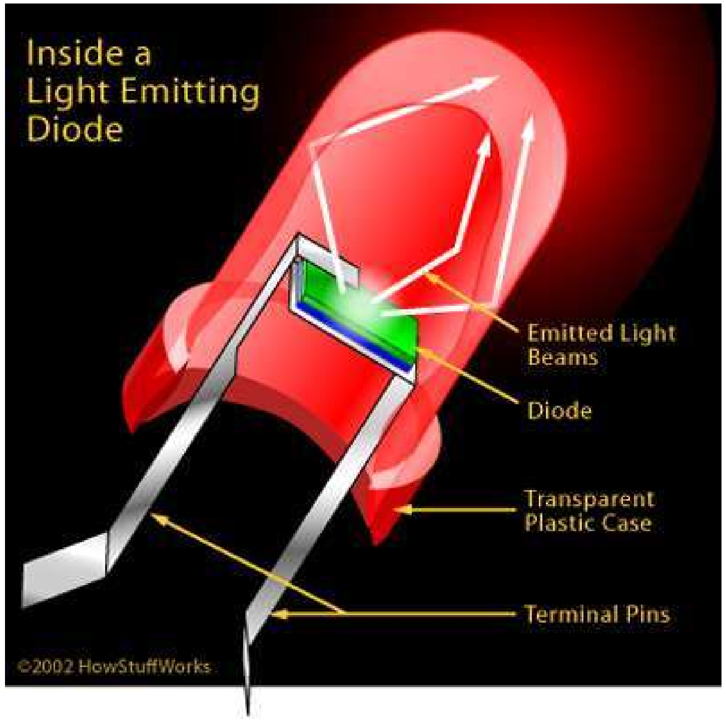
$$P_Z$$


1k
R1
Vout
D4
VIN

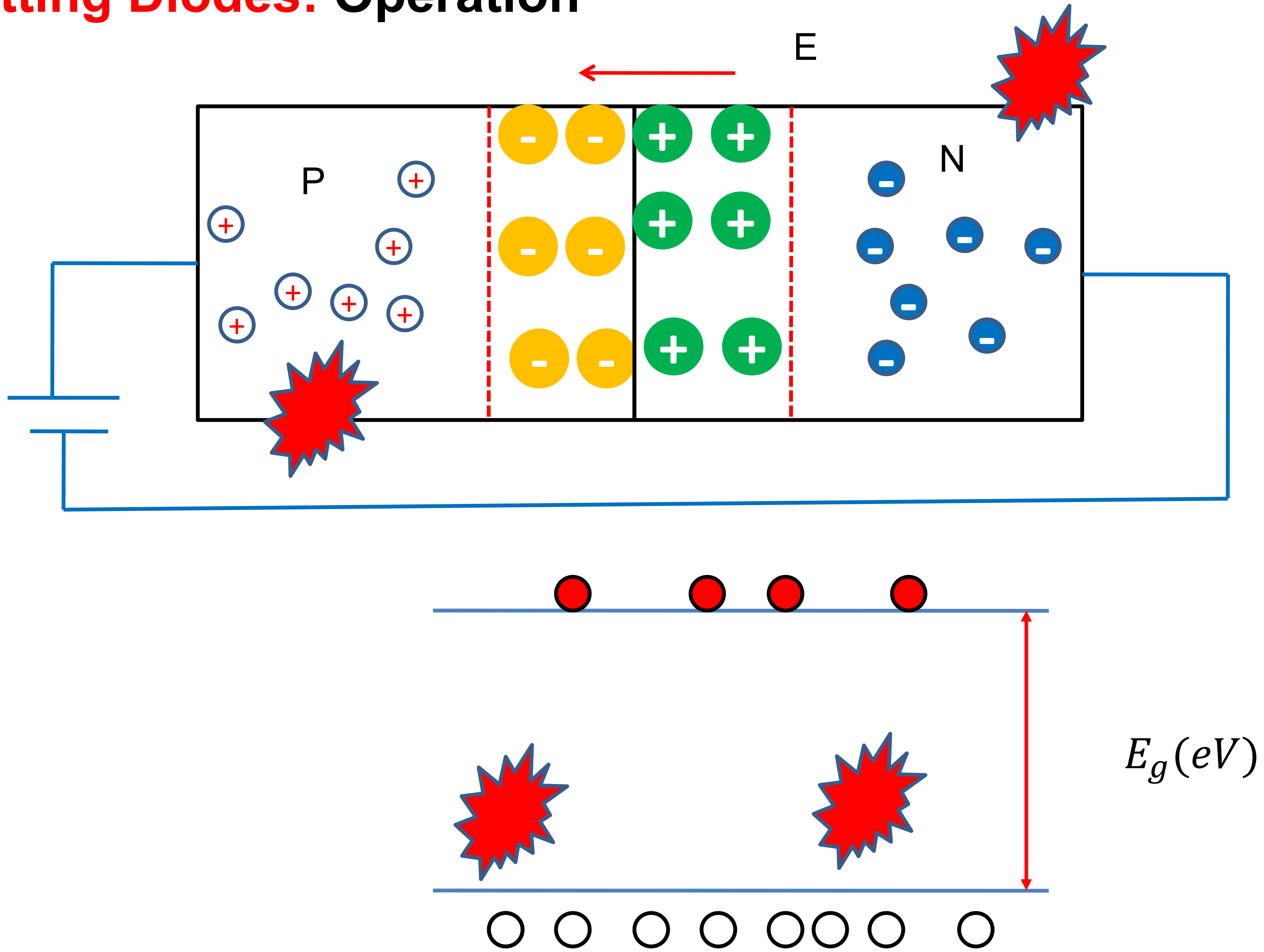

9.00
6.00
3.00
0.00
-3.00
-6.00
0.00m
4.00m
8.00m
12.00m
16.00m
20.00m
V(VOUT) (V)
V(VIN) (V)
T (Secs)


L22_zener_circuit_1.cir
4.00
3.00
2.00
1.00
0.00
-1.00
-3.00
-1.60
0.00
1.60
3.20
5.00
v(Vout) (V)
V(VIN)

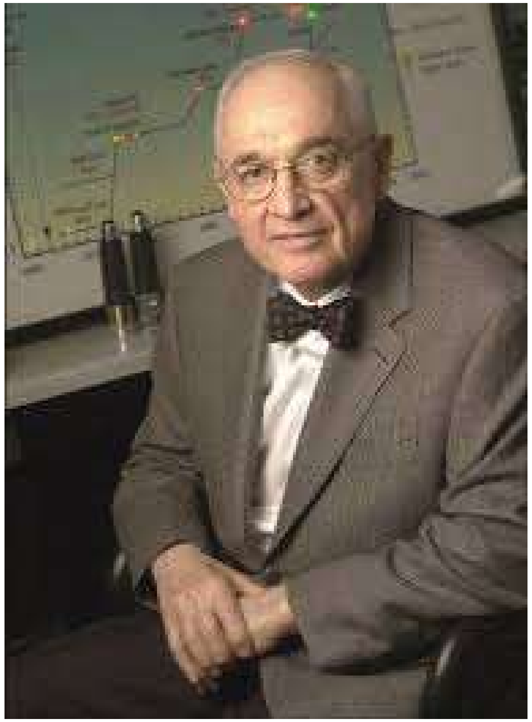
Light Emitting Diodes



Light Emitting Diodes: Operation



Invention of LED

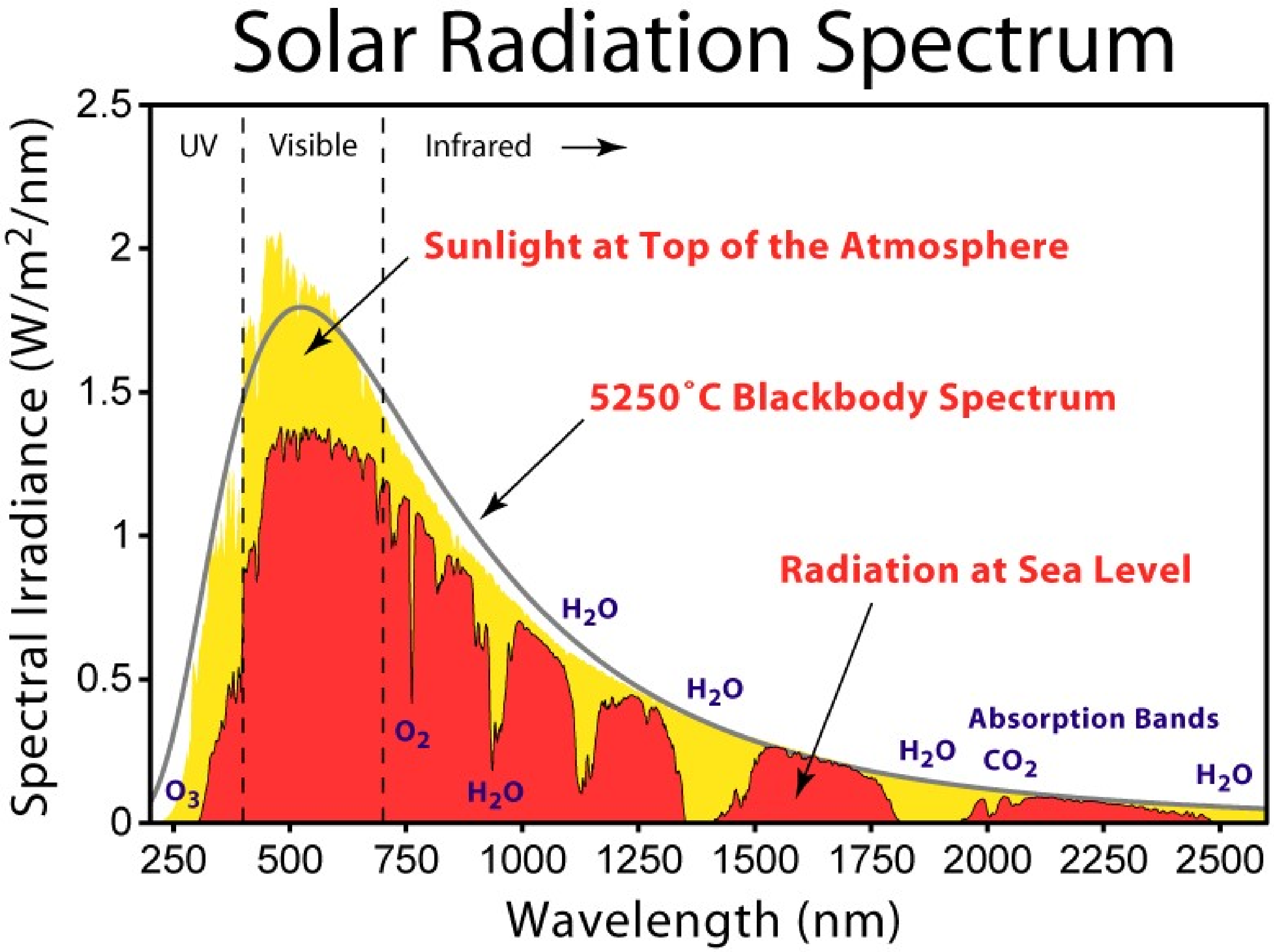


Nick Holonyak
1962; Red LED using GaAsP

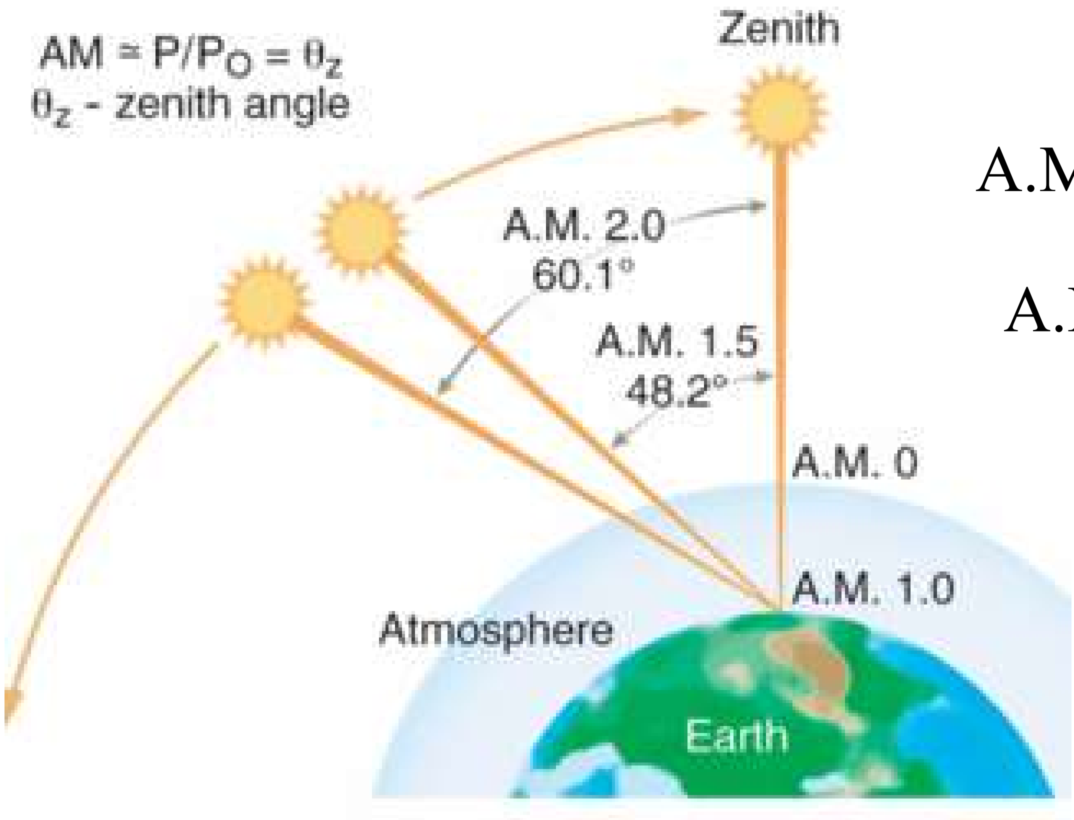
Shuji Nakamura
Blue LED using GaN, 1992
Nobel Prize, 2014

PN Junction as a Solar Cell

Sun as a source of energy



Sun as a source of energy



A.M.0 ~1367 W/m^2

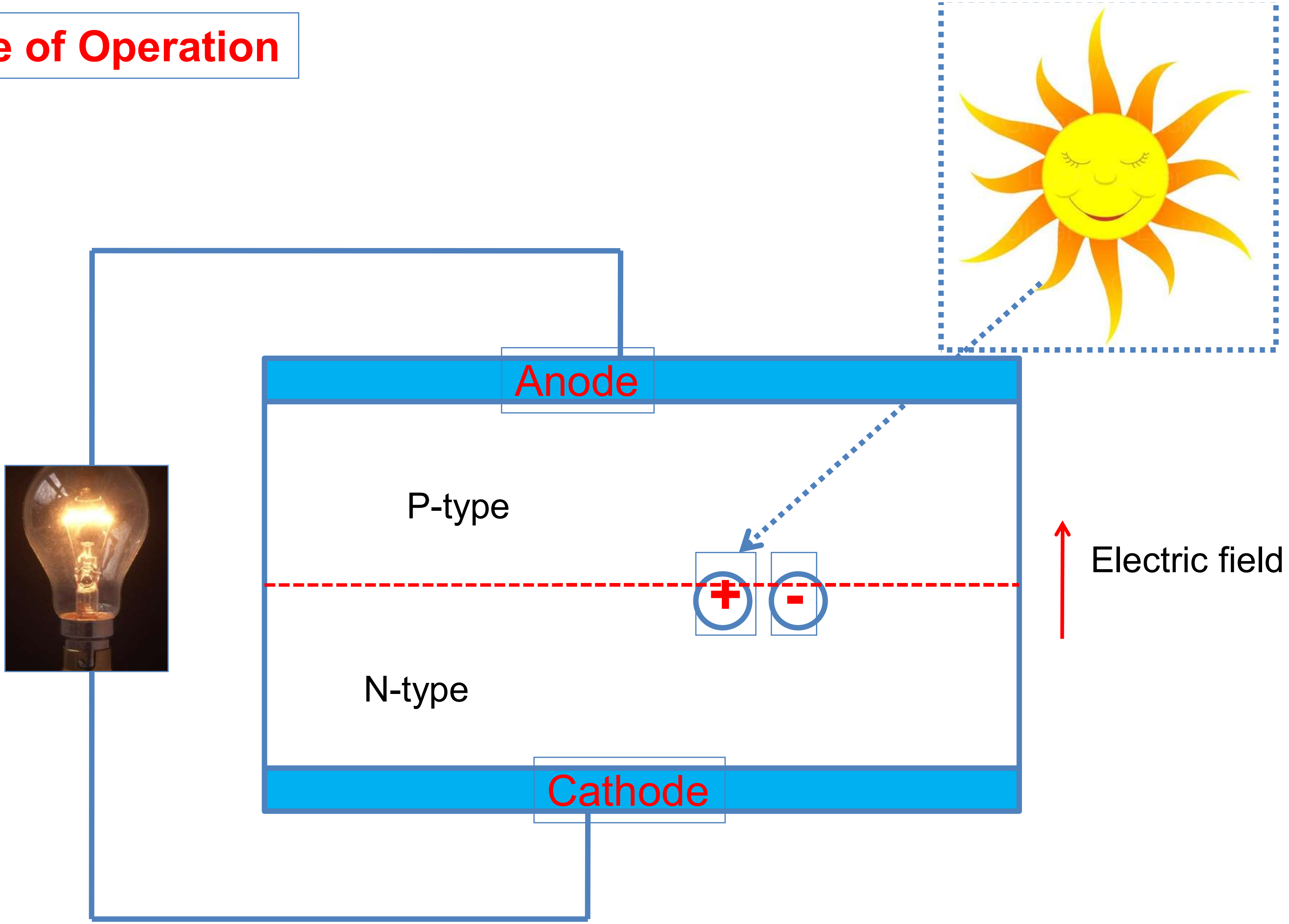
A.M.1 ~925 W/m^2

A.M.1.5 ~844 W/m^2

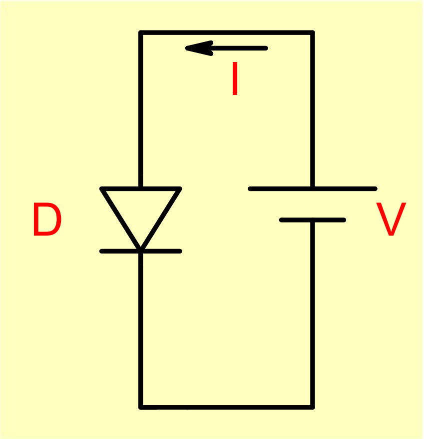
A.M.2 ~691 W/m^2

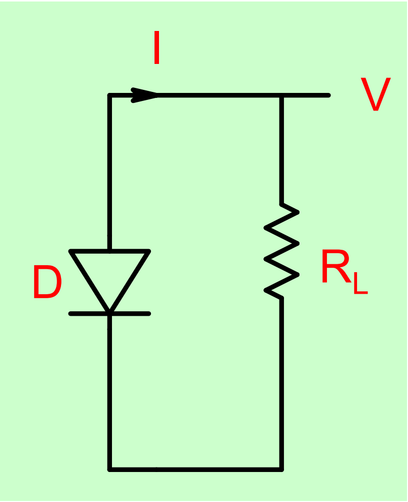
AM: air mass

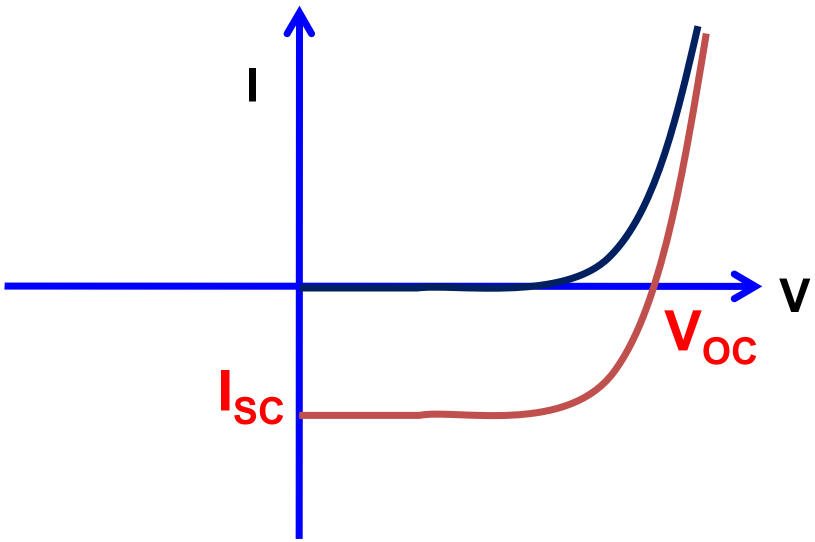
Principle of Operation



Solar cell is a diode

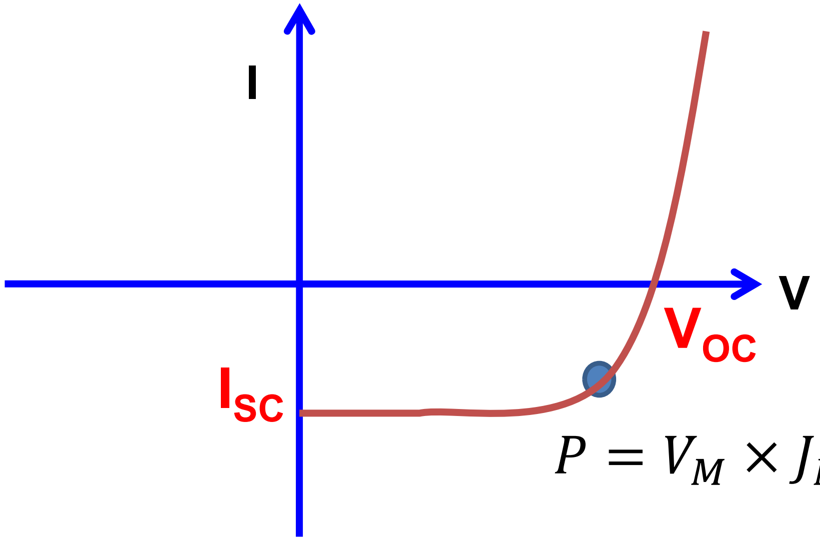






V_{OC} : Open circuit voltage
I_{SC} : Short circuit current

What is the maximum power that can be extracted?



$$P = V_M \times J_M$$

$$P = \frac{V_M \times J_M}{V_{OC} \times J_{SC}} \times V_{OC} \times J_{SC}$$

$$P = FF \times V_{OC} \times J_{SC}$$

Parameters of the Ideal Silicon Cell and the Best PERL Cell, and Achievable Parameters of a PERL Cell (AM1.5)

	Jsc (mA/cm2)	Voc (mV)	FF (%)	Eff. (%)
ideal cell[15]	43.0	769	89.0	29
best PERL[18]	40.8	708	83.1	24
achievable cell[19]	42.5	730	84.0	>26

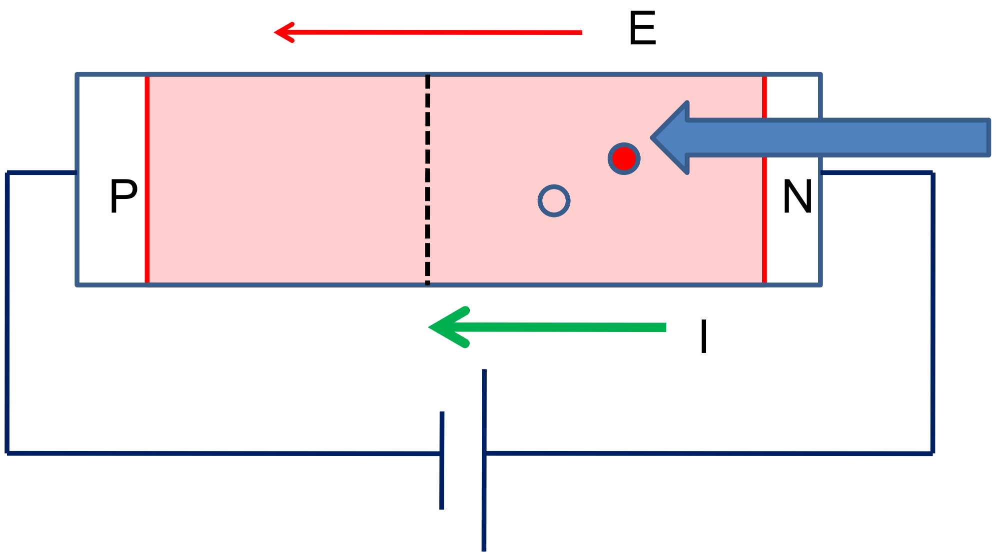
$$P_{ext} = J_{SC} \times V_{OC} \times FF = 43 \times 0.769 \times 0.89 = 29.4mW\ for\ 100mW\ of\ incident\ solar\ power\ (1\ sun)$$

CITY	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	AVG.
AGRA	3.58	4.65	5.53	5.96	6.33	5.98	4.94	4.51	4.68	4.69	3.91	3.42	4.85
ALLAHABAD	3.79	4.83	5.93	6.39	6.55	5.68	4.56	4.31	4.48	4.8	4.23	3.6	4.93
GORAKHPUR	3.41	4.25	5.28	5.88	6.5	6.34	5.66	5.35	5.02	4.54	3.74	3.2	4.93
KANPUR	3.62	4.63	5.68	6.19	6.54	5.88	4.78	4.45	4.45	4.83	4.14	3.52	4.89
LUCKNOW	3.62	4.63	5.68	6.19	6.54	5.88	4.78	4.45	4.45	4.83	4.14	3.52	4.89
MEERUT	3.6	4.53	5.73	6.7	7.28	6.68	5.54	4.9	5.17	5.01	4.15	3.47	5.23

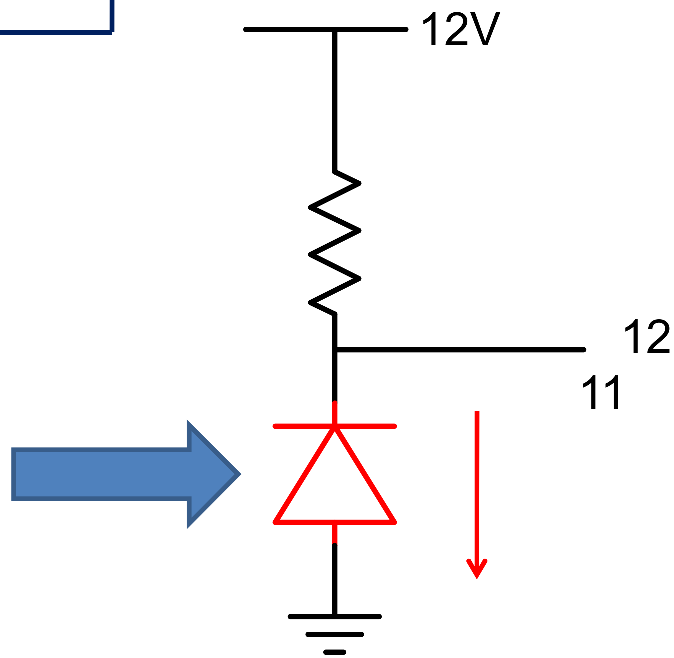
$kWh\ /\ m^2/\text{day}$

$18\%\ efficient\ solar\ panel\ of\ 1\text{m}^2\ would\ generate\ 0.9kWh$

PN Junction as a Photodiode or detector



A specially designed Reverse-biased PN junction is used to detect light.

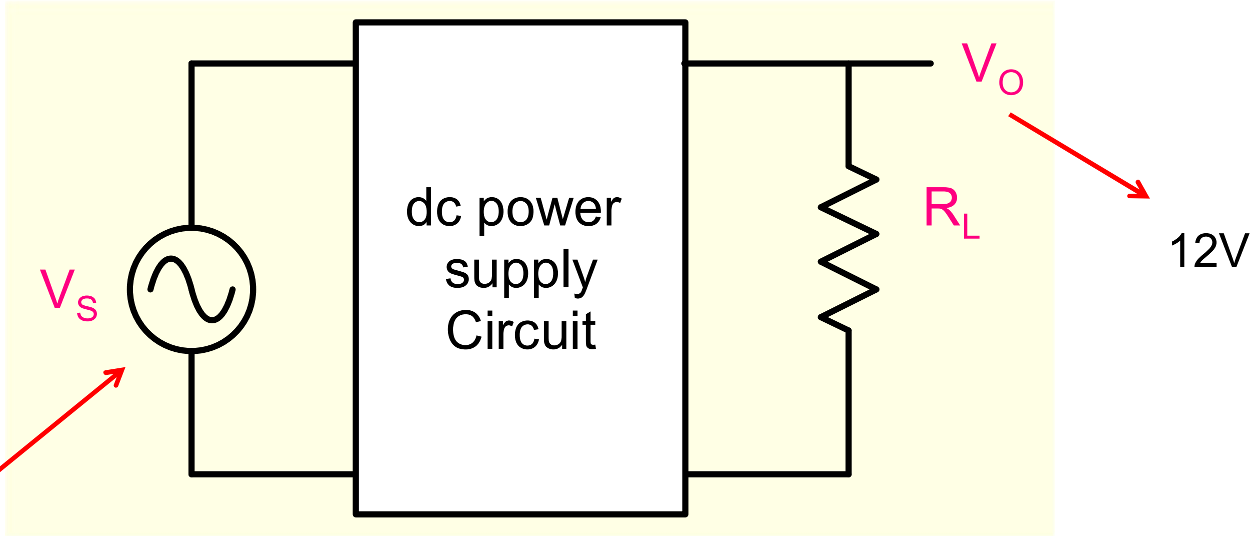


ESC201T : Introduction to Electronics

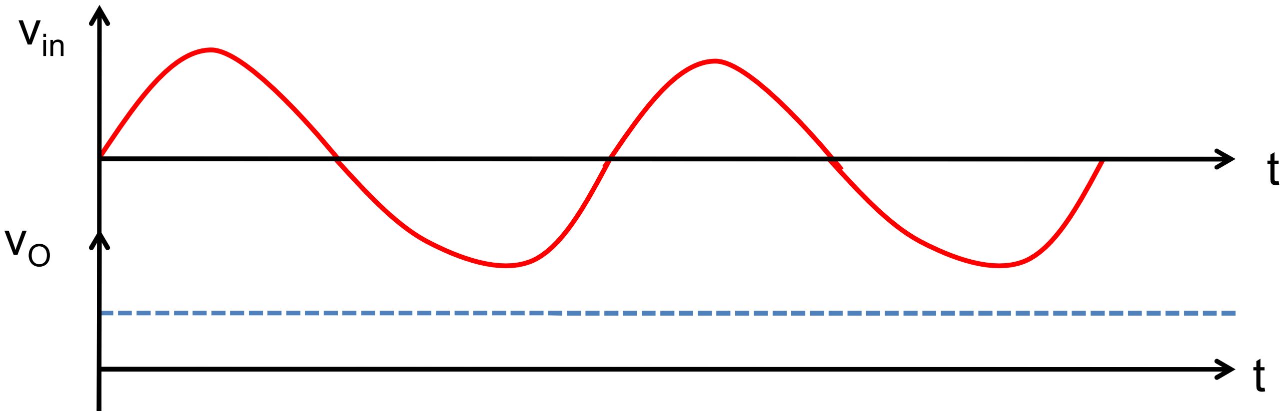
Lecture 23: Power Supply (part-1)

B. Mazhari
Dept. of EE, IIT Kanpur

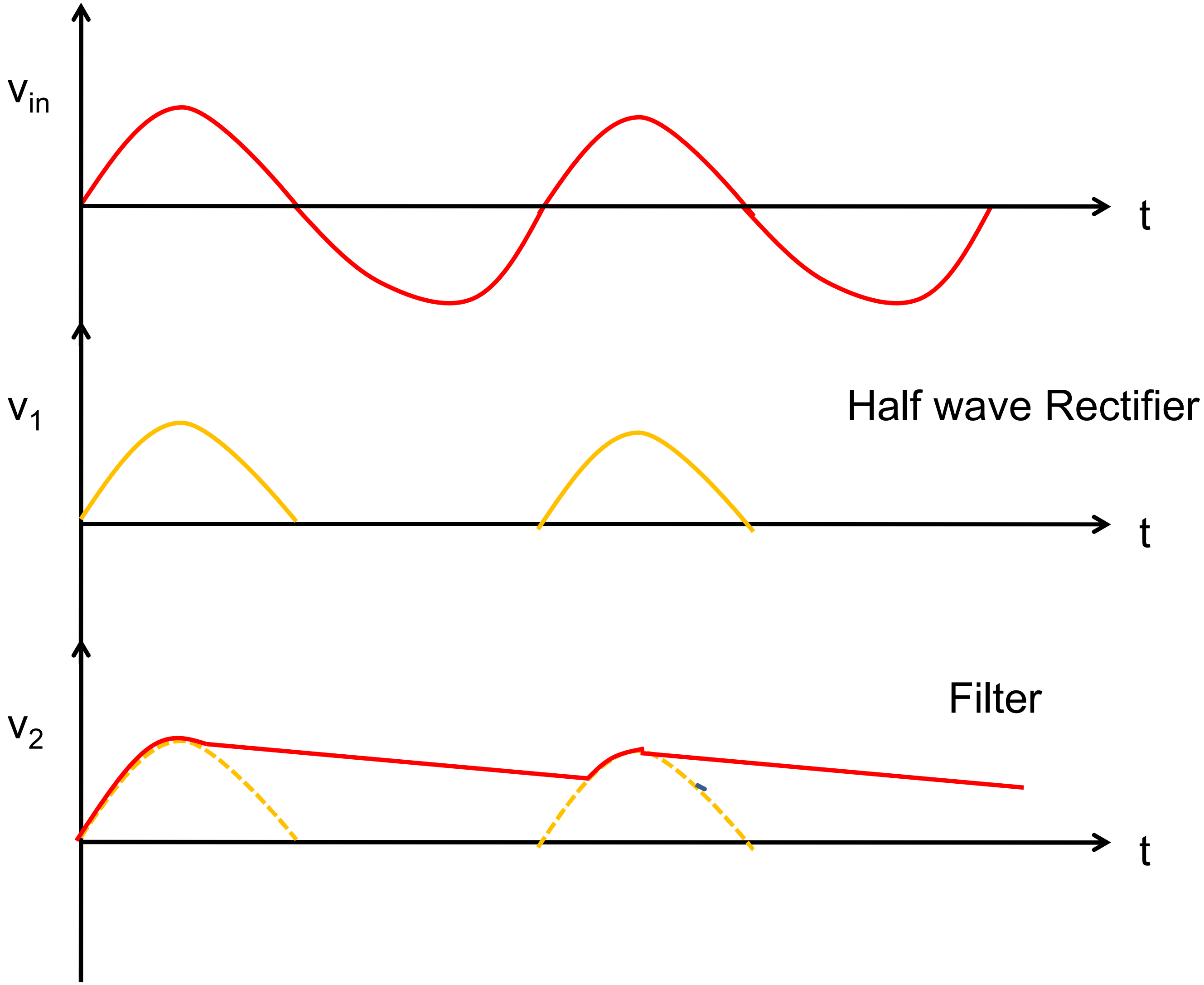
Power Supply



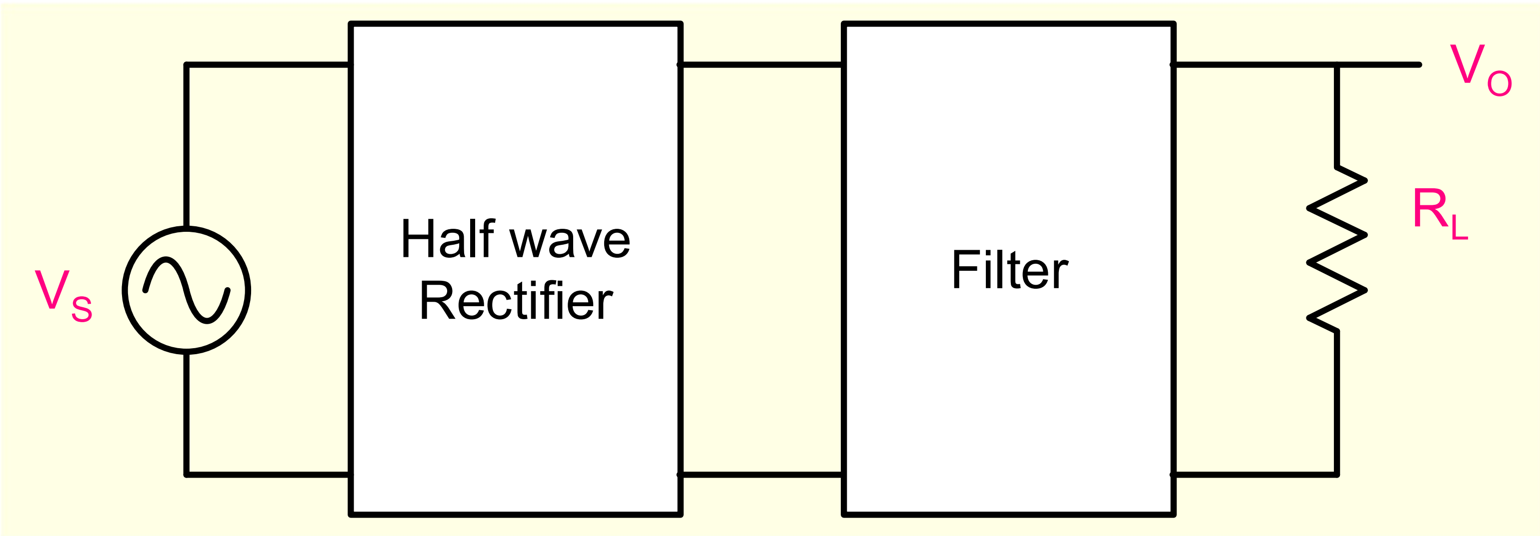
$220V\ rms \Rightarrow 311.127V\ peak\ value$



Strategy

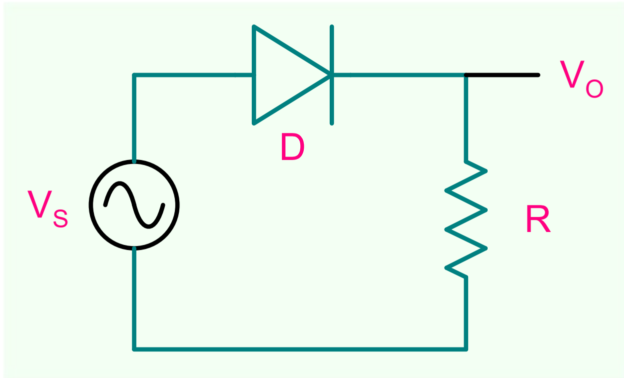


Power Supply: Block diagram

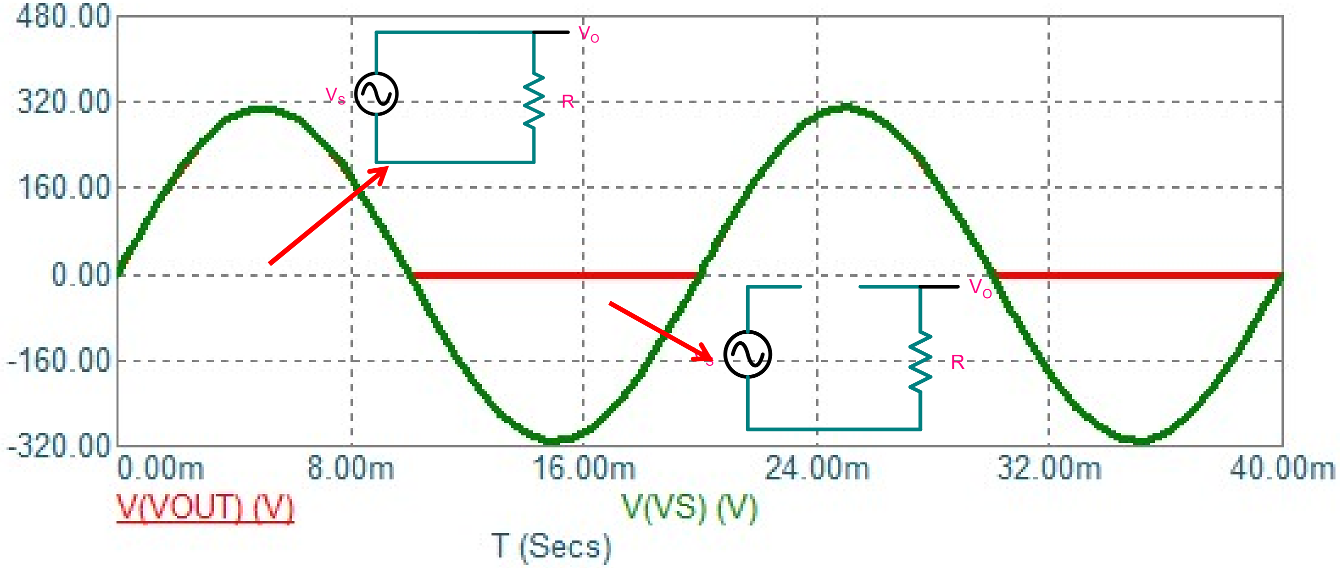


Half wave Rectifier circuit

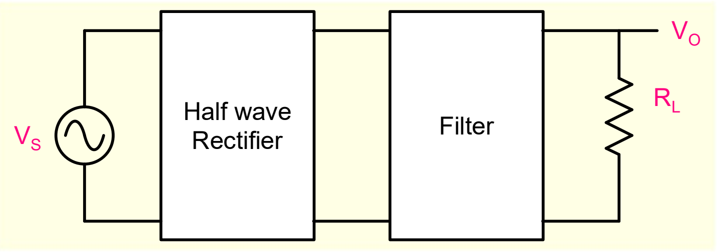
$220V\ rms$

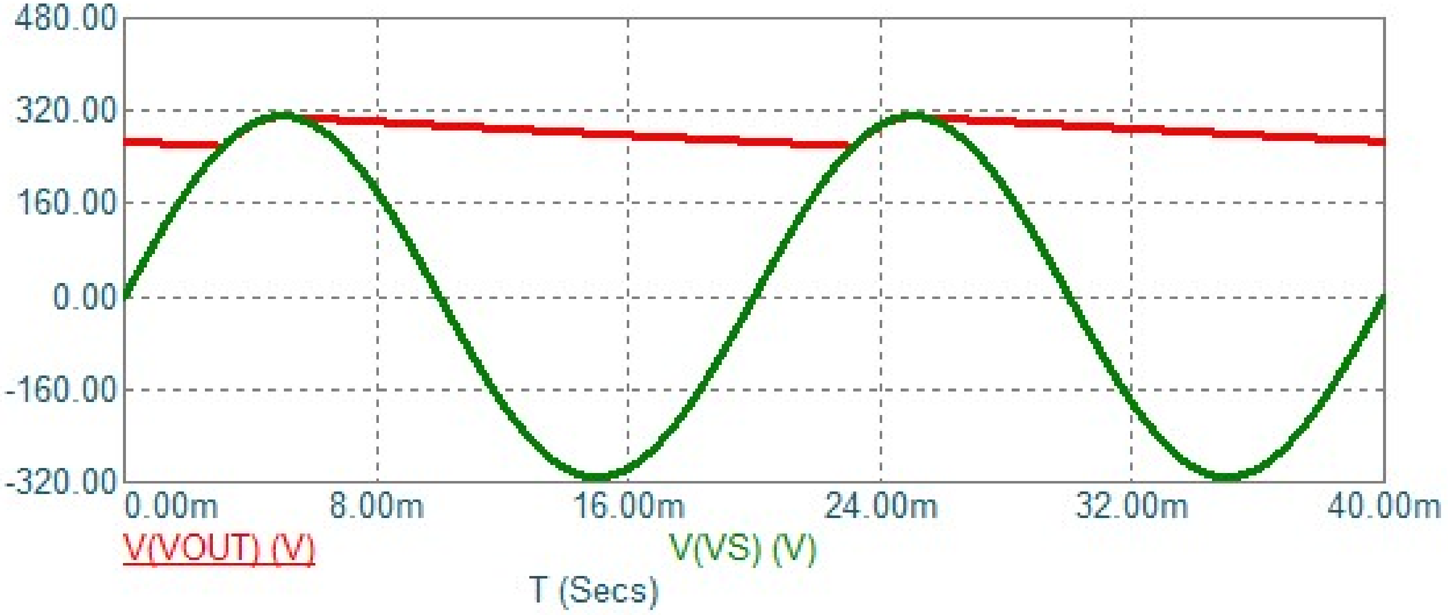


$$220V \times \sqrt{2}$$
$$= 311.127V\ \ peak\ value$$



Filtered output voltage is too large !

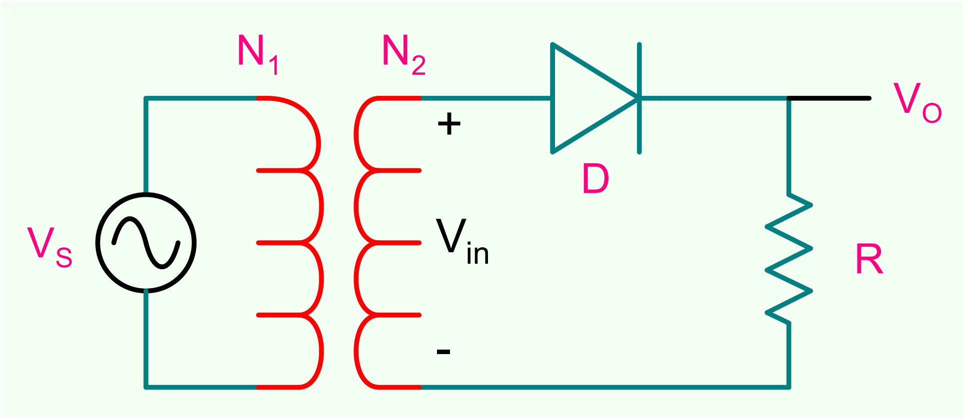


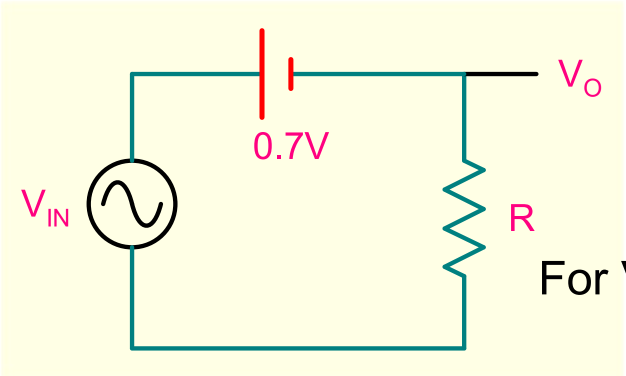


Must reduce the input voltage

Half Wave Rectifier

$$\frac{V_S}{V_{IN}} = \frac{N_1}{N_2}$$

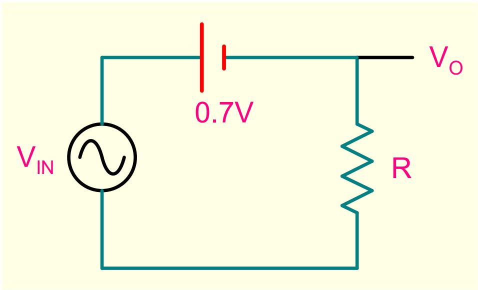




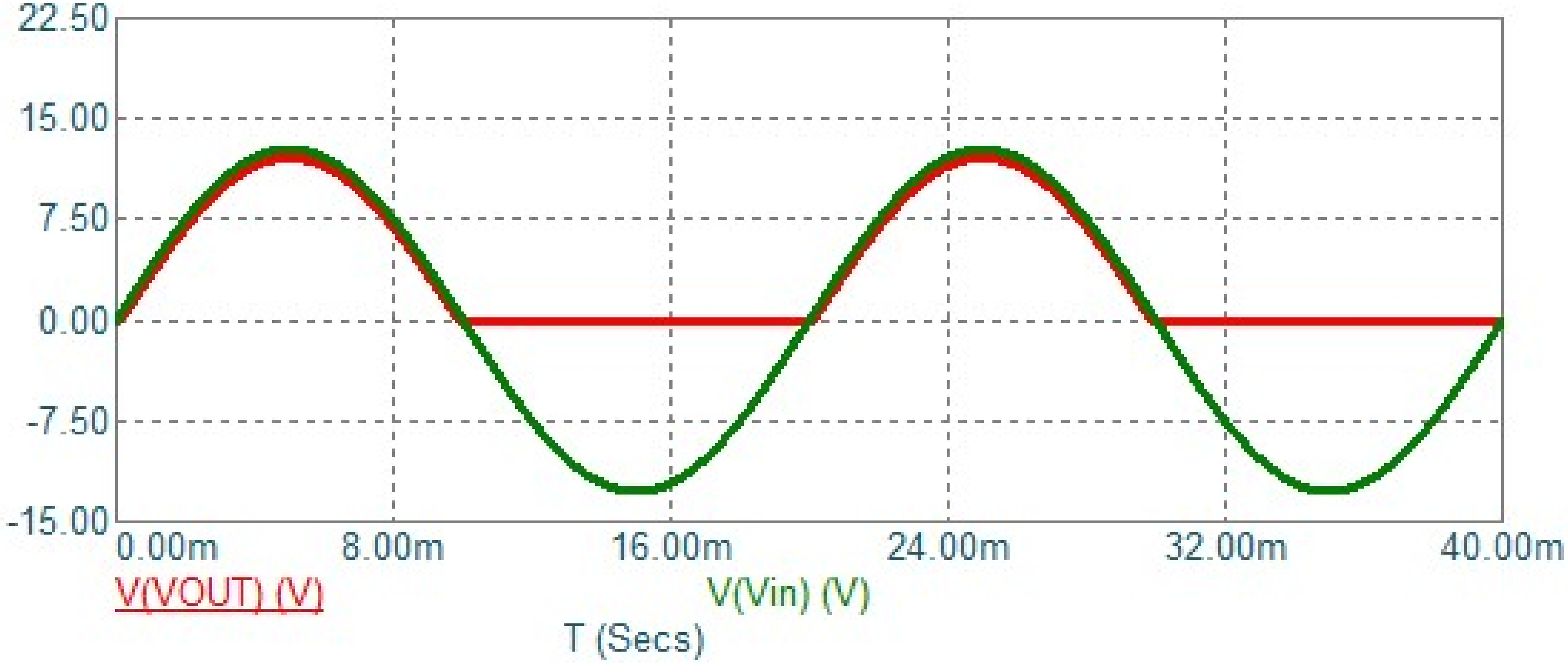
For V_O to be 12V, the input V_{IN} should be ~12.7V

$$V_S = 220V \times \sqrt{2}$$
$$= 311.127V \ \textit{peak value}$$

$$\frac{N_1}{N_2} = 24.5$$

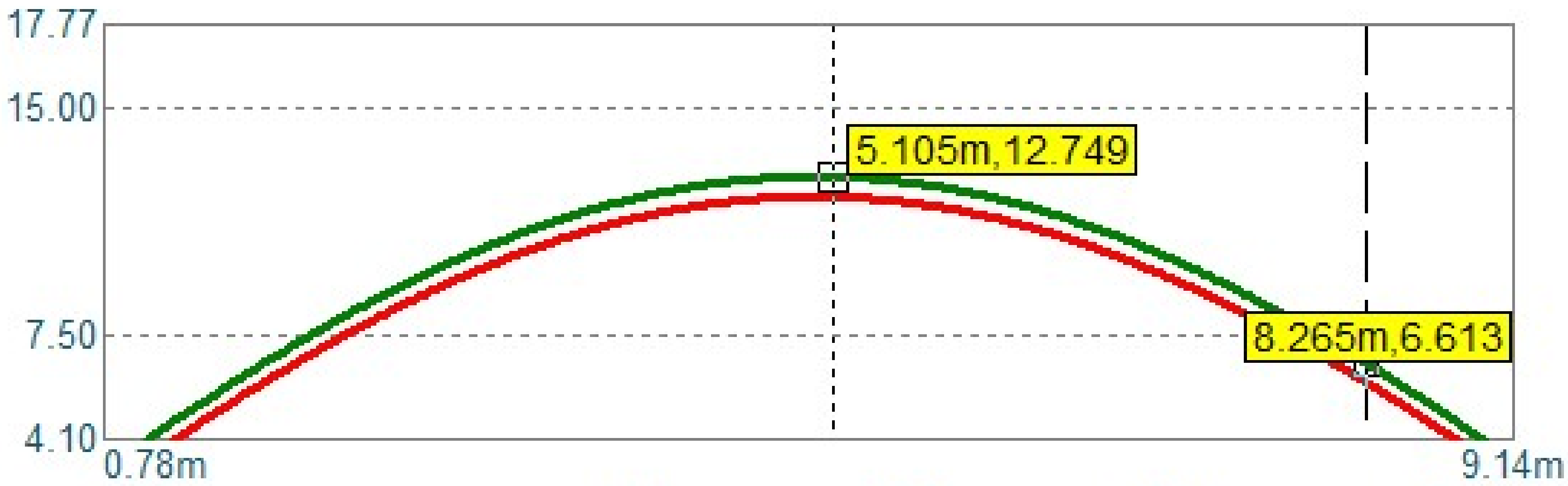


0.7V
V_O
V_{IN}
R

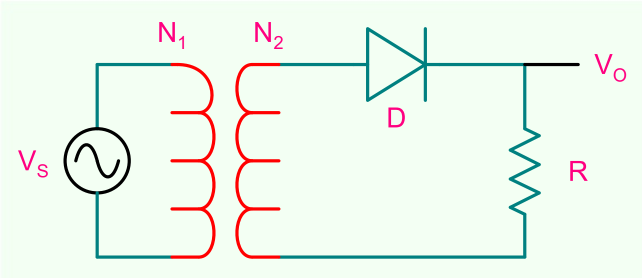


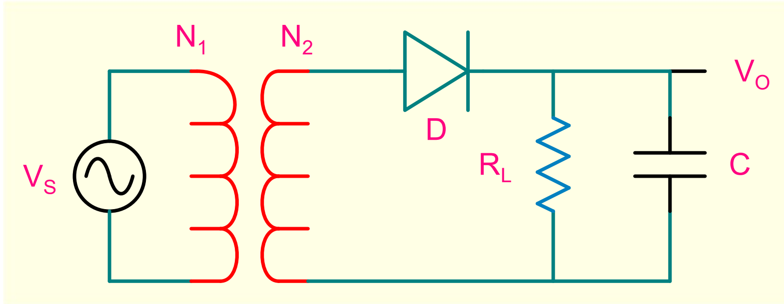
22.50
15.00
7.50
0.00
-7.50
-15.00
0.00m
8.00m
16.00m
24.00m
32.00m
40.00m
V(VOUT) (V)
V(Vin) (V)
T (Secs)

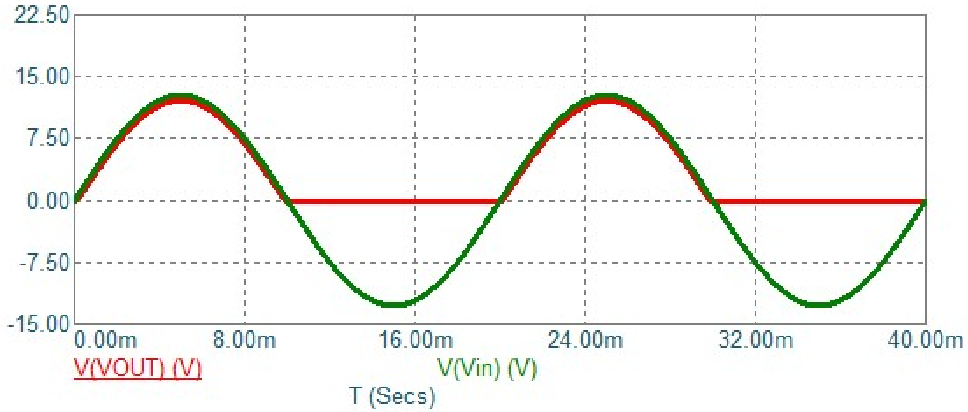
Zoomed view

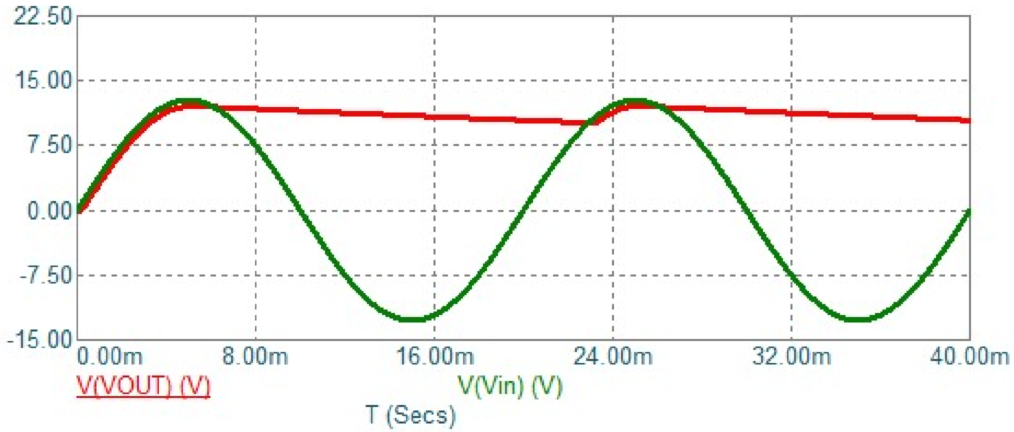


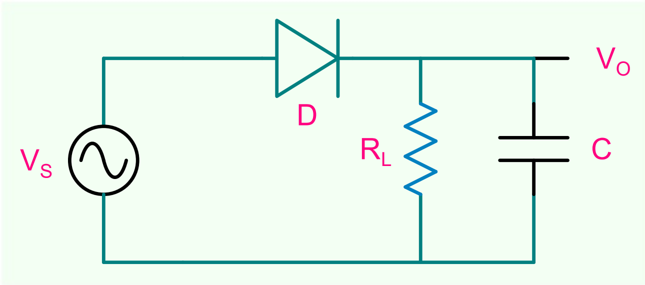
	Left	Right	Delta	Slope
V(VOUT) (V)	12.088	5.983	-6.105	-1.932K
V(Vin) (V)	12.749	6.613	-6.136	-1.942K
T (Secs)	5.105m	8.265m	3.160m	1.000

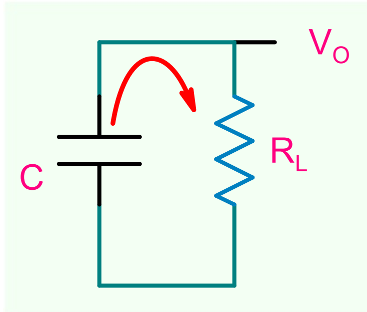

N1
N2
D
VO
VS
R

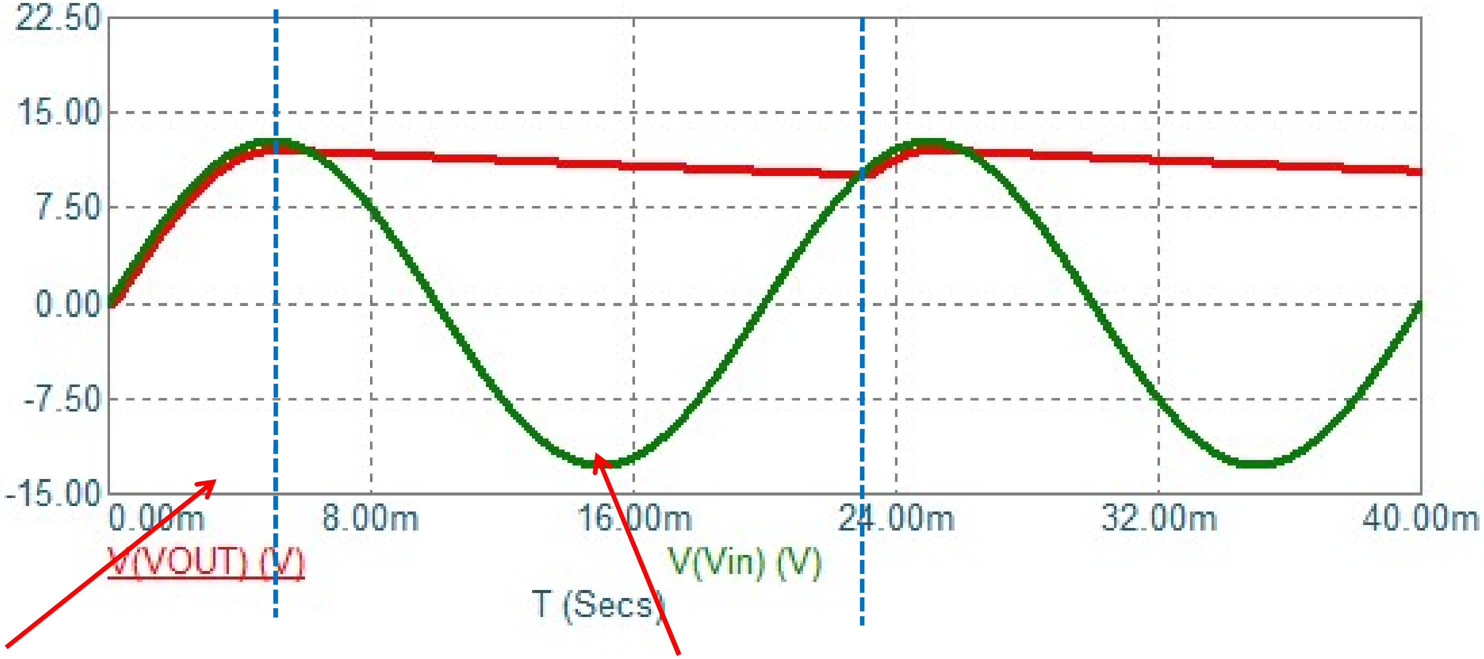

N1
N2
D
VO
VS
RL
C


22.50
15.00
7.50
0.00
-7.50
-15.00
0.00m
8.00m
16.00m
24.00m
32.00m
40.00m
V(VOUT) (V)
V(Vin) (V)
T (Secs)


22.50
15.00
7.50
0.00
-7.50
-15.00
0.00m
8.00m
16.00m
24.00m
32.00m
40.00m
V(VOUT) (V)
V(Vin) (V)
T (Secs)







Diode is forward biased

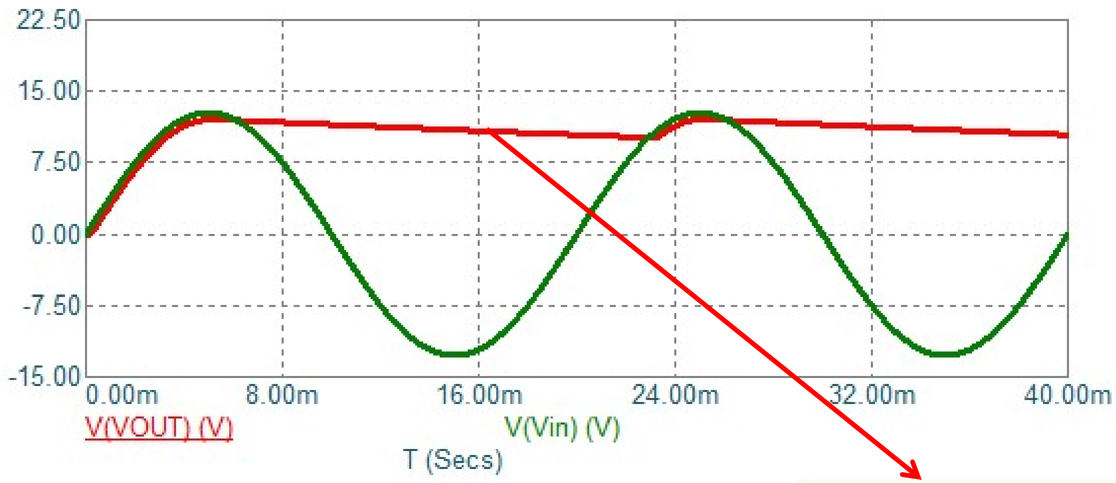
Diode is reverse biased

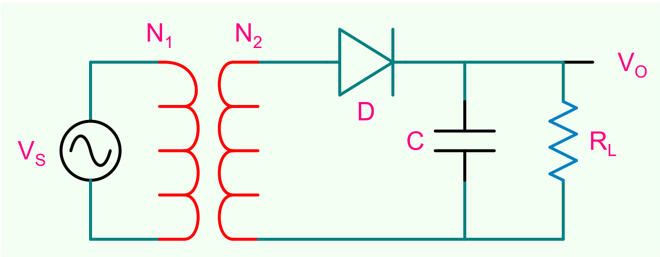
Output has a ripple

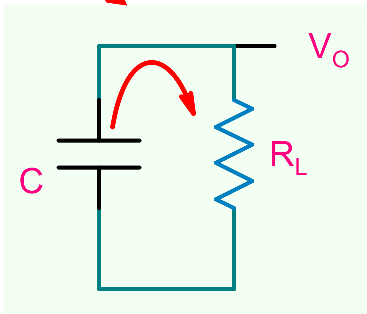
Ripple Voltage : $V_r = V_M - V_L$

Average Output Voltage : $V_O(avg) \cong V_M - \dfrac{V_R}{2}$

What does ripple voltage depend on?

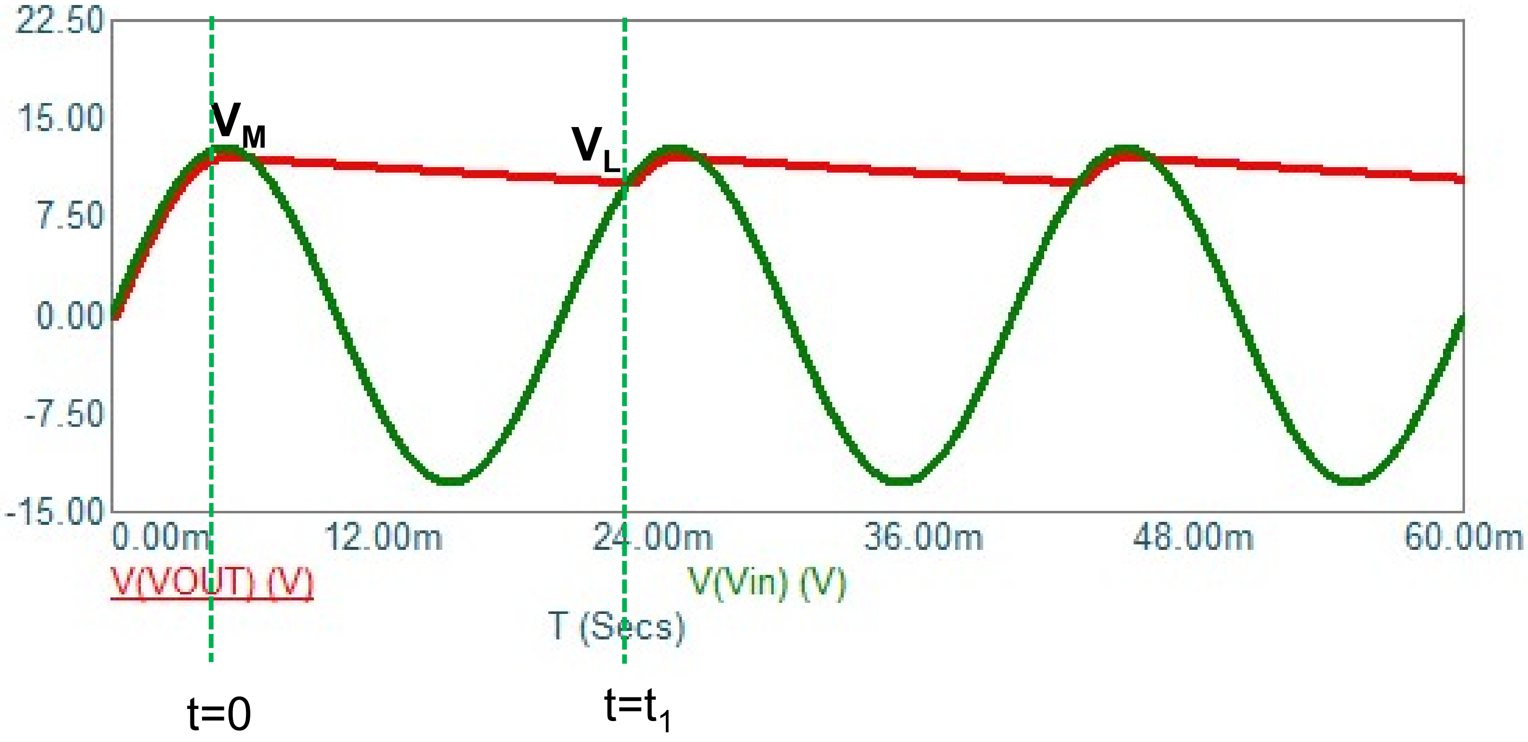






$$C\frac{dV_O}{dt}+\frac{V_O}{R_L}=0 \Rightarrow \frac{dV_O}{dt}=-\frac{V_O}{R_L C}$$

$$V_O(t)=V_M \times e^{-\frac{t}{R_L C}}$$

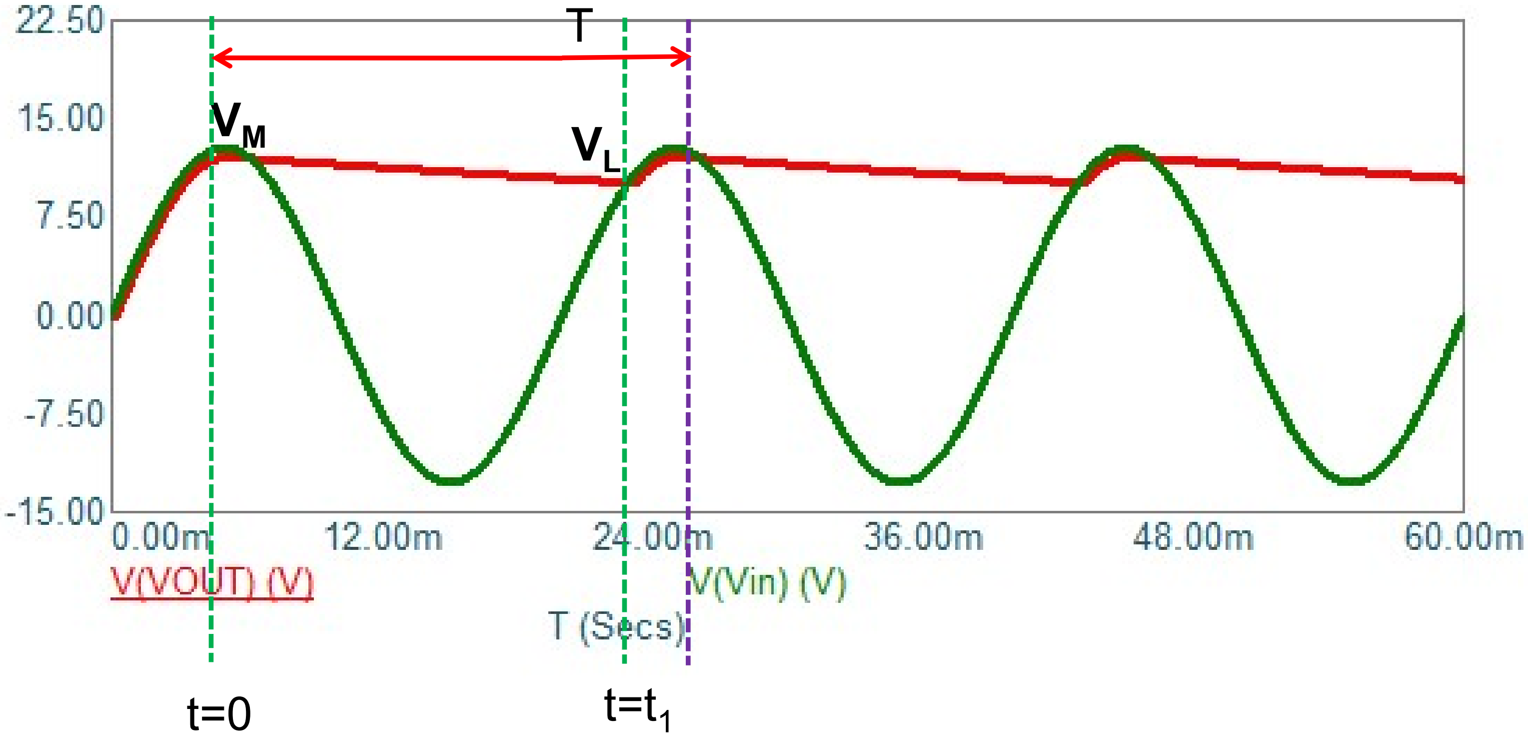


$$V_L = V_M \times e^{-\frac{t_1}{R_L C}}$$

$$V_r = V_M - V_L = V_M \times (1 - e^{-\frac{t_1}{R_L C}})$$

Assuming that $t_1 << R_L\ C$

$$V_r \cong V_M \times \{1 - (1 - \frac{t_1}{R_L C})\} = \frac{V_M t_1}{R_L C}$$

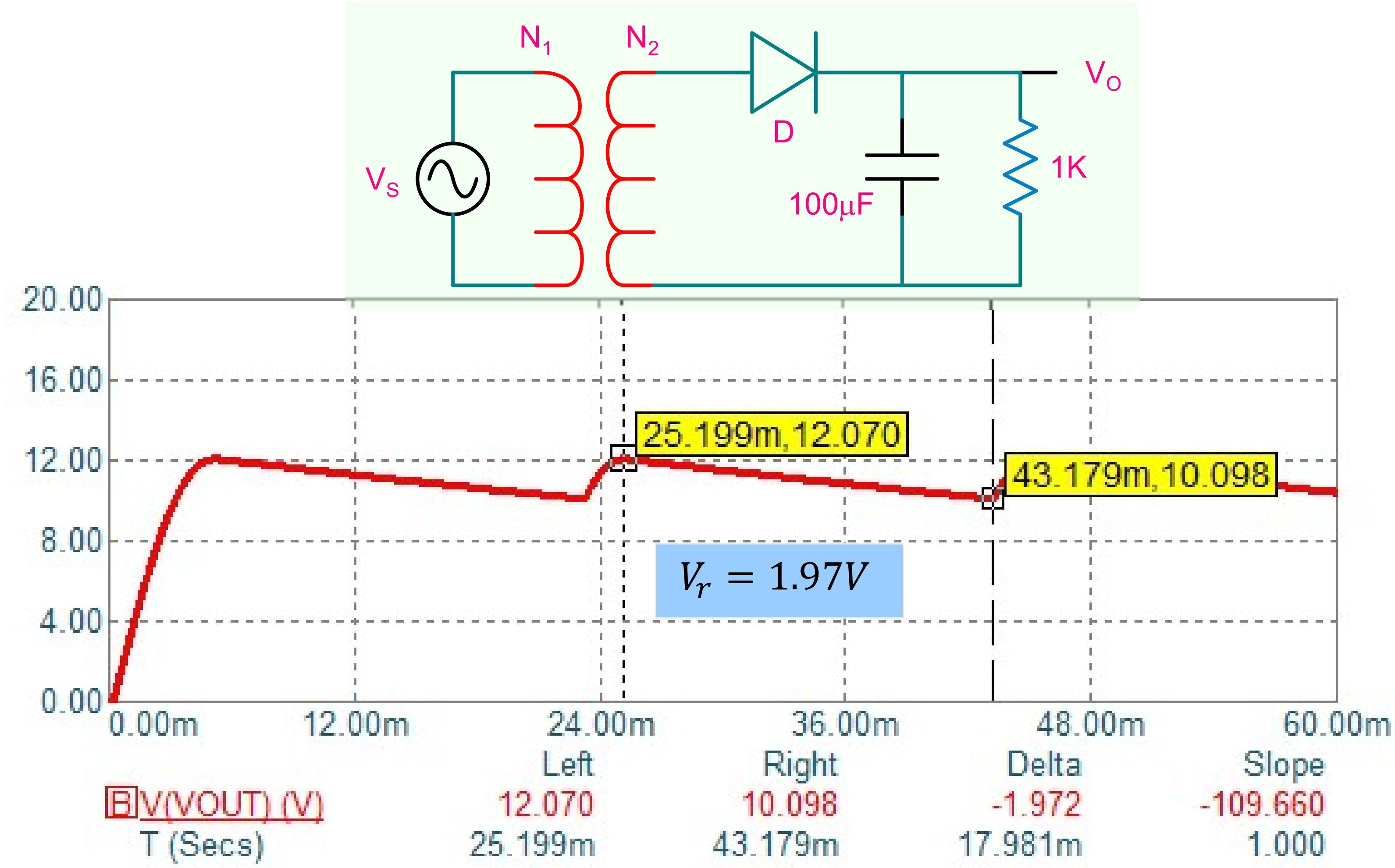


$$t_1 \cong T$$

$$V_r = \frac{V_M t_1}{R_L C} \cong \frac{V_M T}{R_L C}$$

$$V_r \cong \frac{V_M}{f \times R_L C}$$

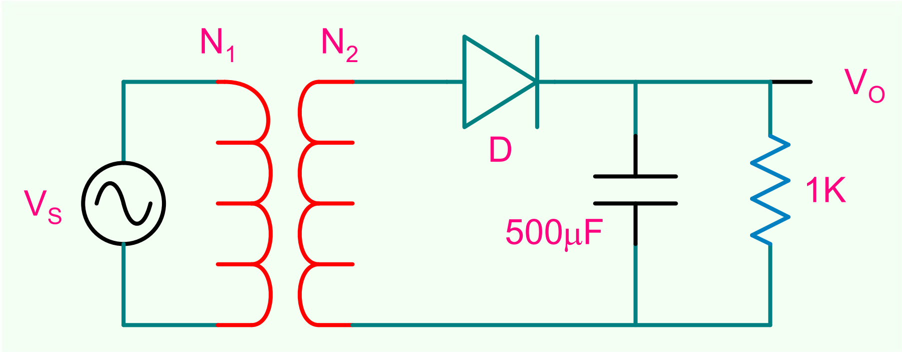
Example

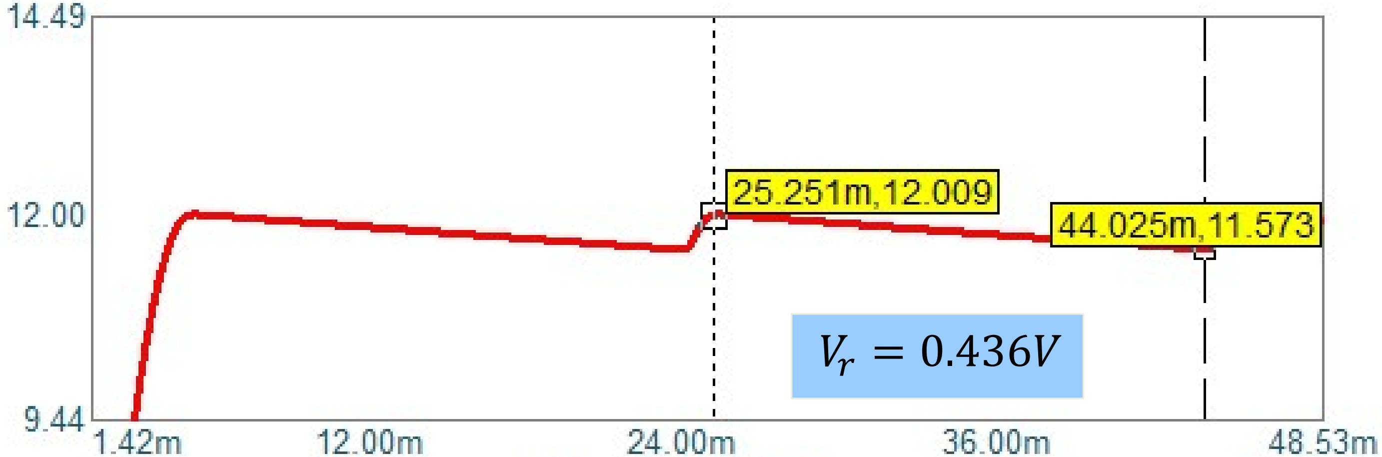


$$V_r \cong \frac{V_M}{f \times R_L\, C} = \frac{12.070}{50 \times 10^3 \times 100 \times 10^{-6}} = 2.4V$$

$$\frac{R_L C}{T} = 5$$

Example





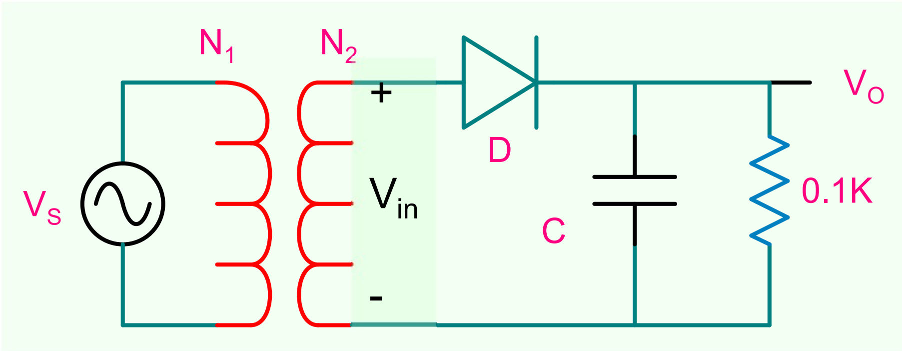
	Left	Right	Delta	Slope
V(VOUT) (V)	12.009	11.573	-436.226m	-23.236
T (Secs)	25.251m	44.025m	18.773m	1.000

$$V_r \cong \frac{V_M}{f \times R_L\, C} = \frac{12}{50 \times 10^3 \times 500 \times 10^{-6}} = 0.48V$$

$$\frac{R_L C}{T} = 25$$

Design Example

Design a power supply that will supply 6V to a load of 100Ω with ripple voltage less than 0.1V.



For V_O to be 6V, the input V_{IN} should be ~6.7V

$$\frac{N_1}{N_2} = \frac{311.127}{6.7} = 46.4$$

$$V_r \cong \frac{V_M}{fR_L C} = 0.1 \Rightarrow C = 12mF$$

How do we choose a diode for this application?

Diode Specifications

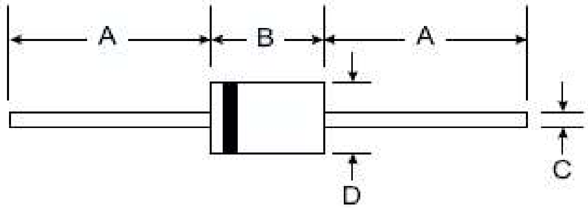
DIODES INCORPORATED

1N4001/L - 1N4007/L

1.0A RECTIFIER

Features

- Diffused Junction
- High Current Capability and Low Forward Voltage Drop
- Surge Overload Rating to 30A Peak
- Low Reverse Leakage Current
- Plastic Material: UL Flammability Classification Rating 94V-0



	DO-41 Plastic		A-405	
Dim	Min	Max	Min	Max
A	25.40	—	25.40	—
B	4.06	5.21	4.10	5.20
C	0.71	0.864	0.53	0.64
D	2.00	2.72	2.00	2.70
All Dimensions in mm				

"L" Suffix Designates A-405 Package
No Suffix Designates DO-41 Package

Mechanical Data

- Case: Molded Plastic
- Terminals: Plated Leads Solderable per MIL-STD-202, Method 208
- Polarity: Cathode Band
- Weight: DO-41 0.30 grams (approx)
  A-405 0.20 grams (approx)
- Mounting Position: Any
- Marking: Type Number

Maximum Ratings and Electrical Characteristics

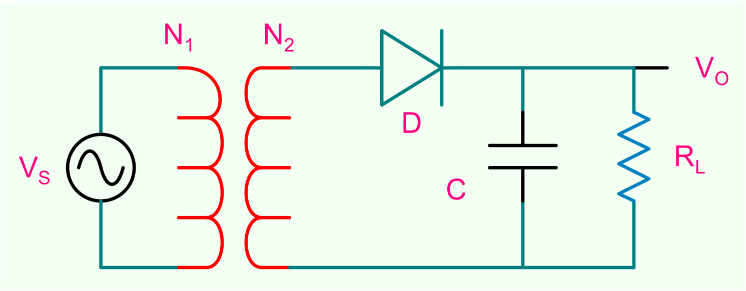
@ $T_A = 25°C$ unless otherwise specified

Single phase, half wave, 60Hz, resistive or inductive load.
For capacitive load, derate current by 20%.

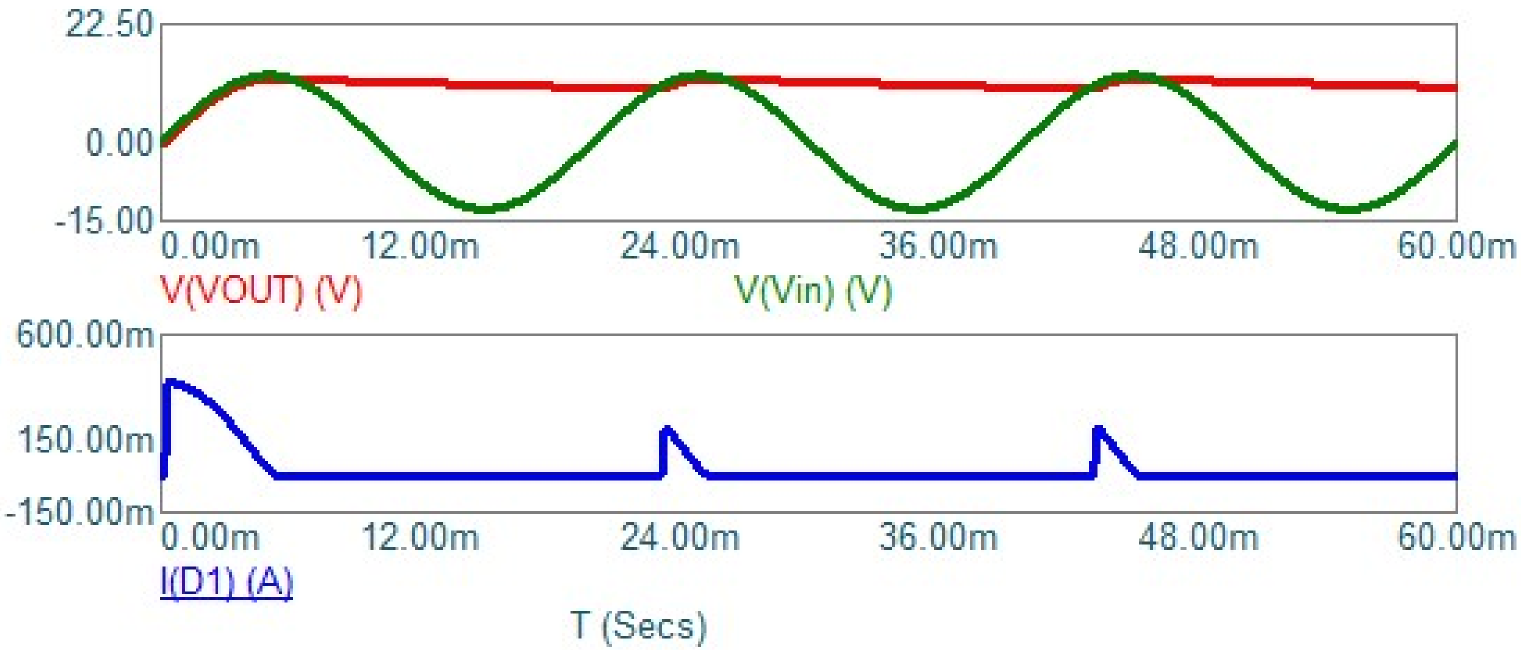
Characteristic	Symbol	1N 4001/L	1N 4002/L	1N 4003/L	1N 4004/L	1N 4005/L	1N 4006/L	1N 4007/L	Unit
Peak Repetitive Reverse Voltage Working Peak Reverse Voltage DC Blocking Voltage	V_{RRM} V_{RWM} V_R	50	100	200	400	600	800	1000	V
RMS Reverse Voltage	$V_{R(RMS)}$	35	70	140	280	420	560	700	V
Average Rectified Output Current (Note 1) @ $T_A = 75°C$	I_O	1.0							A
Non-Repetitive Peak Forward Surge Current 8.3ms single half sine-wave superimposed on rated load (JEDEC Method)	I_{FSM}	30							A
Forward Voltage @ $I_F = 1.0A$	V_{FM}	1.0							V
Peak Reverse Current @ $T_A = 25°C$ at Rated DC Blocking Voltage @ $T_A = 100°C$	I_{RM}	5.0 50							μA
Typical Junction Capacitance (Note 2)	C_j	15				8			pF
Typical Thermal Resistance Junction to Ambient	$R_{\theta JA}$	100							K/W
Maximum DC Blocking Voltage Temperature	T_A	+150							°C
Operating and Storage Temperature Range (Note 3)	T_j, T_{STG}	-65 to +175							°C

Notes: 1. Leads maintained at ambient temperature at a distance of 9.5mm from the case.
2. Measured at 1. MHz and applied reverse voltage of 4.0V DC.
3. JEDEC Value.

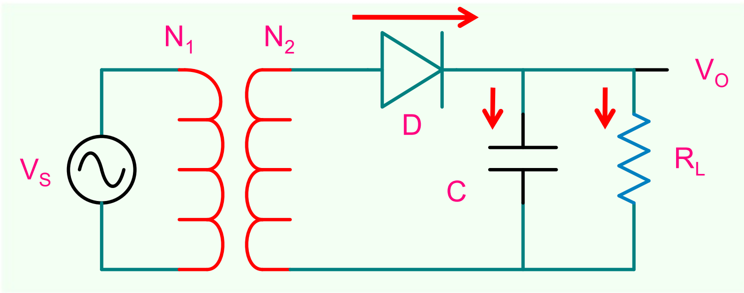
How do we choose a diode for this application?



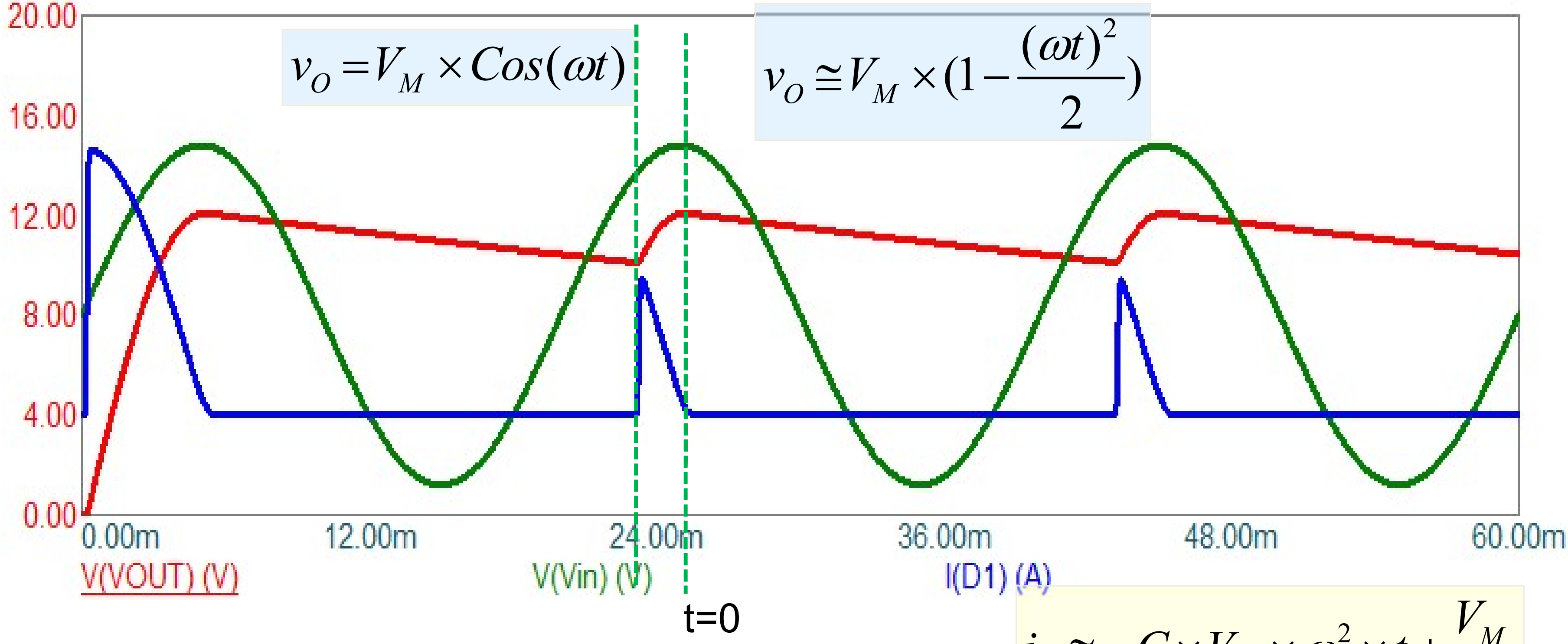
Determine peak and average diode currents; peak inverse voltage



Diode forward bias current



$$i_D = C \times \frac{dv_O}{dt} + \frac{v_O}{R_L}$$



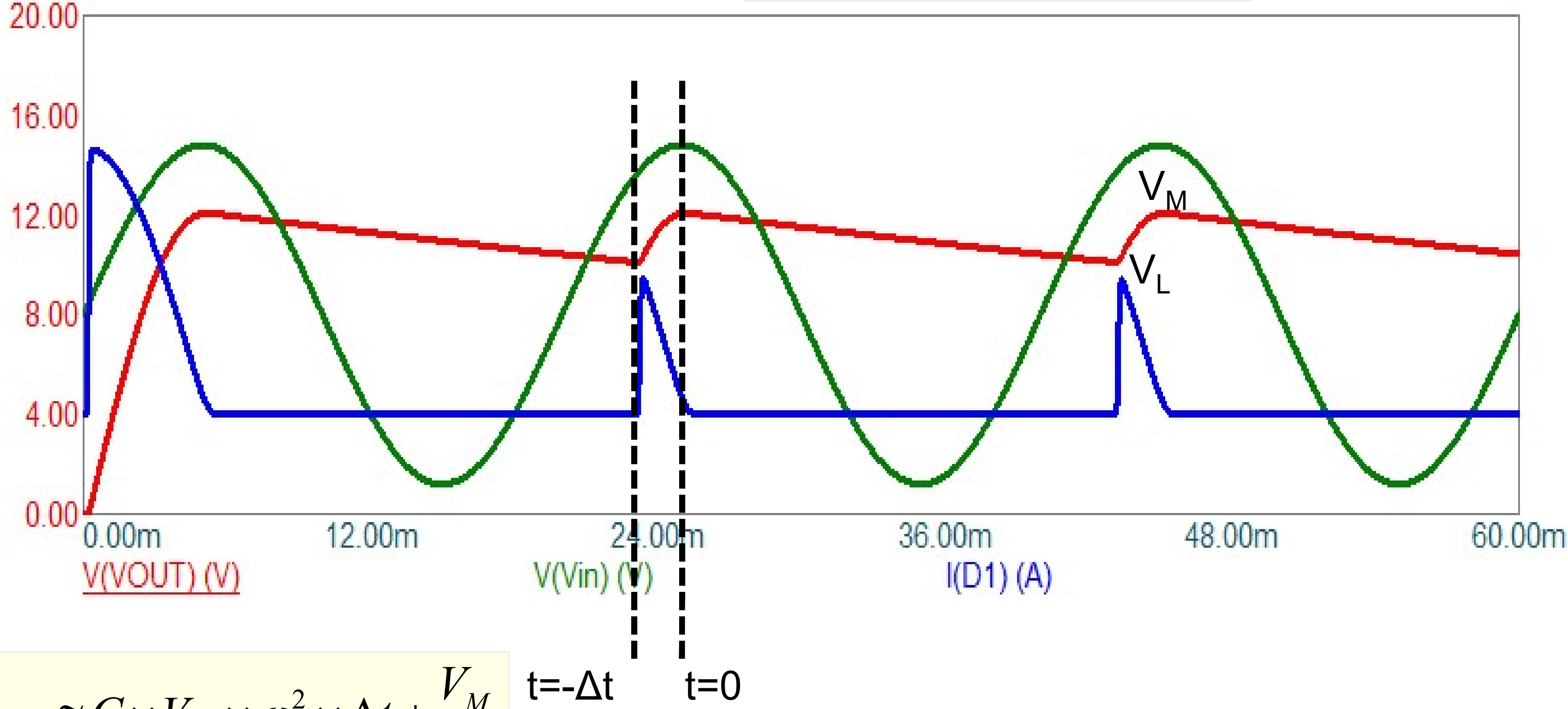
$$v_O = V_M \times Cos(\omega t)$$

$$v_O \cong V_M \times \left(1 - \frac{(\omega t)^2}{2}\right)$$

$$i_D \cong -C \times V_M \times \omega^2 \times t + \frac{V_M}{R_L}$$

$$v_O \cong V_M \times \left(1 - \frac{(\omega t)^2}{2}\right)$$

$$i_D \cong -C \times V_M \times \omega^2 \times t + \frac{V_M}{R_L}$$



$$i_{D\max} \cong C \times V_M \times \omega^2 \times \Delta t + \frac{V_M}{R_L}$$

$$V_L \cong V_M \times \left(1 - \frac{(\omega \Delta t)^2}{2}\right) \Rightarrow \Delta t = \frac{1}{\omega}\sqrt{\frac{2V_r}{V_M}}$$

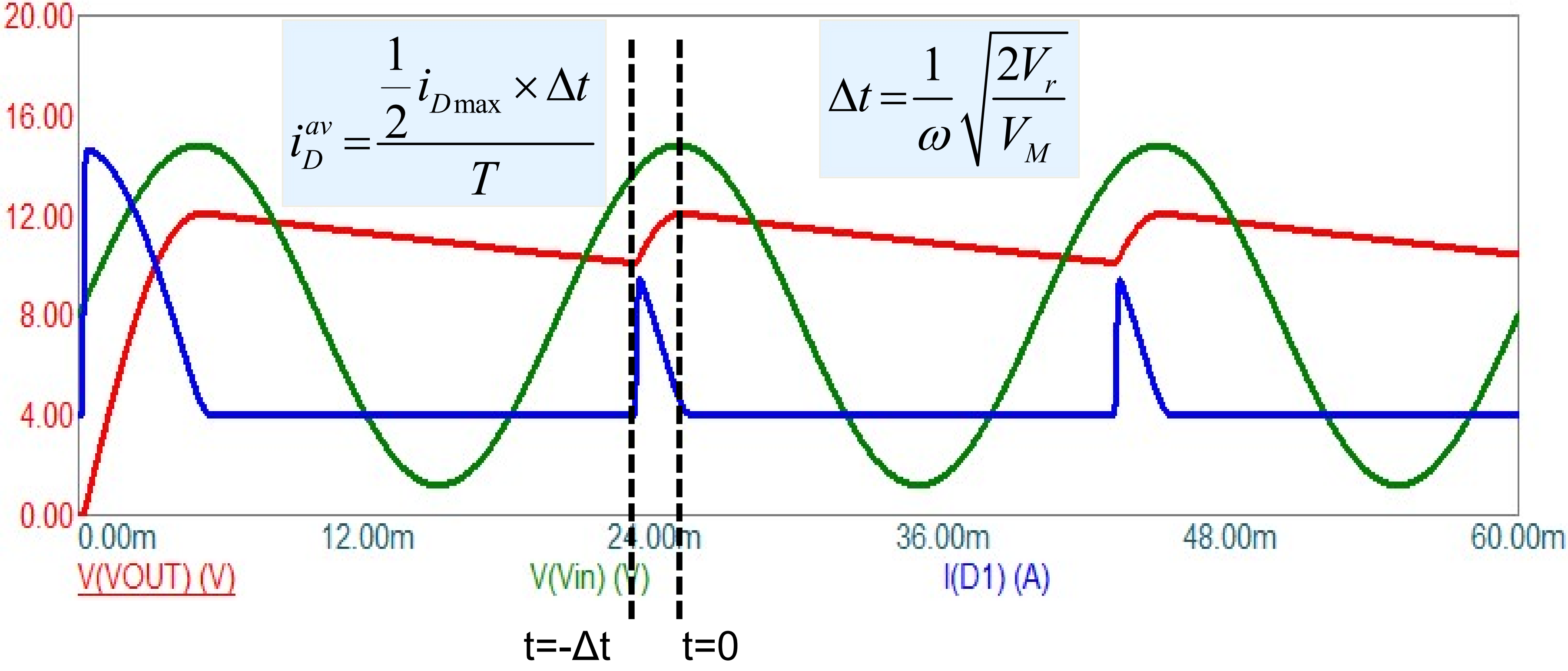
$$i_{D\max} \cong \omega C \times \sqrt{2V_r V_M} + \frac{V_M}{R_L}$$

Peak and Average Diode Currents

$$i_{D\max} \cong \omega C \times \sqrt{2V_r V_M} + \frac{V_M}{R_L}$$

$$i_D^{av} = \frac{\frac{1}{2} i_{D\max} \times \Delta t}{T}$$

$$\Delta t = \frac{1}{\omega}\sqrt{\frac{2V_r}{V_M}}$$



$$i_D^{av} = \frac{i_{D\max}}{4\pi} \times \sqrt{\frac{2V_r}{V_M}}$$

$$i_D^{av} = \frac{V_M}{R_L} + \frac{\sqrt{2V_r V_M}}{4\pi R_L} \cong \frac{V_M}{R_L}$$

$$i_{D\max} \cong \omega C \times \sqrt{2V_r V_M} + \frac{V_M}{R_L}$$

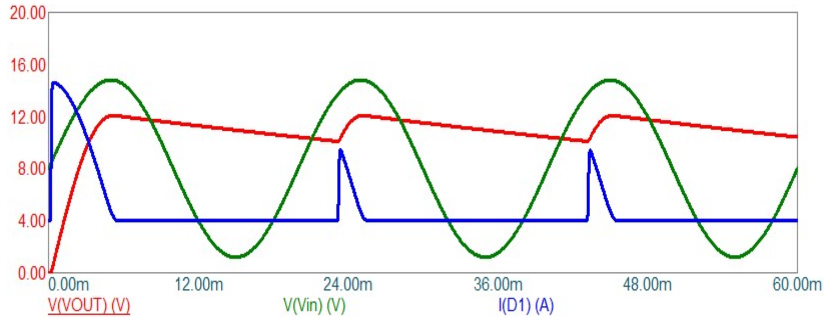
$$V_r \cong \frac{V_M}{fR_L C}$$

$$i_{Davg.} \cong \frac{V_M}{R_L}$$

$$i_{D\max} \cong 2\pi \times \sqrt{2f \times C \times V_M \times i_{Davg.}} + i_{Davg.}$$

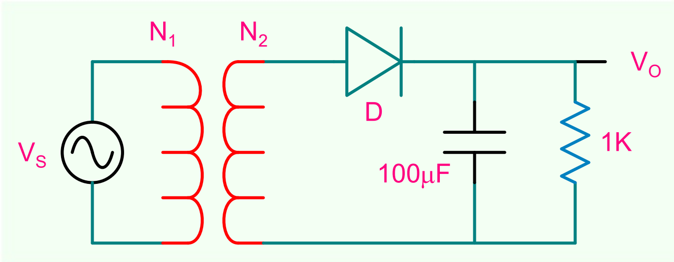
$$i_{D\max} \cong 2\pi \times \sqrt{2f \times C \times V_M \times i_{Davg.}}$$

$$\left(\frac{i_{Dmax}}{i_{Davg}}\right) \times \sqrt{\frac{V_r}{V_M}} = 2\sqrt{2}\pi$$



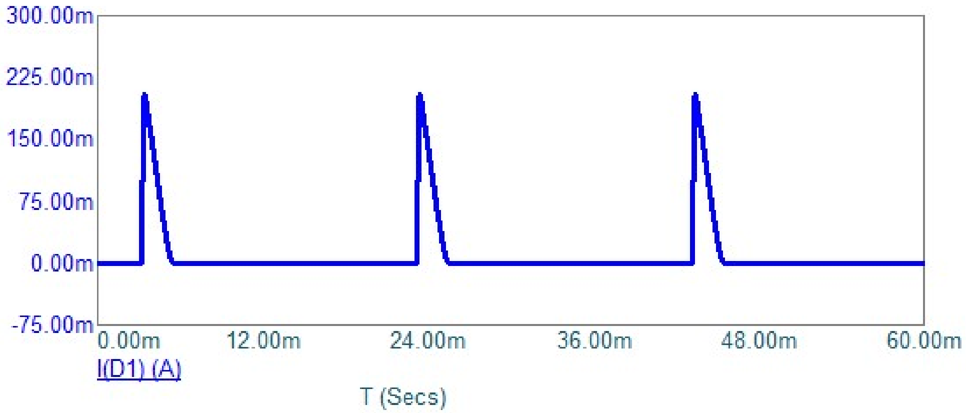
One can see a tradeoff between ripple voltage and peak diode current

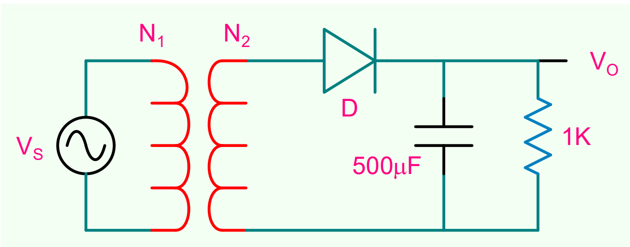
Peak and Average Diode Currents



$$V_r = 1.95V$$

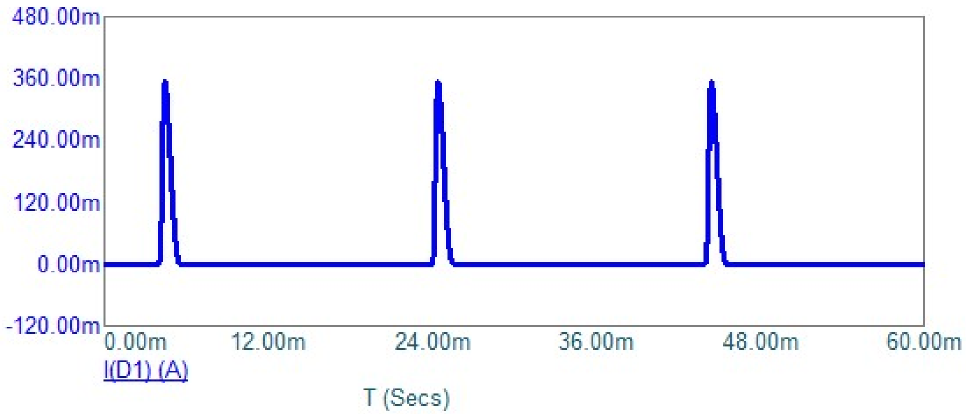
$$i_D^{av} \cong \frac{V_M}{R_L} = 12mA$$





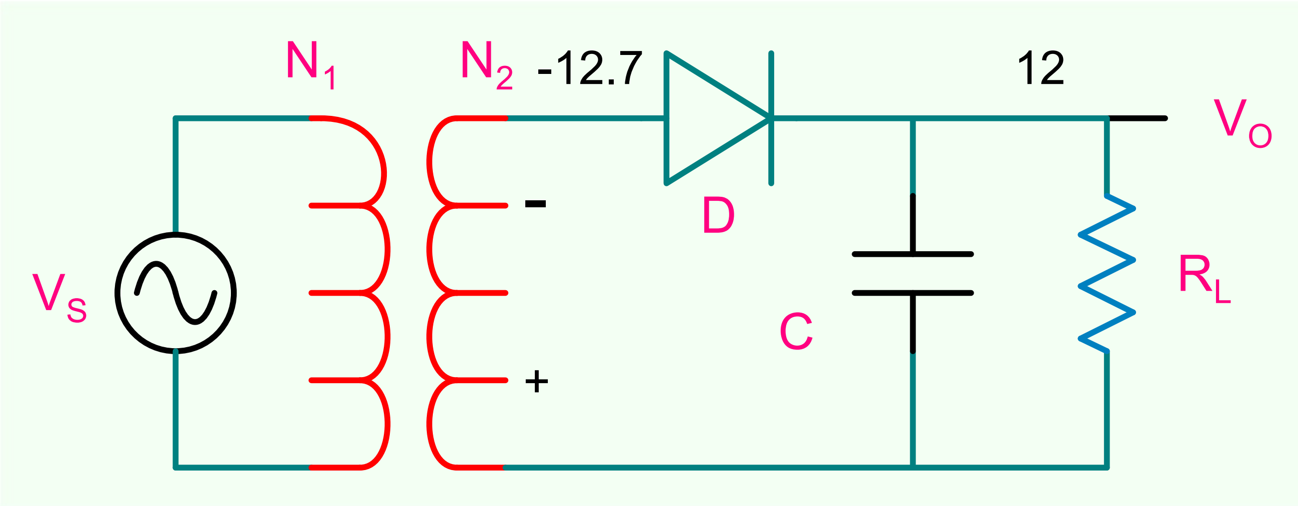
$$V_r = 0.438V$$

$$i_D^{av} \cong \frac{V_M}{R_L} = 12mA$$



Peak diode current increases as ripple reduces

Peak Inverse Voltage

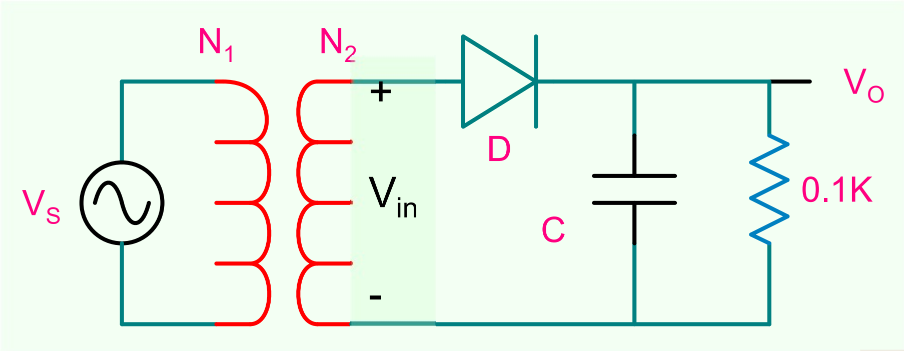


12+12.7=24.7V

$$PIV \cong 2v_O + 0.7$$

Design Example

Design a power supply that will supply 6V to a load of 100Ω with ripple voltage less than 0.1V.



$$i_{D\max} \cong \omega C \times \sqrt{2V_r V_M} + \frac{V_M}{R_L}$$

For V_O to be 6V, the input V_{IN} should be ~6.7V

$$\frac{N_1}{N_2} = \frac{311.127}{6.7} = 46.4$$

$$V_r \cong \frac{V_M}{fR_L C} = 0.1 \Rightarrow C = 12mF$$

How do we choose a diode for this application?

$$i_{Dmax} \approx \omega C \times \sqrt{2V_r \times V_M} + \frac{V_M}{R_L} = 344A$$

$$i_D^{av} \cong \frac{V_M}{R_L} = 60mA$$

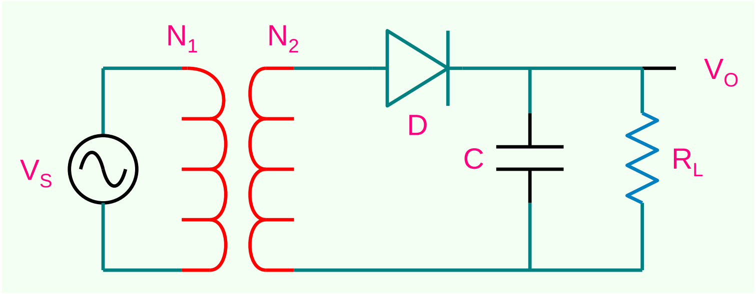
$$PIV \cong 2v_O + 0.7 = 12.7V$$

ESC201T : Introduction to Electronics

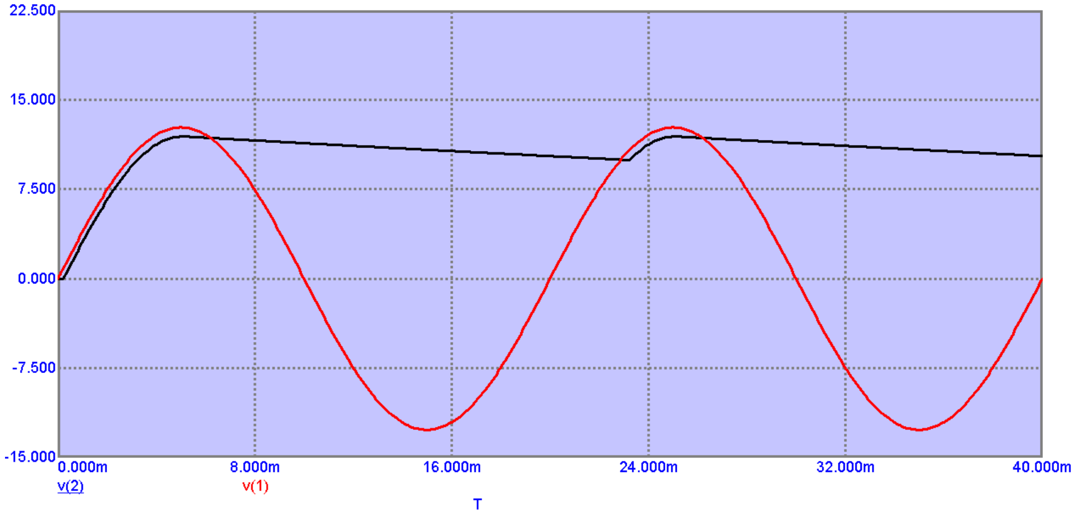
Lecture 24: Power Supply (part-2)

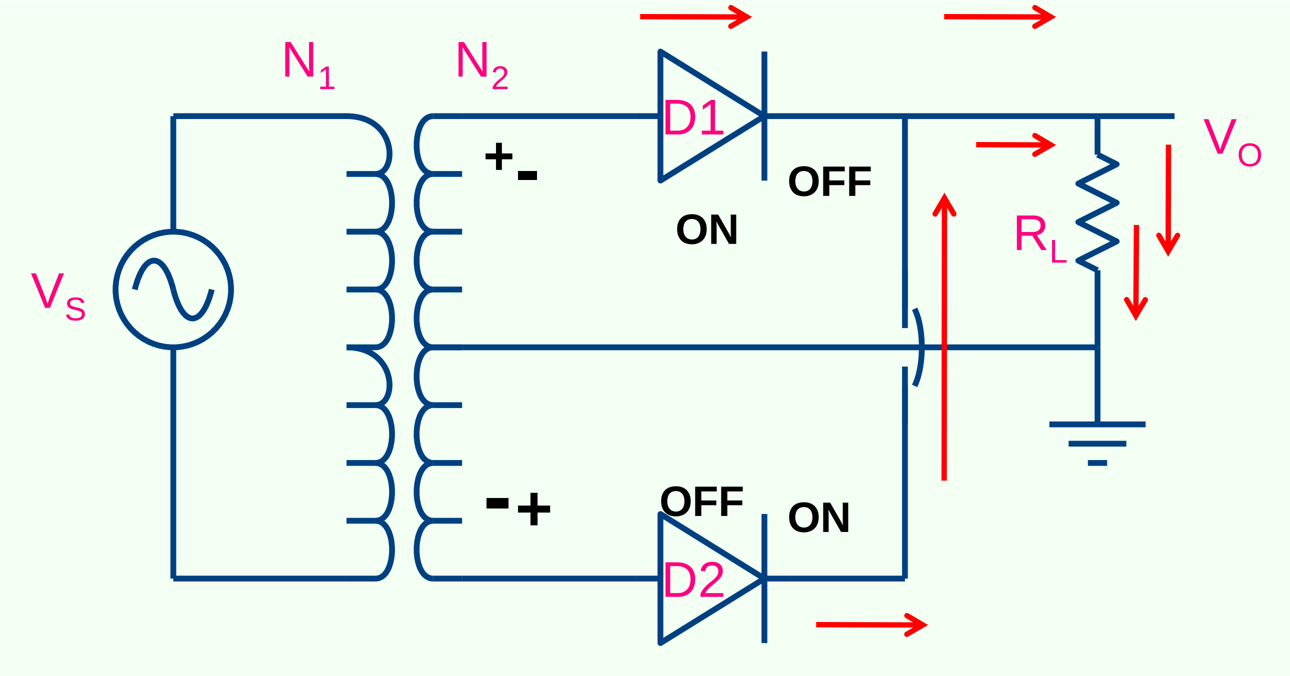
B. Mazhari
Dept. of EE, IIT Kanpur

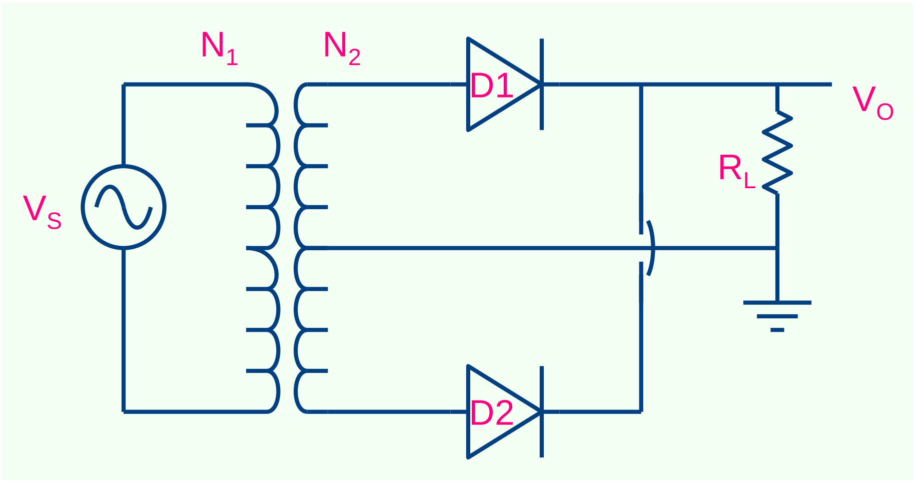
Full wave Rectifier

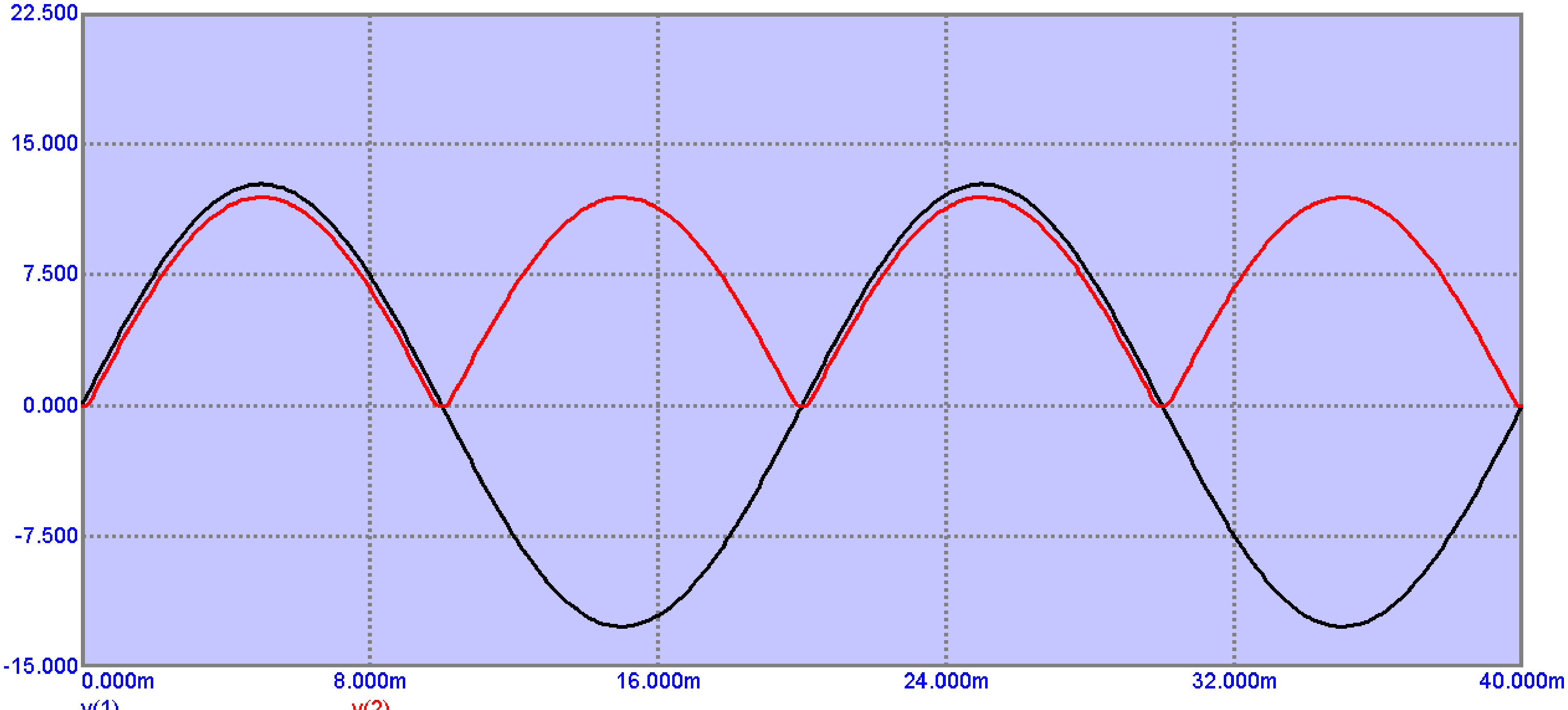


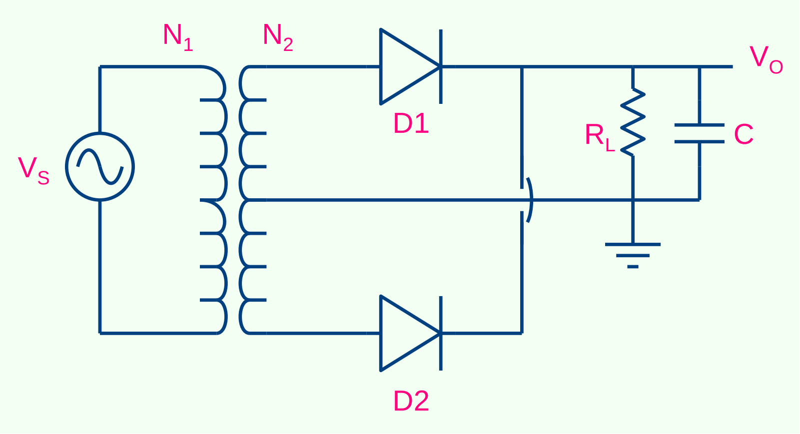
$$V_r \cong \frac{V_M}{fR_L C}$$

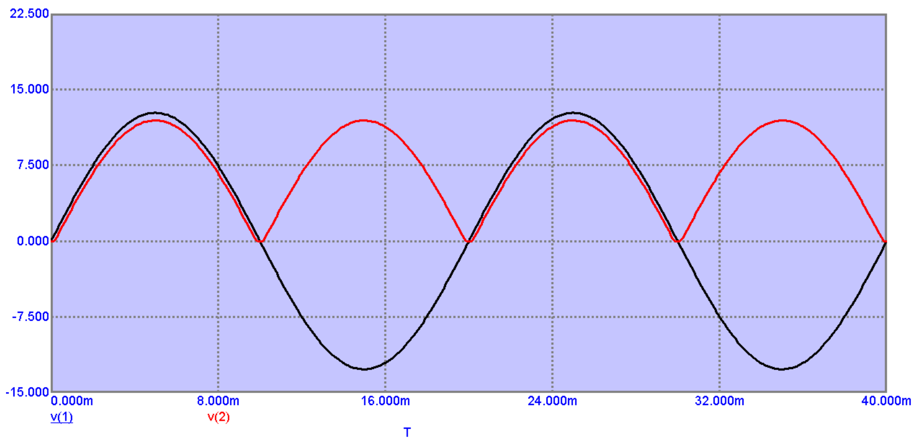


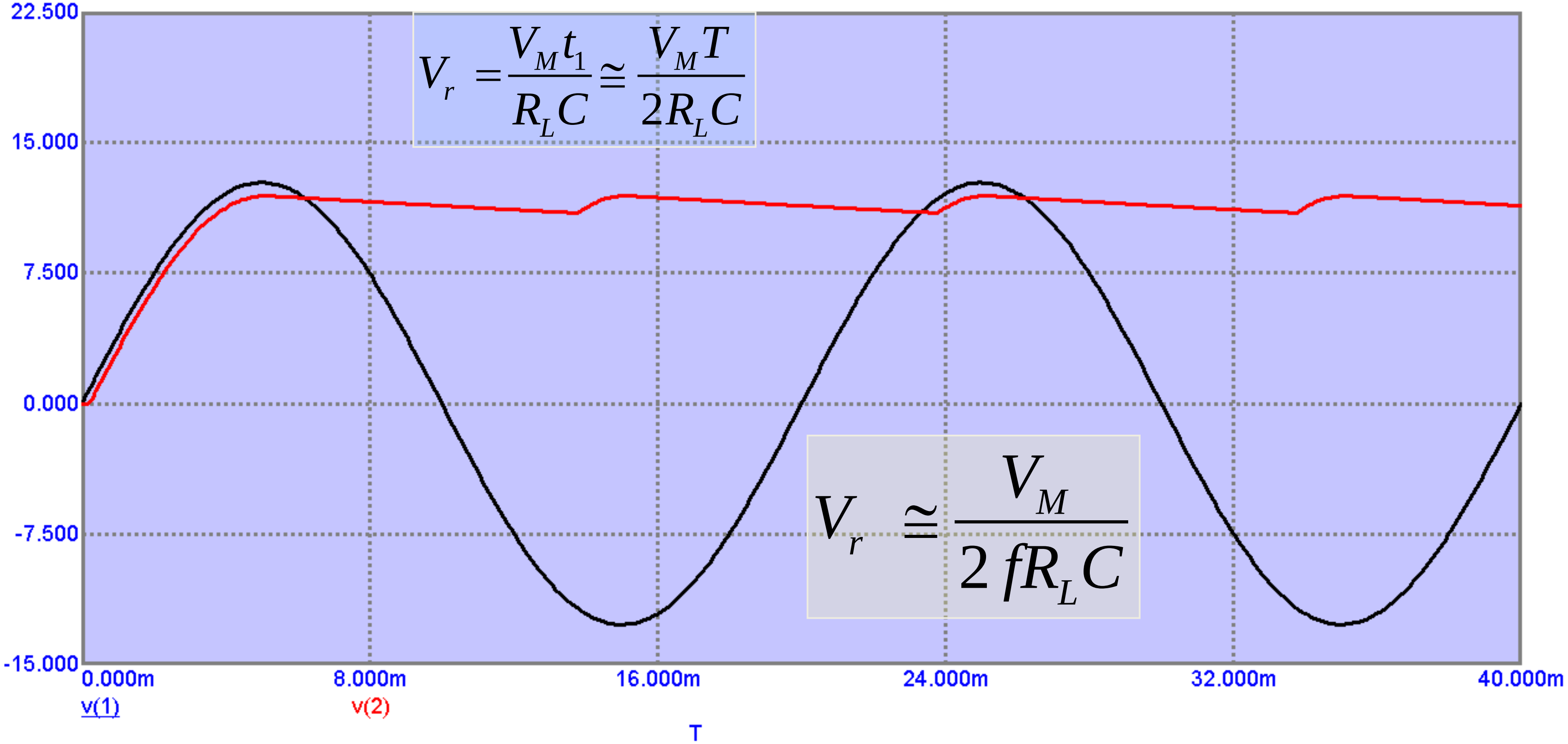



N1
N2
D1
D2
VO
RL
VS


22.500
15.000
7.500
0.000
-7.500
-15.000
0.000m
8.000m
16.000m
24.000m
32.000m
40.000m

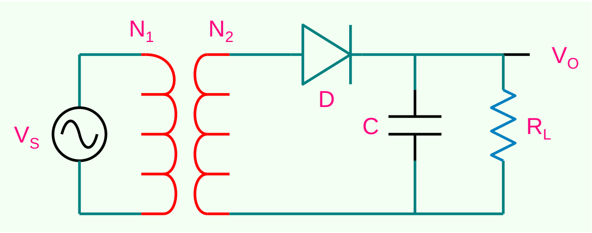

N1
N2
D1
D2
VO
VS
RL
C

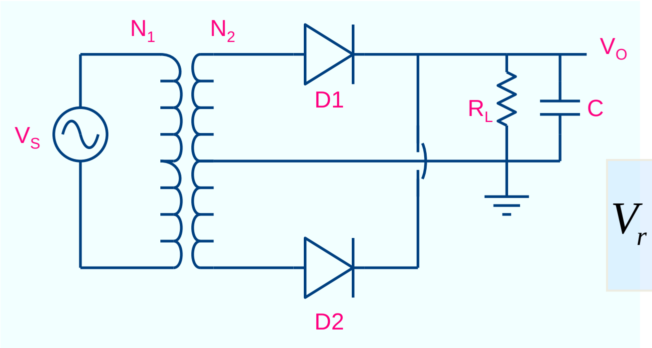

22.500
15.000
7.500
0.000
-7.500
-15.000
0.000m
8.000m
16.000m
24.000m
32.000m
40.000m
v(1)
v(2)
T


$$V_r = \frac{V_M t_1}{R_L C} \cong \frac{V_M T}{2 R_L C}$$
$$V_r \cong \frac{V_M}{2 f R_L C}$$
22.500
15.000
7.500
0.000
-7.500
-15.000
0.000m
8.000m
16.000m
24.000m
32.000m
40.000m
v(1)
v(2)
T

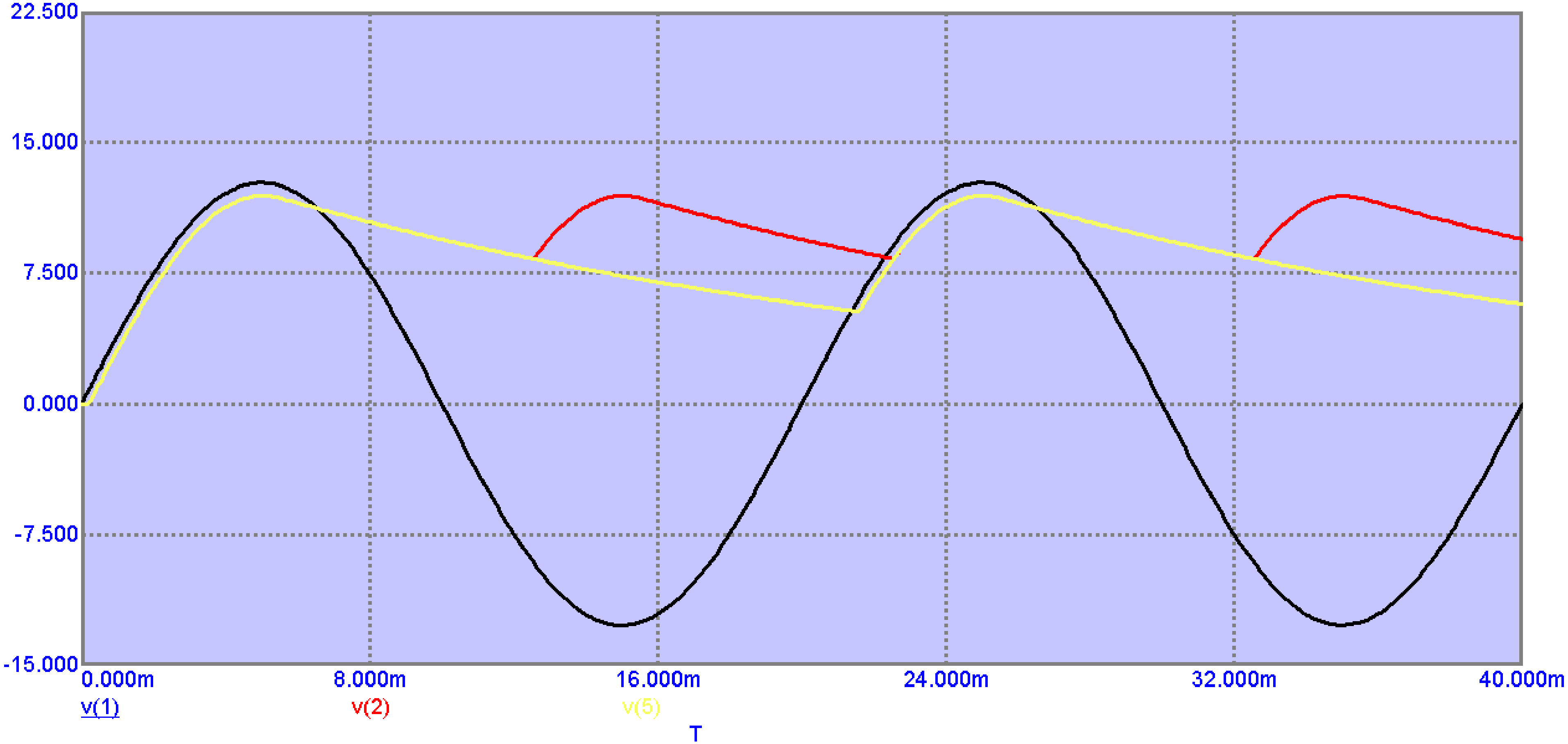
Comparison of full and half Wave Rectifier

$$V_r \cong \frac{V_M}{fR_LC}$$

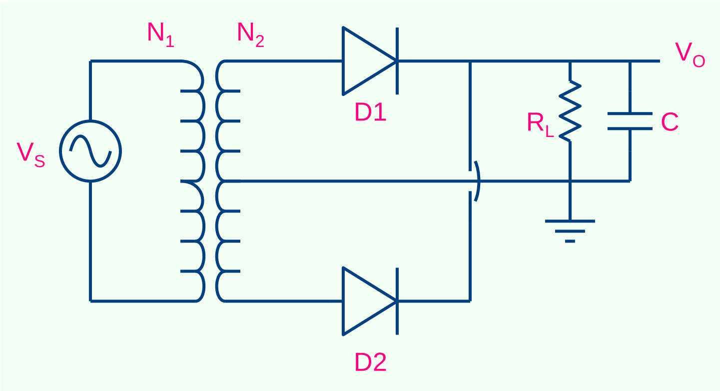


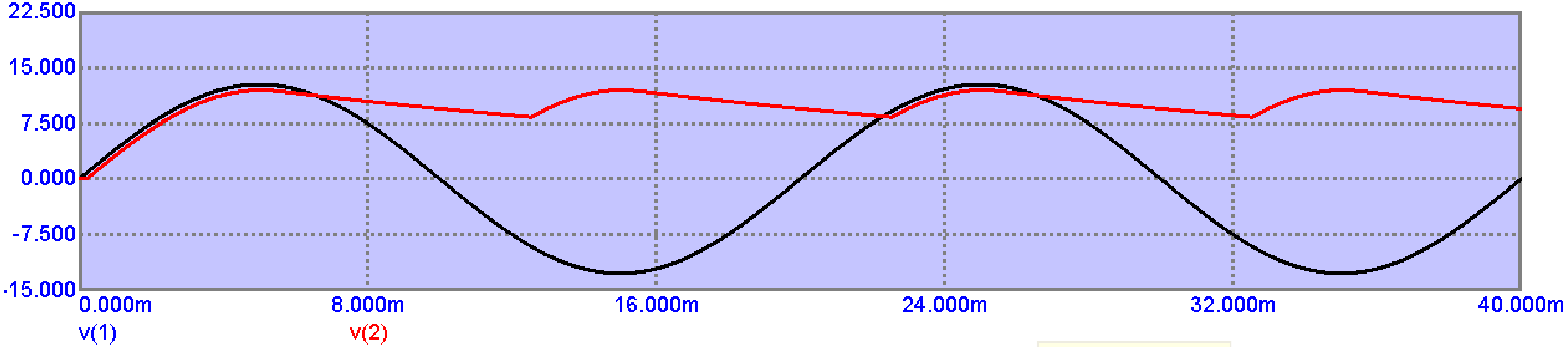


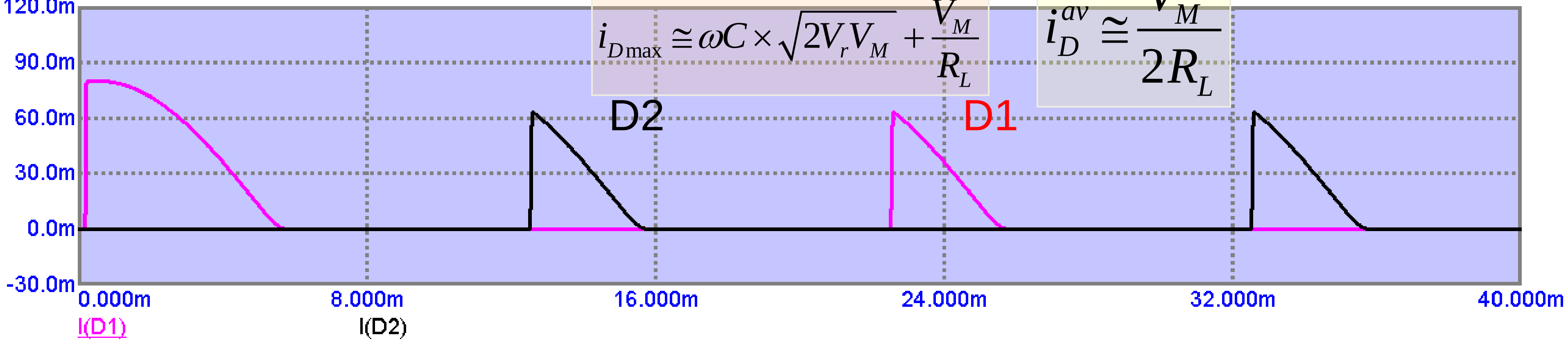
$$V_r \cong \frac{V_M}{2\,fR_LC}$$



Diode Currents in Full wave Rectifier



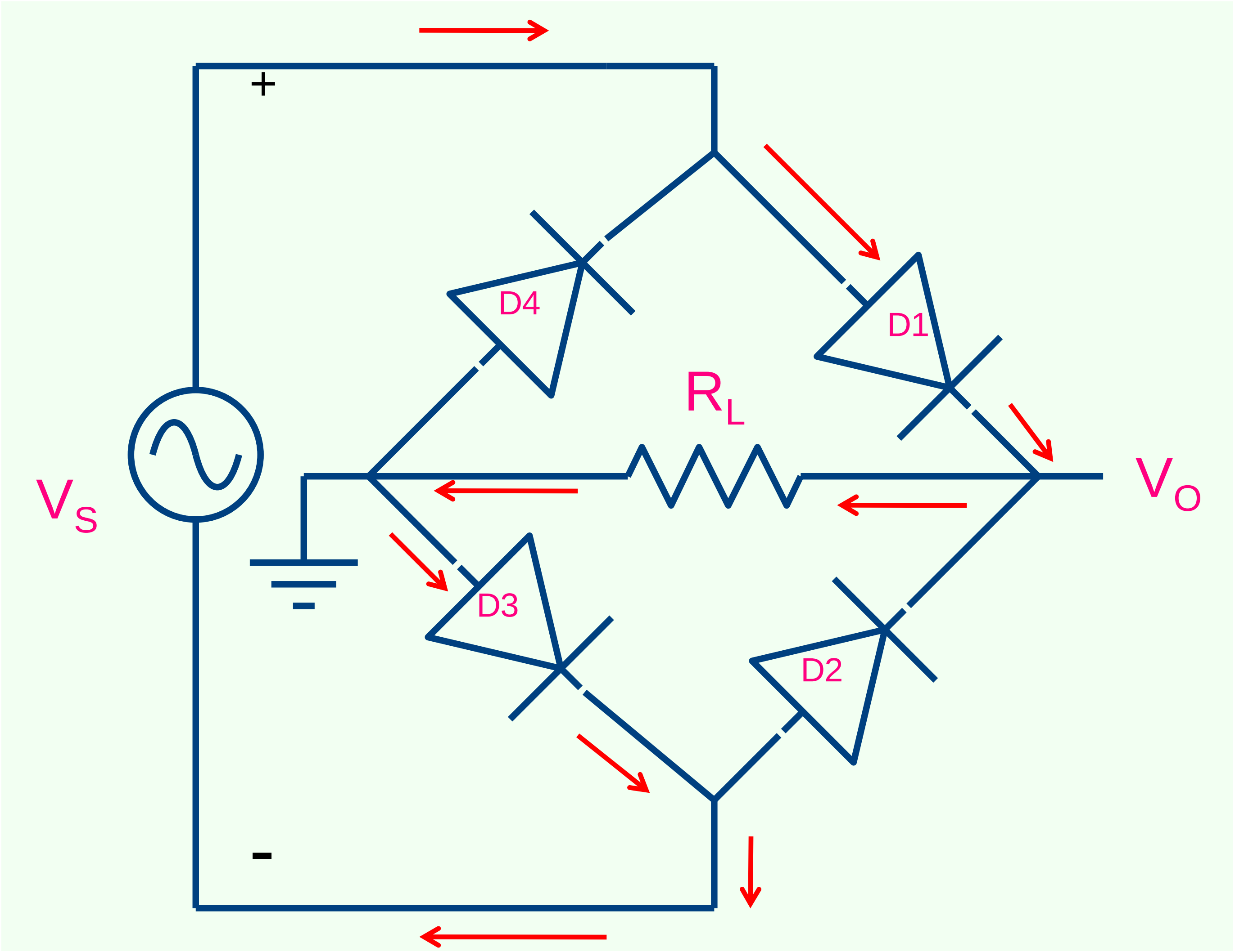


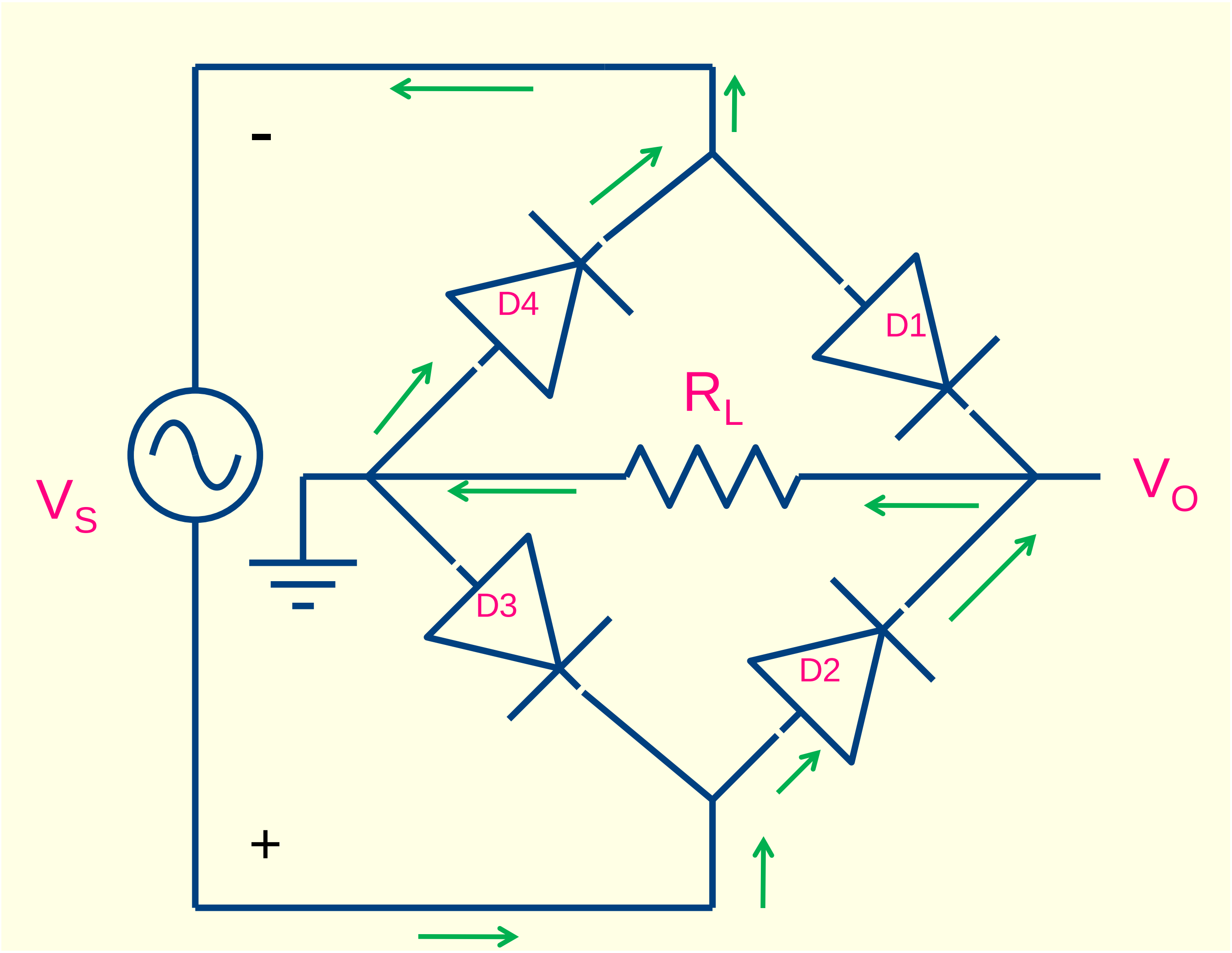


$$i_{D\max} \cong \omega C \times \sqrt{2V_r V_M} + \frac{V_M}{R_L}$$

$$i_D^{av} \cong \frac{V_M}{2R_L}$$

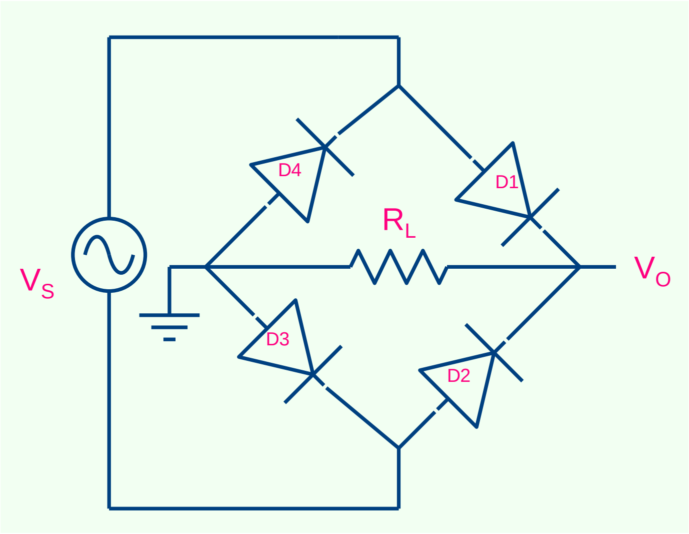
Bridge Rectifier

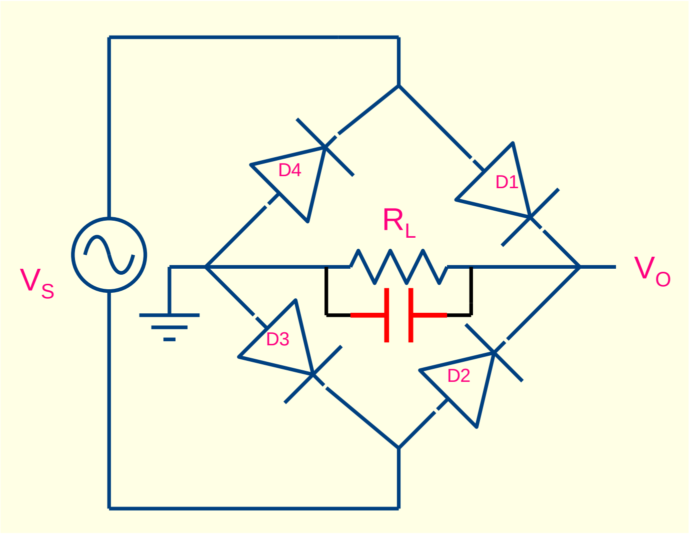


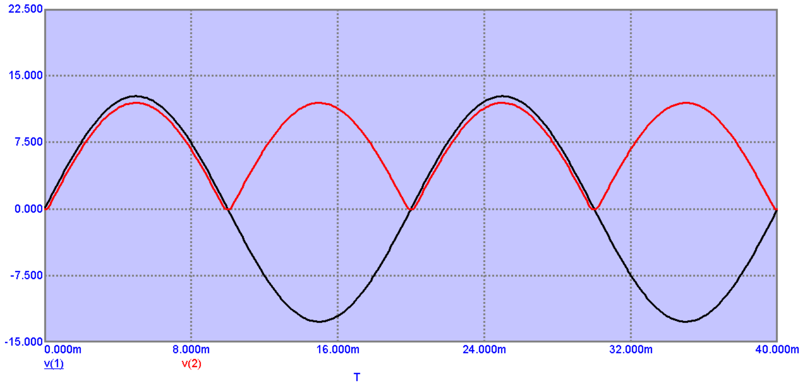


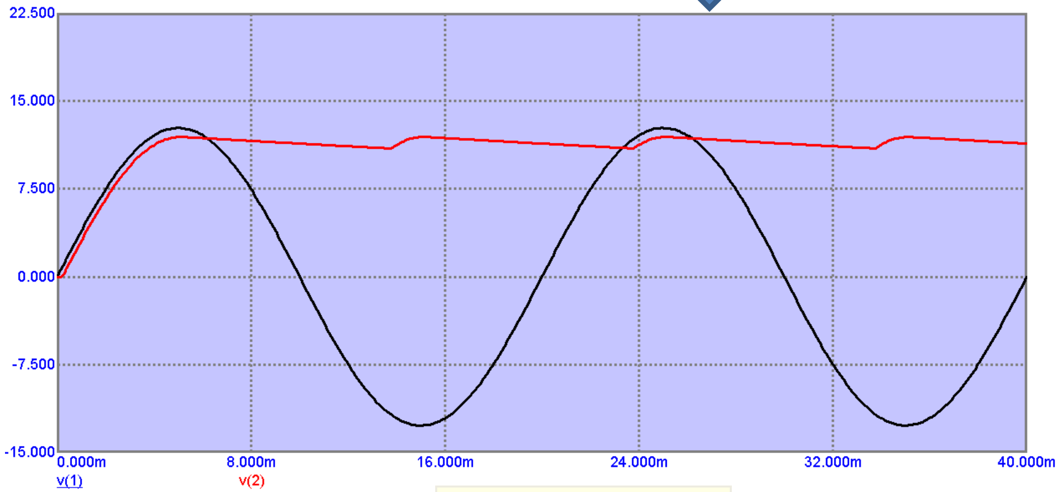
-
+
V S
D4
D1
D3
D2
R L
V O

Power supply using full wave Rectifier





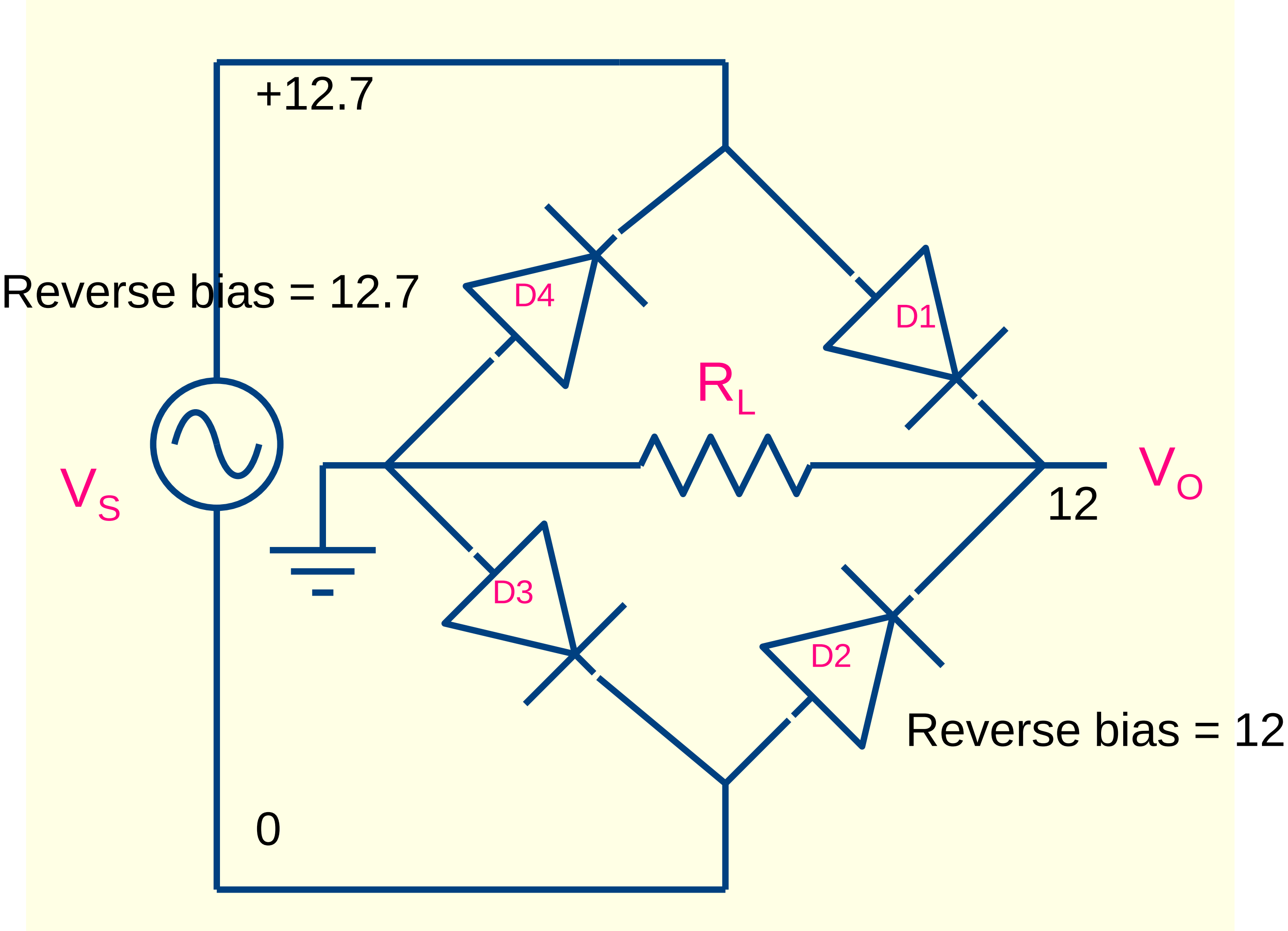




$$V_r \cong \frac{V_M}{2\,fR_L C}$$

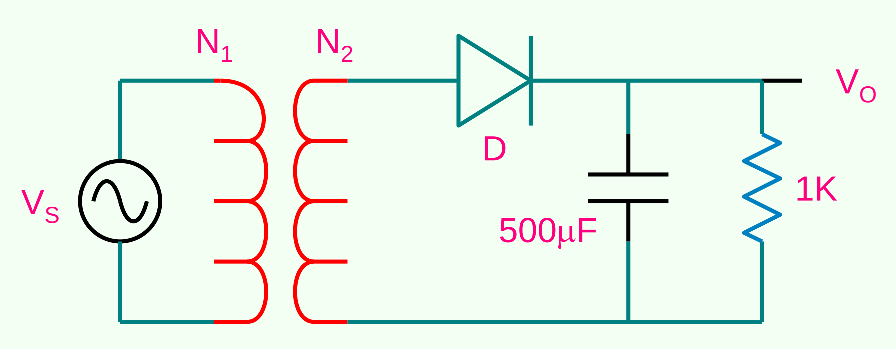
Ripple is smaller in full wave rectifier based power supply

Peak Inverse Voltage

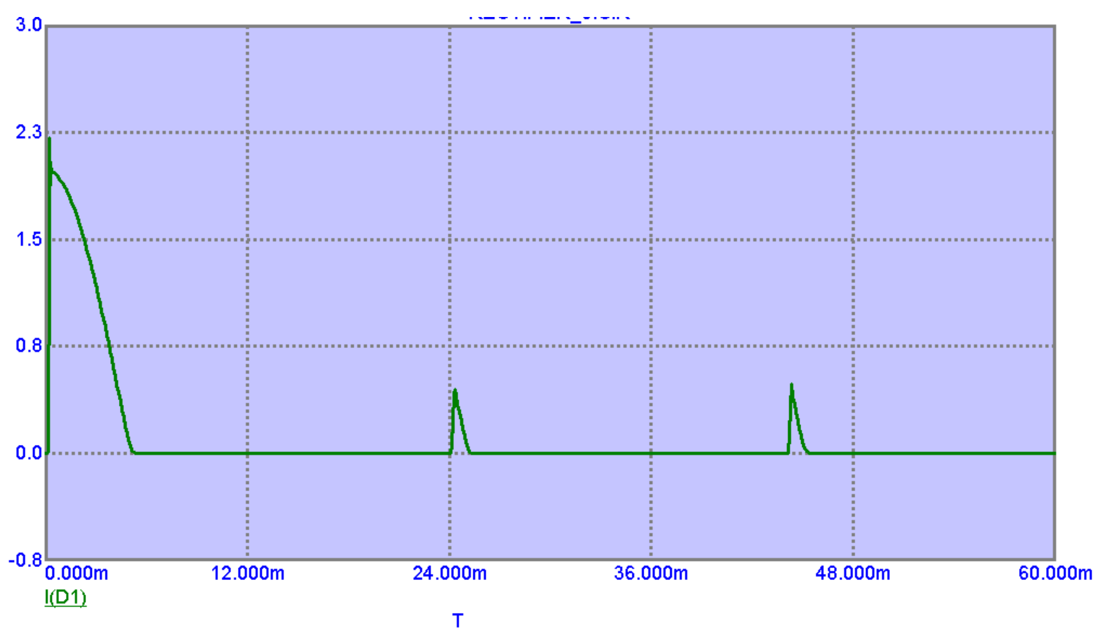


$$PIV \cong v_O + 0.7$$

Reducing Ripple to a very small value is not easy !

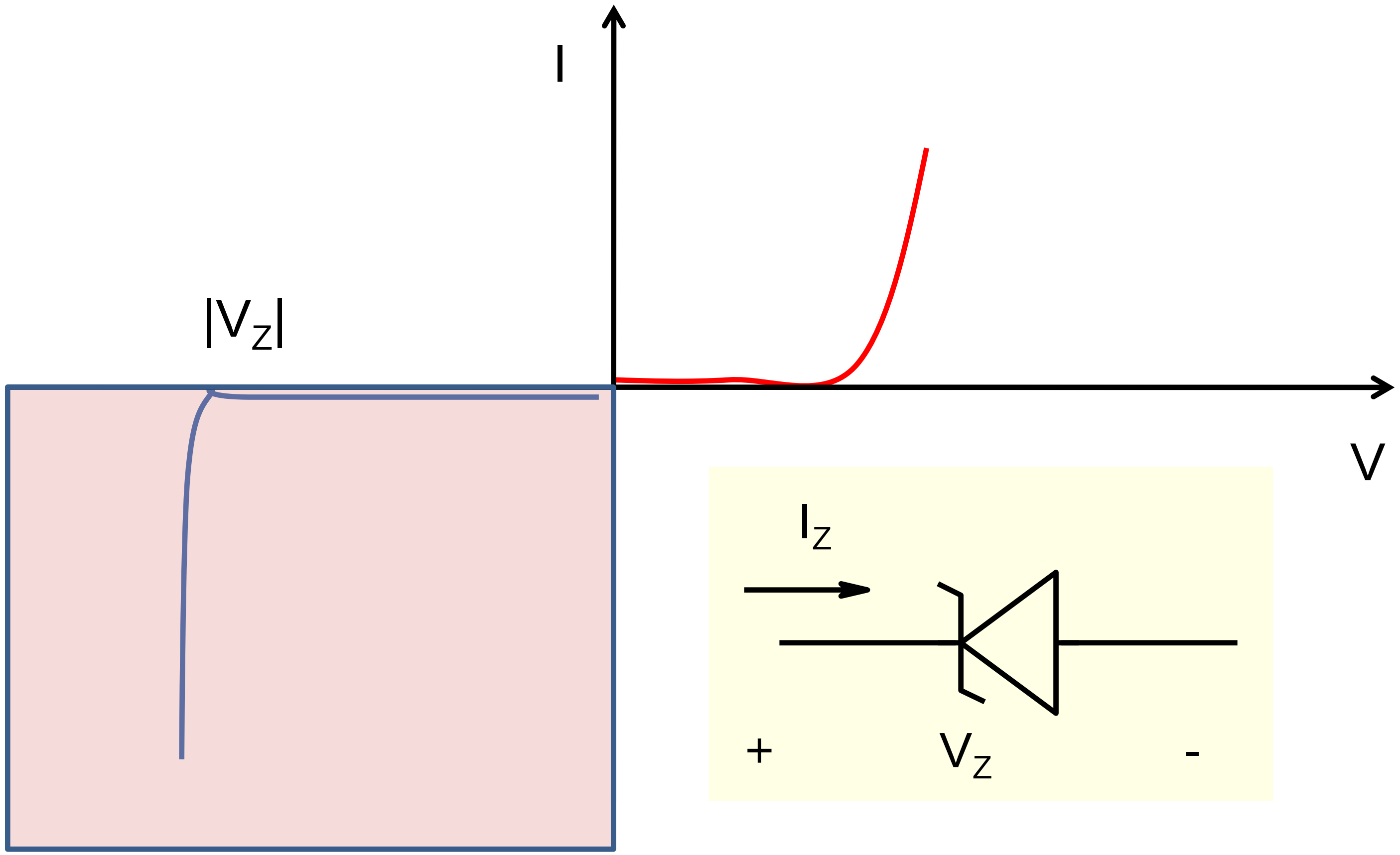


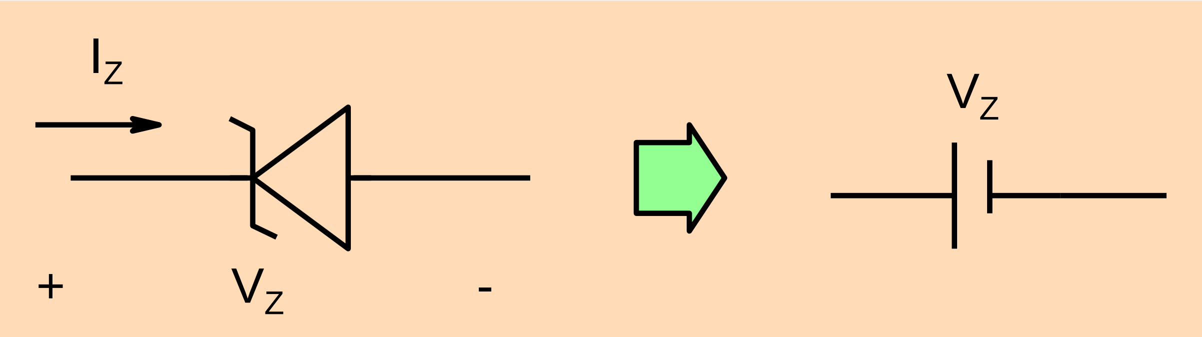
$$V_r = 0.438V$$



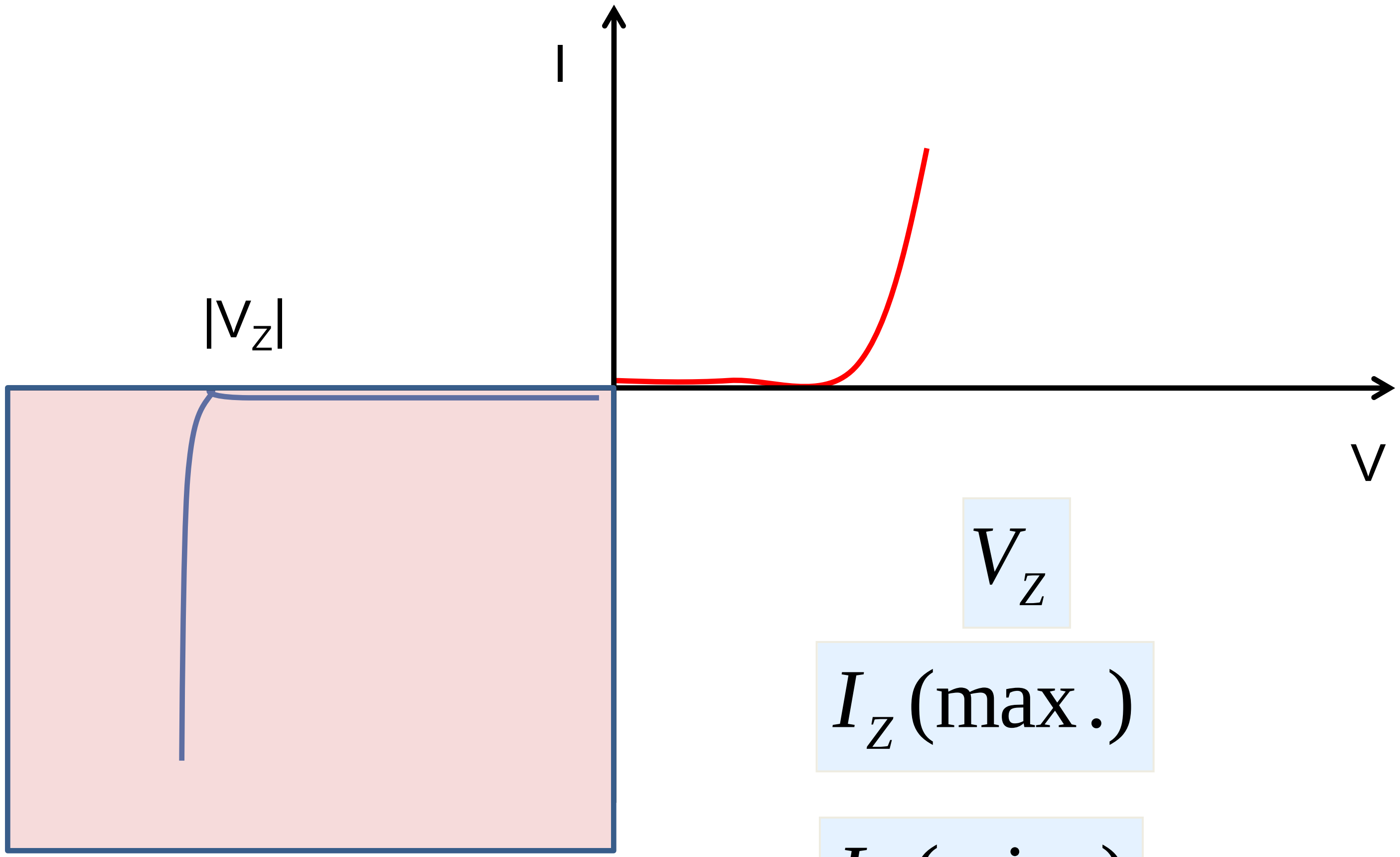
Zener Diode

A diode specially designed to operate in reverse bias in ‘breakdown’ region





Zener diode: Important Characteristics

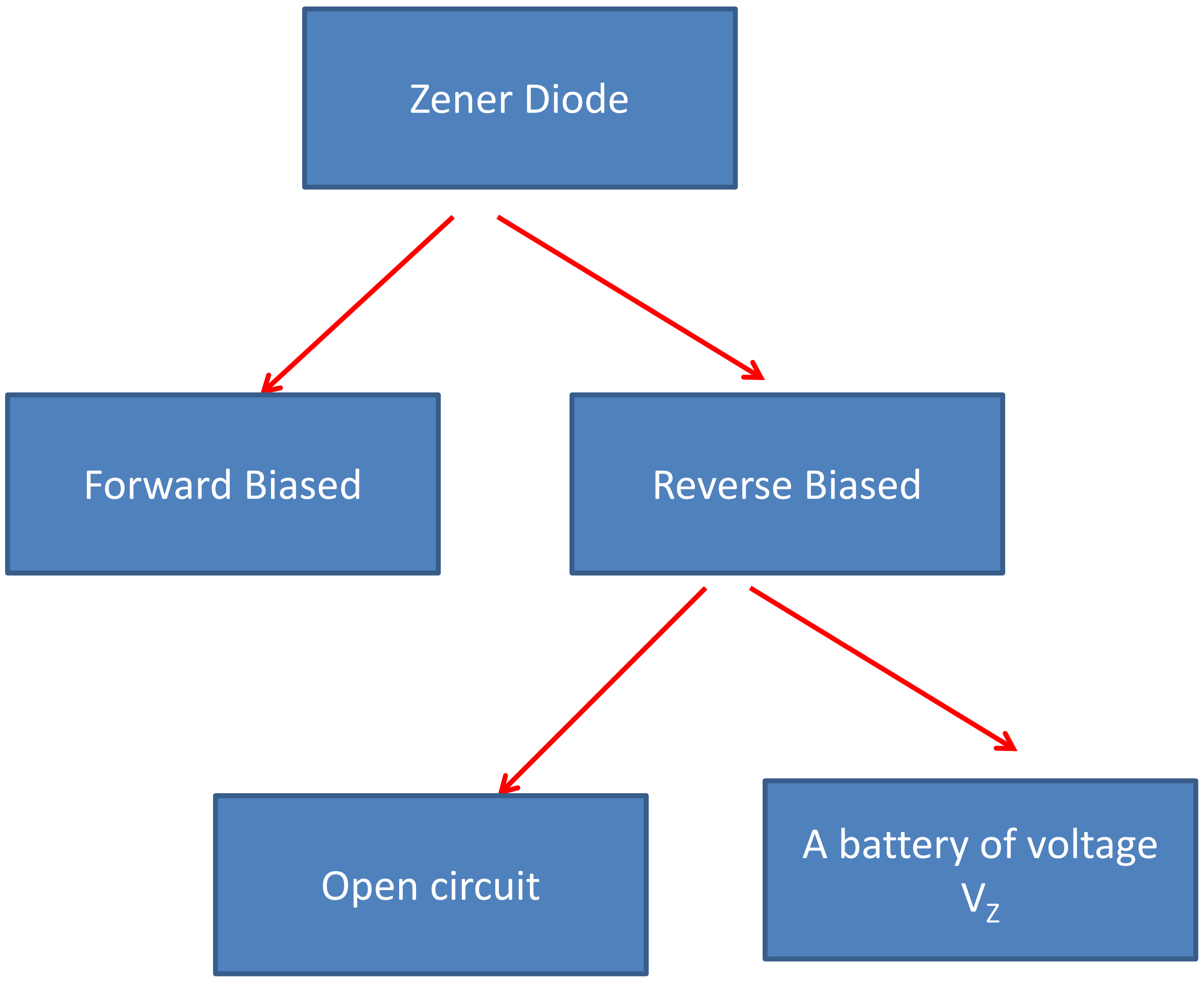


$$V_Z$$

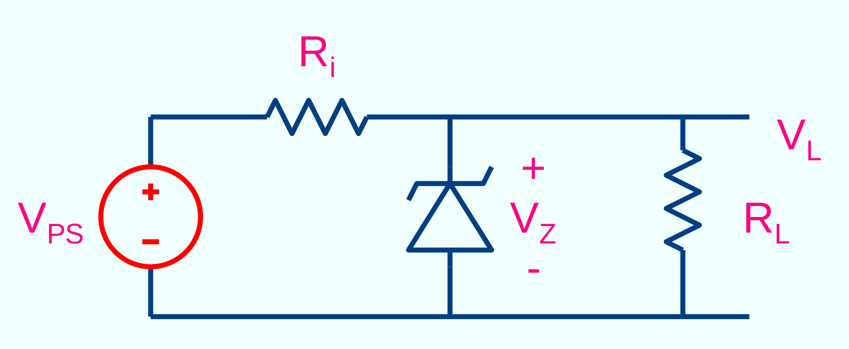
$$I_Z(\max.)$$

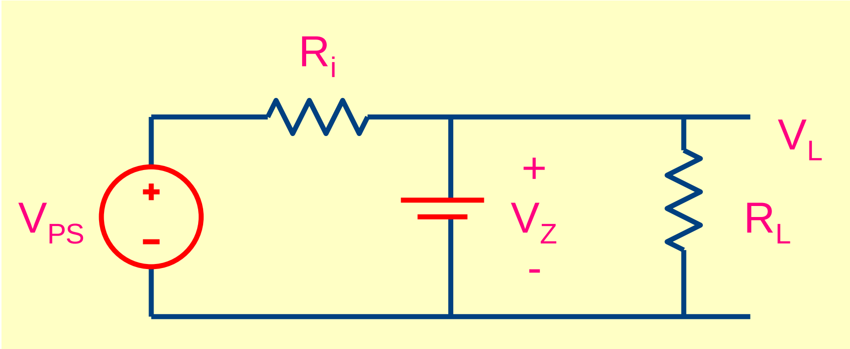
$$I_Z(\min.)$$

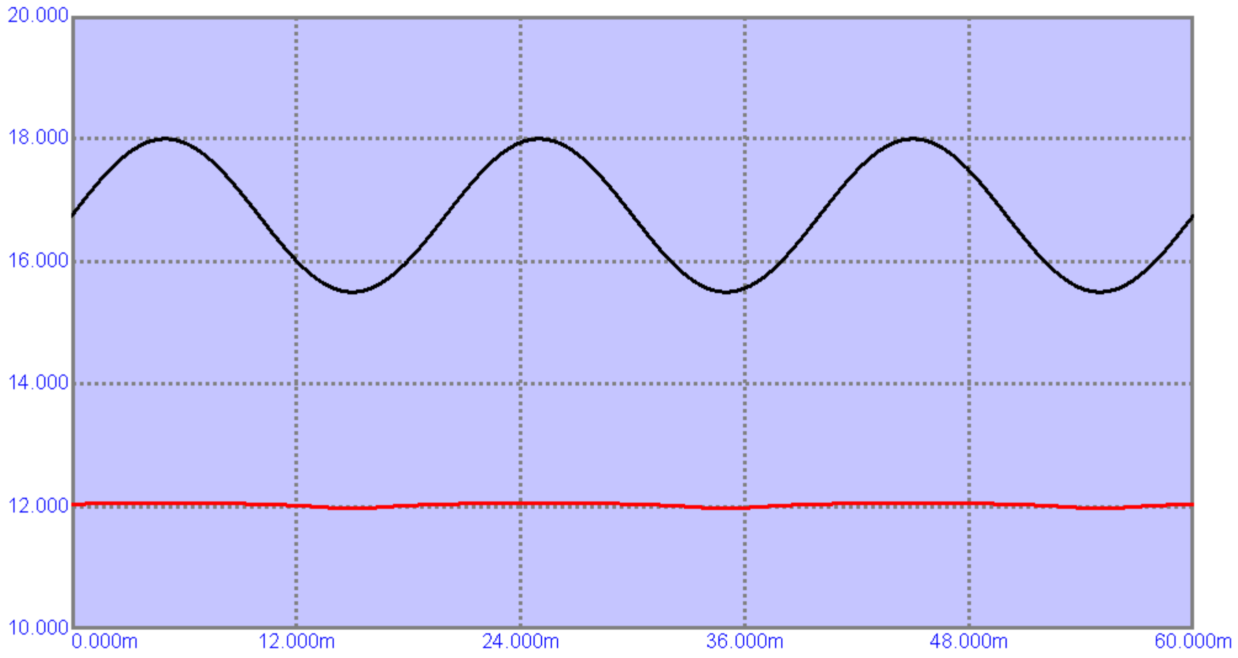
$$P_Z$$


Zener Diode
Forward Biased
Reverse Biased
Open circuit
A battery of voltage V_Z

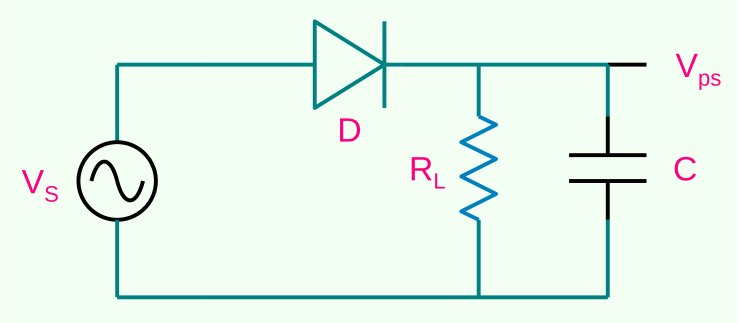
Voltage Reference Circuit

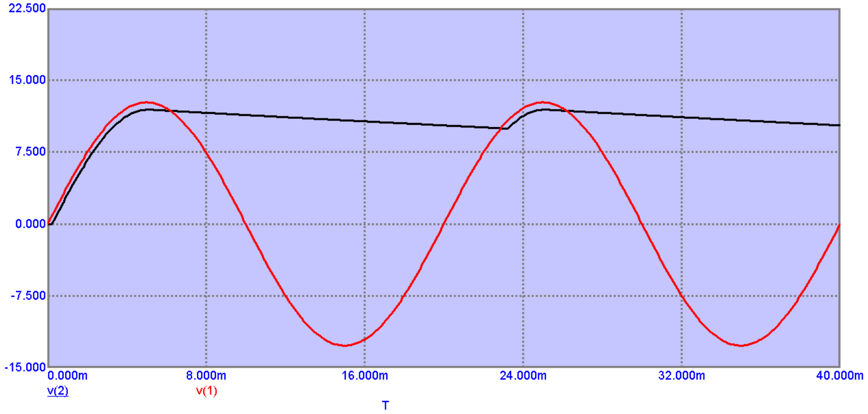


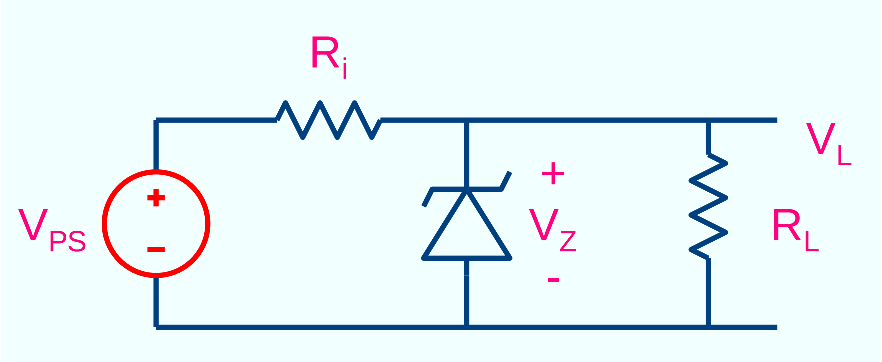


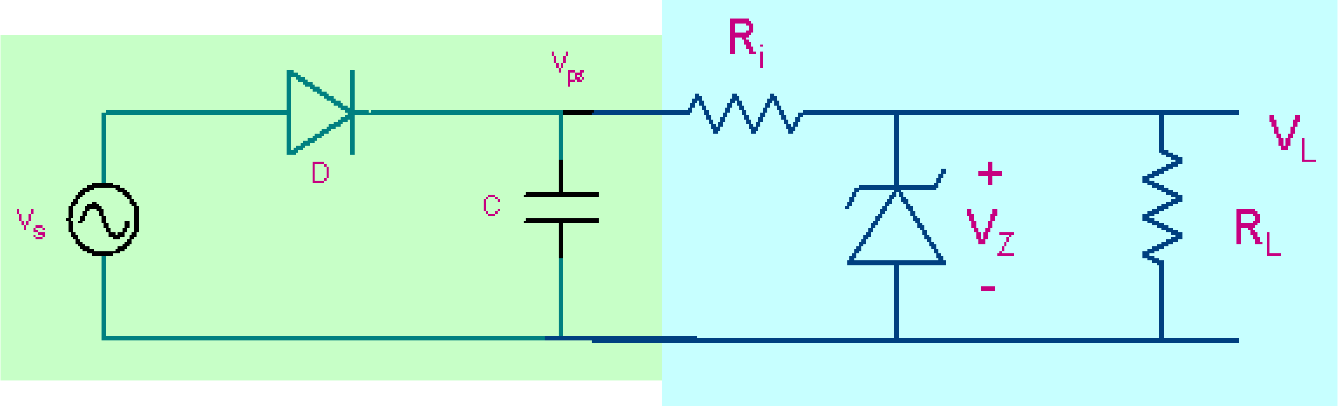


Power supply with regulator

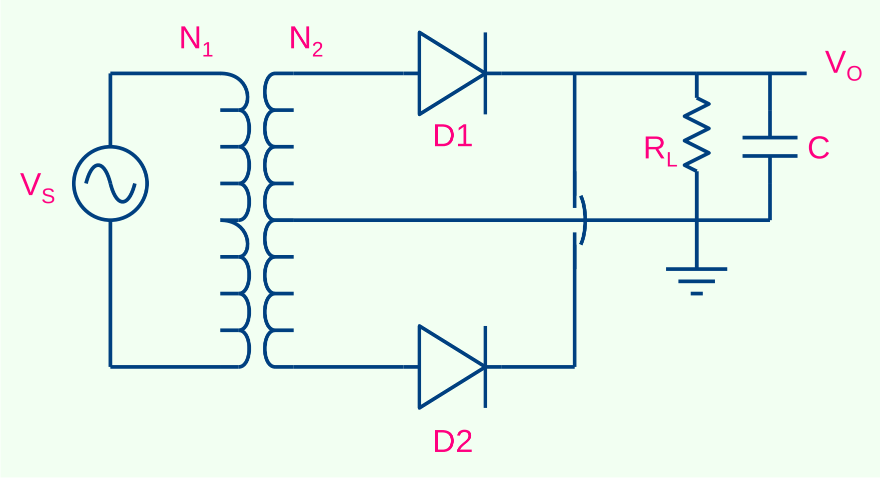


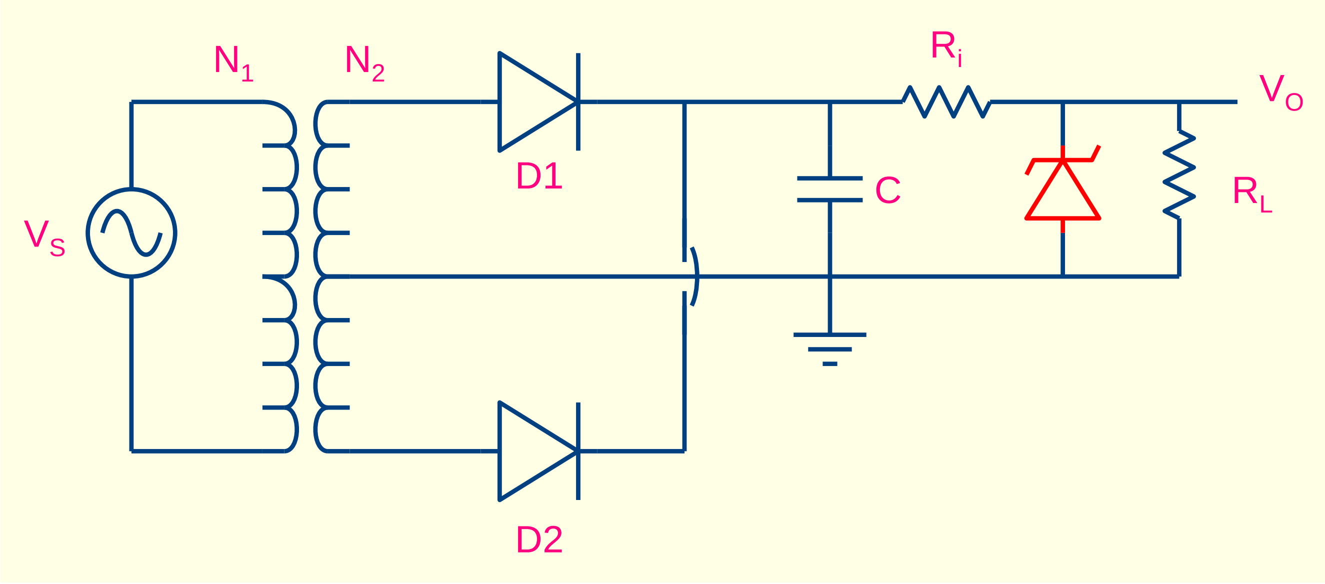


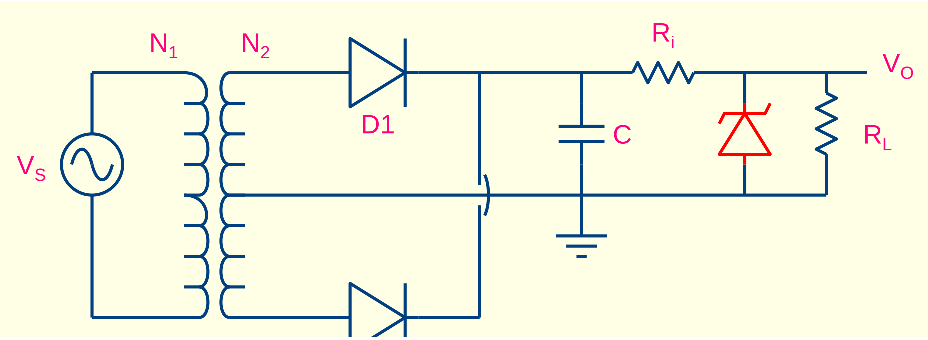




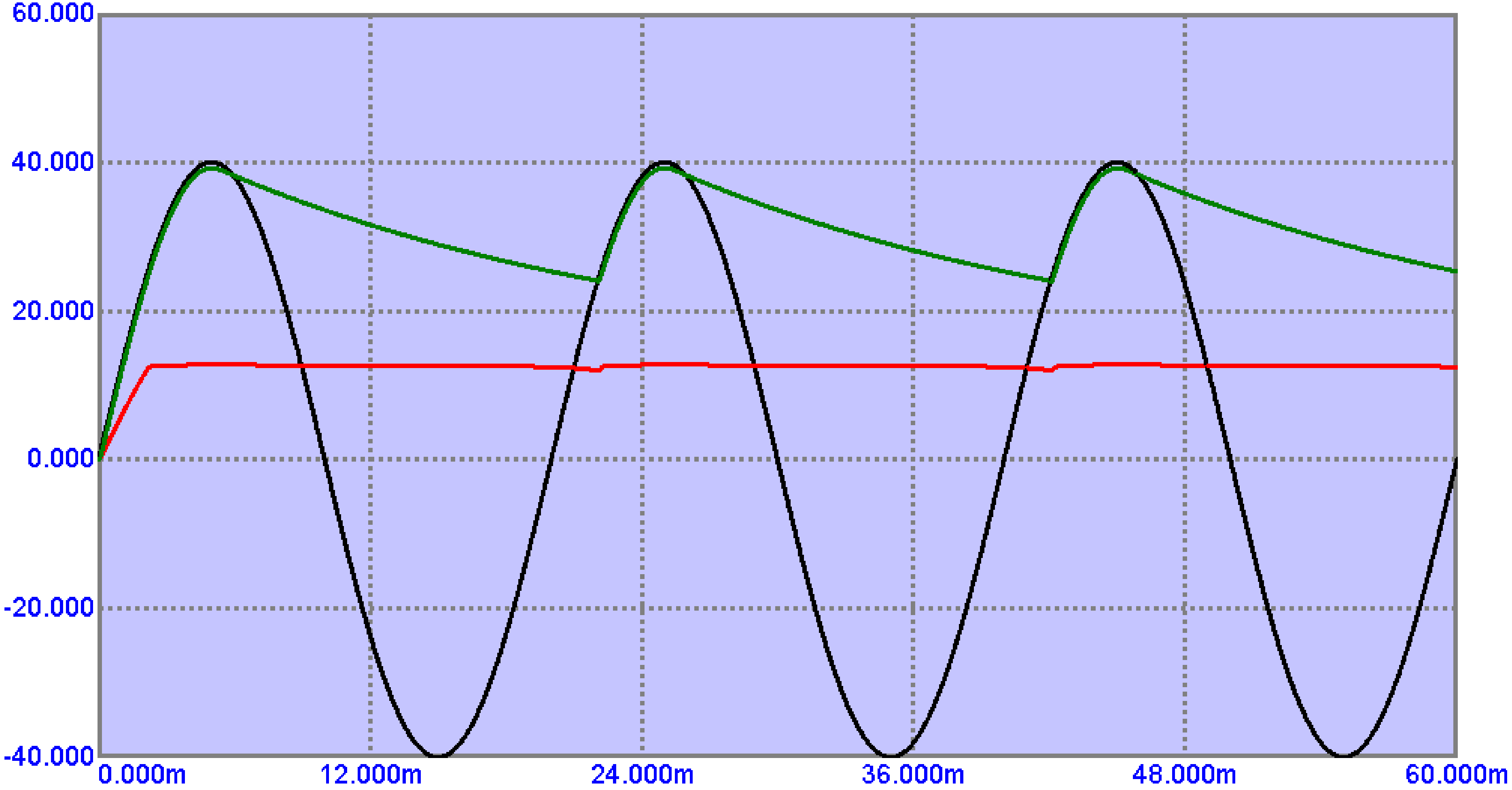
Zener diode as Voltage Regulator





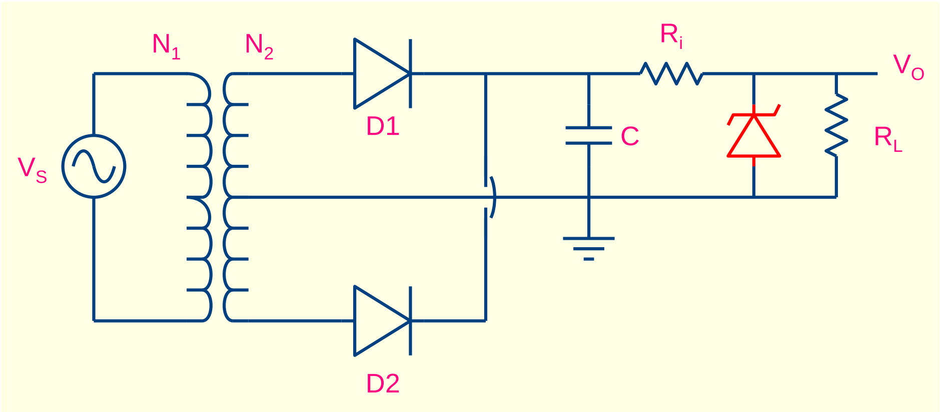


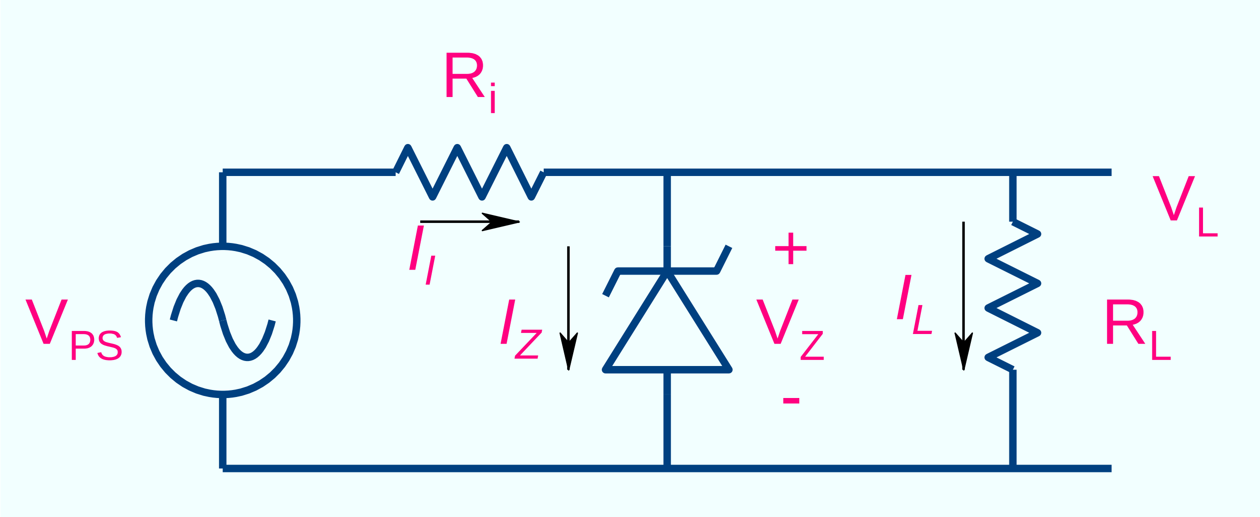
N1
N2
D1
Ri
VO
C
RL
VS



60.000
40.000
20.000
0.000
-20.000
-40.000
0.000m
12.000m
24.000m
36.000m
48.000m
60.000m

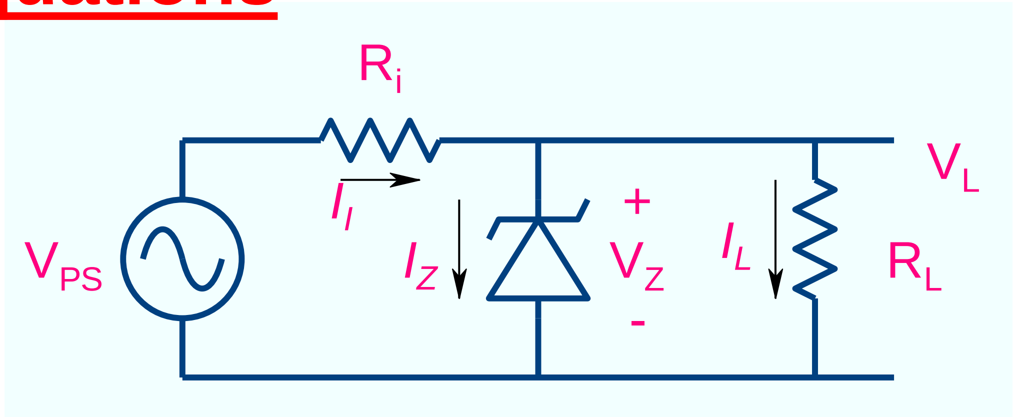
Voltage Reference Circuit





Design Problem: Determine R_i and zener diode specifications such that output voltage is +12V, load current can vary between 0 to 0.1A. The input voltage may vary between 18 to 15.5V.

Voltage Reference Equations



$$I_i = \frac{V_{PS} - V_Z}{R_i} = I_Z + I_L$$

$$I_Z = \frac{V_{PS} - V_Z}{R_i} - I_L$$

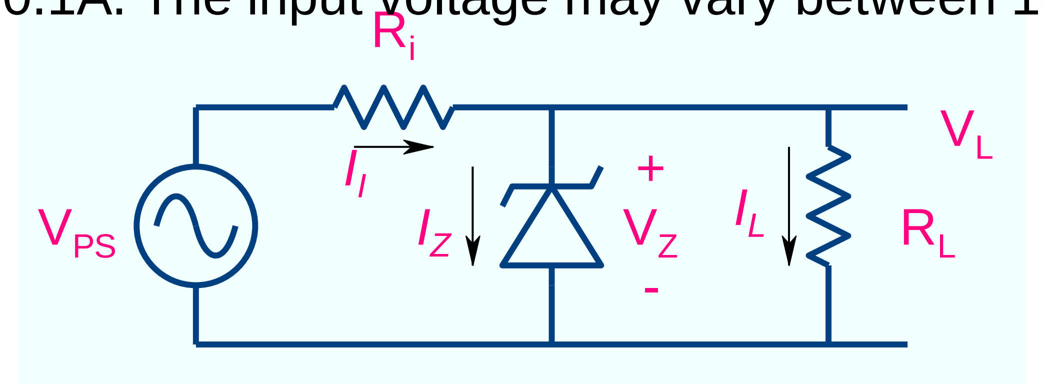
$$I_{Z\max} = \frac{V_{PS\max} - V_Z}{R_i} - I_{L\min}$$

$$I_{Z\min} = \frac{V_{PS\min} - V_Z}{R_i} - I_{L\max}$$

$$P_{Z\max} = V_Z I_{Z\max}$$

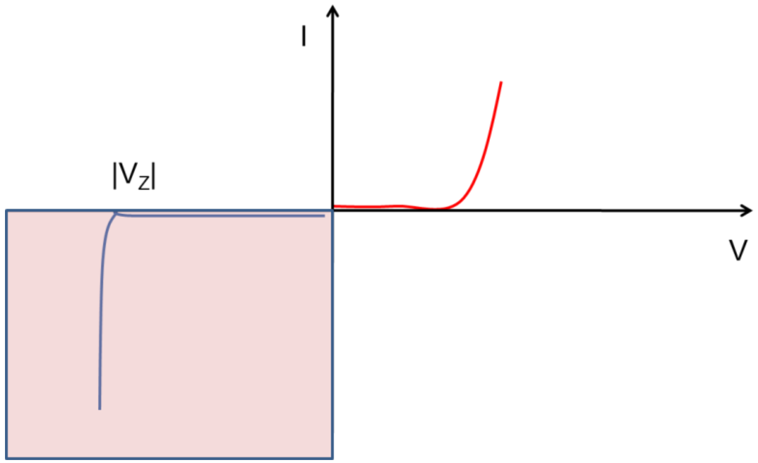
Check correctness of design by checking compliance with Zener diode ratings

Design Problem: Determine R_i and zener diode specifications such that output voltage is +12V, load current can vary between 0 to 0.1A. The input voltage may vary between 18 to 15.5V.



$$I_i = \frac{V_{PS} - V_Z}{R_i} = I_Z + I_L$$

$$I_Z = \frac{V_{PS} - V_Z}{R_i} - I_L$$



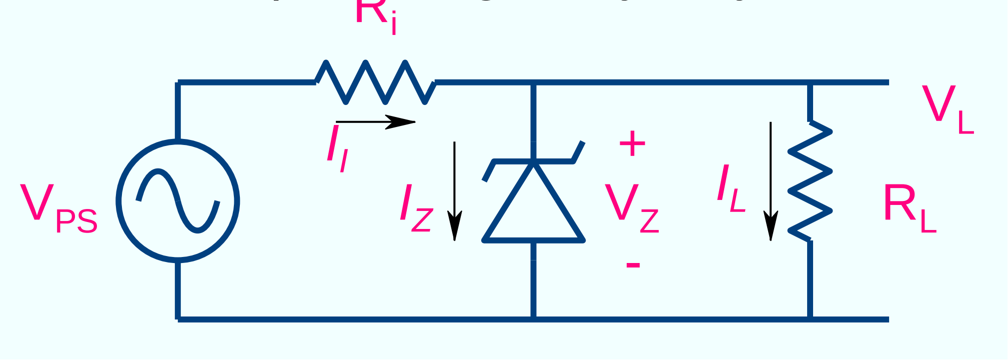
$$I_{Z\max} = \frac{V_{PS\max} - V_Z}{R_i} - I_{L\min}$$

$$I_{Z\min} = \frac{V_{PS\min} - V_Z}{R_i} - I_{L\max}$$

$$R_i = 40\Omega \Rightarrow I_{Zmax} = 0.15A; I_{Zmin} = -0.013A$$

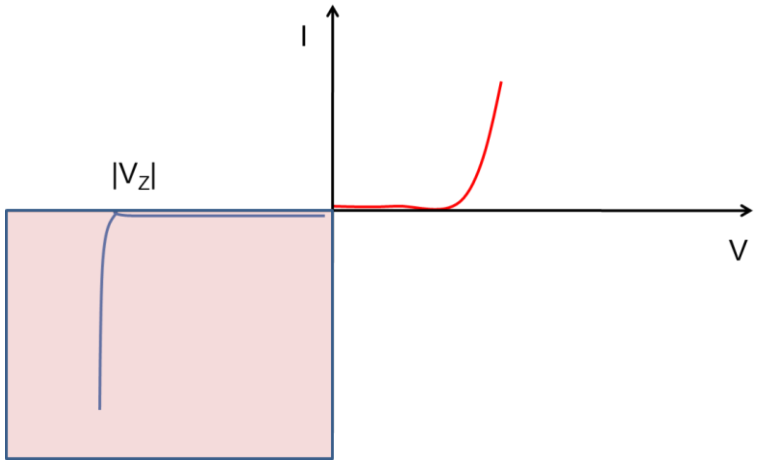
$$R_i = 10\Omega \Rightarrow I_{Zmax} = 0.6A; I_{Zmin} = 0.25A$$

Design Problem: Determine R_i and zener diode specifications such that output voltage is +12V, load current can vary between 0 to 0.1A. The input voltage may vary between 18 to 15.5V.



$$I_i = \frac{V_{PS} - V_Z}{R_i} = I_Z + I_L$$

$$I_Z = \frac{V_{PS} - V_Z}{R_i} - I_L$$



$$I_{Z\max} = \frac{V_{PS\max} - V_Z}{R_i} - I_{L\min}$$

$$I_{Z\min} = \frac{V_{PS\min} - V_Z}{R_i} - I_{L\max}$$

$$\frac{I_{Z\max}}{I_{Z\min}} \cong 10$$

$$R_i = \frac{V_{PS\min} - 0.1V_{PS\max} - 0.9V_Z}{I_{L\max}}$$

$$P_{Z\max} = V_Z I_{Z\max}$$

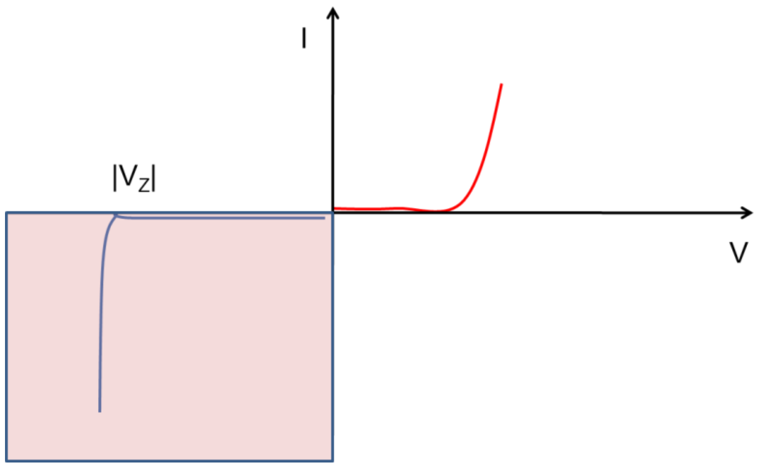
Design Problem: Determine R_i and zener diode specifications such that output voltage is +12V, load current can vary between 0 to 0.1A. The input voltage may vary between 18 to 15.5V.

$$R_i = \frac{V_{PS\,min} - 0.1V_{PS\,max} - 0.9V_Z}{I_{L\,max}} = 29\Omega$$

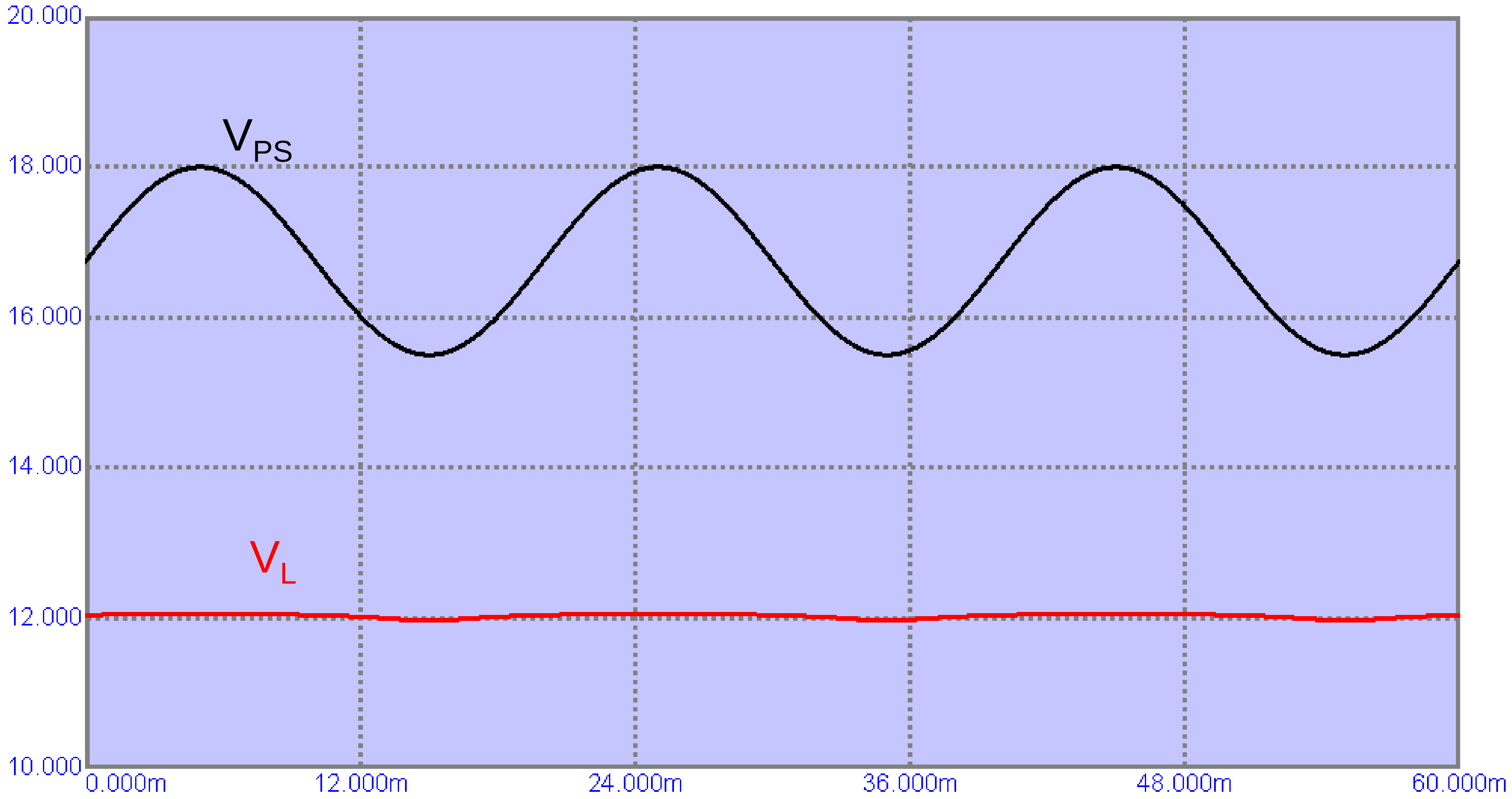
$$I_{Z\,max} = \frac{V_{PS\,max} - V_Z}{R_i} - I_{L\,min} = 0.207A$$

$$I_{Z\,min} = \frac{V_{PS\,min} - V_Z}{R_i} - I_{L\,max} = 0.0207$$

$$P_{Z\,max} = V_Z I_{Z\,max} = 2.48W$$



Check the design through simulations



20.000
18.000
16.000
14.000
12.000
10.000
0.000m
12.000m
24.000m
36.000m
48.000m
60.000m
V_{PS}
V_L

Design Problem-2: Determine R_i and zener diode specifications such that output voltage is +12V, load current can vary between 0 to 0.1A. The input voltage may vary between 15 to 12.915V.

$$R_i = \frac{V_{PS\min} - 0.1V_{PS\max} - 0.9V_Z}{I_{L\max}} = 6.1\Omega$$

$$I_{Z\max} = \frac{V_{PS\max} - V_Z}{R_i} - I_{L\min} = 0.488A$$

$$I_{Z\min} = \frac{V_{PS\min} - V_Z}{R_i} - I_{L\max} = 0.049$$

$$P_{Z\max} = V_Z I_{Z\max} = 5.85W$$