# EE 330
# Lecture 13

## Devices in Semiconductor Processes

- Resistors
- Diodes
- Capacitors
- MOSFETs
- BJTs

# Fall 2025 Exam Schedule

Exam 1     Friday Sept 26

Review from Last Lecture

# Basic Devices

- Standard CMOS Process
  - MOS Transistors
    - n-channel
    - p-channel
  - Capacitors
  - Resistors
  - Diodes
  - BJT ( decent in some processes)
    - npn
    - pnp
  - JFET (in some processes)
    - n-channel
    - p-channel
- Standard Bipolar Process
  - BJT
    - npn
    - pnp
  - JFET
    - n-channel
    - p-channel
  - Diodes
  - Resistors
  - Capacitors
- Niche Devices
  - Photodetectors (photodiodes, phototransistors, photoresistors)
  - MESFET
  - HBT
  - Schottky Diode (not Shockley)
  - MEM Devices
  - TRIAC/SCR
  - ….

**Primary Consideration in This Course** (Standard CMOS Process devices)

**Some Consideration in This Course** (Standard Bipolar Process devices)

(devices are available in some CMOS processes)

**Some Consideration in This Course** (TRIAC/SCR)

## Review from Last Lecture

http://www.cleanroom.byu.edu/ResistivityCal.phtml

**Resistivity & Mobility Calculator/Graph for Various Doping Concentrations in Silicon**

Dopant: (•) Arsenic ( ) Boron ( ) Phosphorus

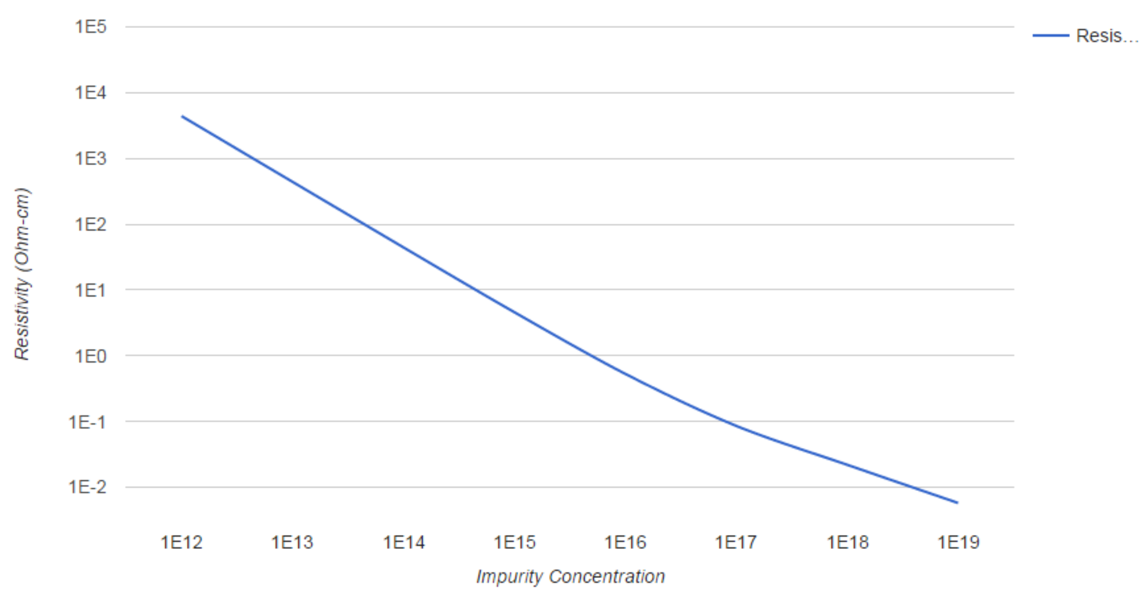
Impurity Concentration: 1e15 ($cm^{-3}$)

[Calculate] [Export to CSV]

Mobility: 1358.6941377290254 [$cm^2/V\text{-}s$]

Resistivity: 4.593746148183427 [Ω-cm]

Calculations are for a silicon substrate.



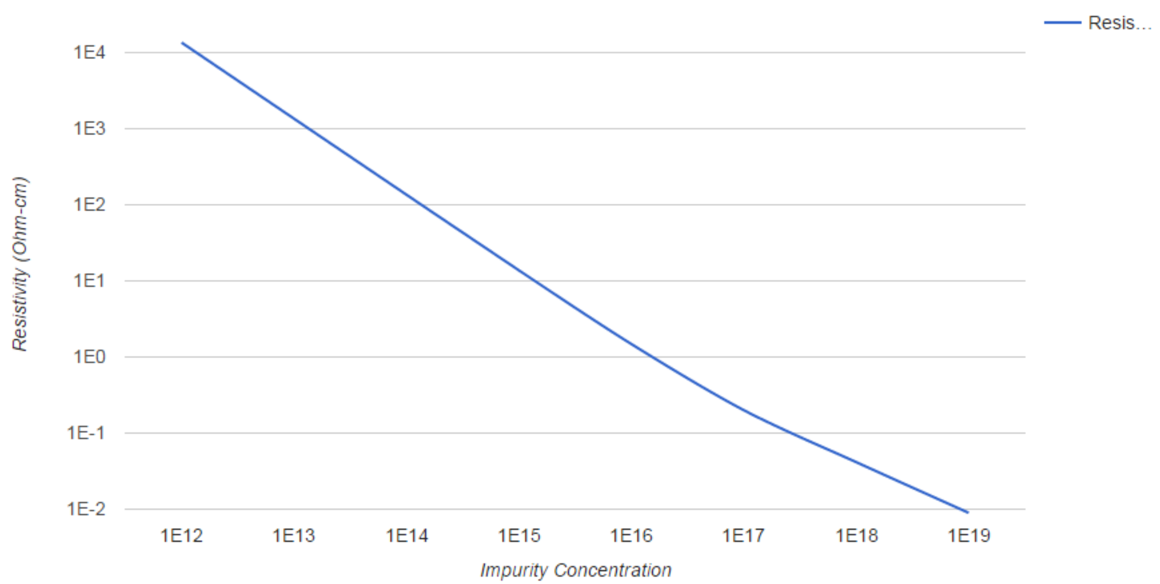
## Review from Last Lecture

http://www.cleanroom.byu.edu/ResistivityCal.phtml

**Resistivity & Mobility Calculator/Graph for Various Doping Concentrations in Silicon**

| | |
|---|---|
| Dopant: | ○ Arsenic<br>◉ Boron<br>○ Phosphorus |
| Impurity Concentration: | 1e15 ($cm^{-3}$) |
| | Calculate / Export to CSV |
| Mobility: | 461.9540345952693 [$cm^2$/V-s] |
| Resistivity: | 13.511075765839905 [Ω-cm] |

Calculations are for a silicon substrate.



# Review from Last Lecture

http://www.cleanroom.byu.edu/ResistivityCal.phtml

**Resistivity & Mobility Calculator/Graph for Various Doping Concentrations in Silicon**

Dopant:
- Arsenic
- Boron
- Phosphorus (selected)

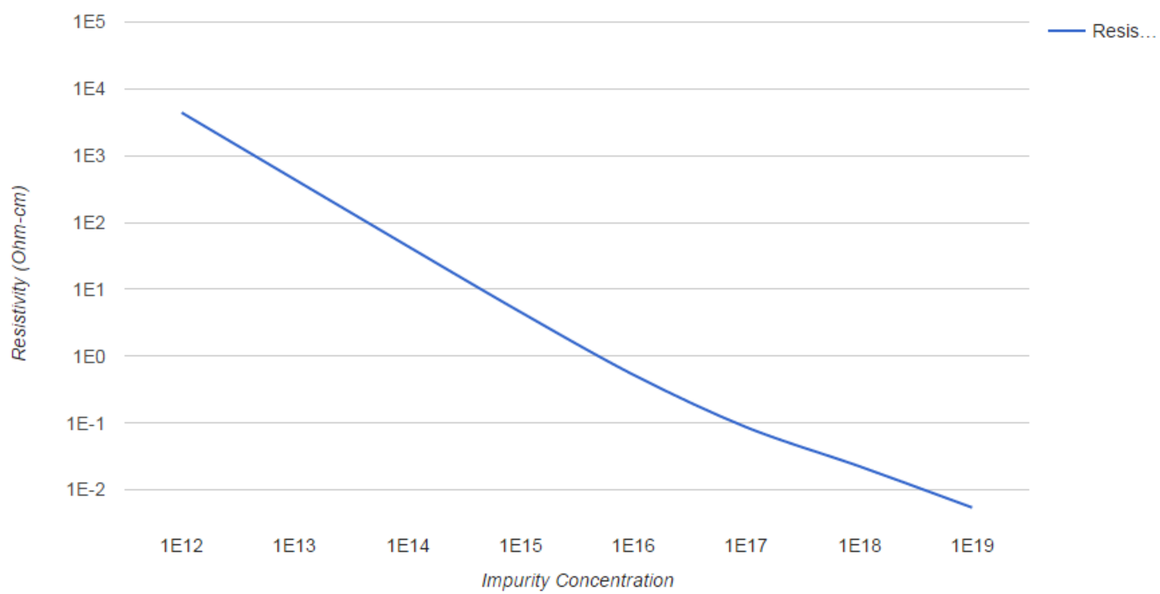
Impurity Concentration: 1e15 ($cm^{-3}$)

Calculate | Export to CSV

Mobility: 1362.0563795030084 [$cm^2$/V-s]

Resistivity: 4.582406466925789 [Ω-cm]

Calculations are for a silicon substrate.



# Temperature Coefficients

Used for indicating temperature sensitivity of resistors & capacitors

**For a resistor:**

$$\mathbf{TCR} = \left( \frac{1}{R} \frac{dR}{dT} \right) \Bigg|_{\text{op. temp}} \bullet 10^6 \ \text{ppm}/^\circ\text{C}$$

This differential eqn can easily be solved if TCR is a constant

$$R(T_2) = R(T_1) e^{\frac{T_2 - T_1}{10^6} TCR}$$

If x is small, $e^x \cong 1 + x$

It follows that If TCR*($T_2$-$T_1$) is small,

$$R(T_2) \approx R(T_1) \left[ 1 + (T_2 - T_1) \frac{TCR}{10^6} \right]$$

Identical Expressions for Capacitors

Review from Last Lecture

# Voltage Coefficients

Used for indicating voltage sensitivity of resistors & capacitors

**For a resistor:**

$$\mathbf{VCR} = \left.\left(\frac{1}{R}\frac{dR}{dV}\right)\right|_{\text{ref voltage}} \bullet 10^6 \text{ ppm/V}$$

This diff eqn can easily be solved if VCR is a constant

$$R(V_2) = R(V_1)\, e^{\frac{V_2 - V_1}{10^6} VCR}$$

It follows that If VCR*($V_2$-$V_1$) is small,

$$R(V_2) \approx R(V_1)\left[1 + (V_2 - V_1)\frac{VCR}{10^6}\right]$$

Identical Expressions for Capacitors

# Review from Last Lecture

| Type of layer | Sheet Resistance Ω/□ | Accuracy (absolute) % | Temperature Coefficient ppm/°C | Voltage Coefficient ppm/V |
|---|---|---|---|---|
| n + diff | 30 - 50 | 20 - 40 | 200 - 1K | 50 - 300 |
| p + diff | 50 -150 | 20 - 40 | 200 - 1K | 50 - 300 |
| n - well | 2K - 4K | 15 - 30 | 5K | 10K |
| p - well | 3K - 6K | 15 - 30 | 5K | 10K |
| pinched n - well | 6K - 10K | 25 - 40 | 10K | 20K |
| pinched p - well | 9K - 13K | 25 - 40 | 10K | 20K |
| first poly | 20 - 40 | 25 - 40 | 500 - 1500 | 20 - 200 |
| second poly | 15 - 40 | 25 - 40 | 500 - 1500 | 20 - 200 |

(relative accuracy much better and can be controlled by designer)

From:F. Maloberti : Design of CMOS Analog Integrated Circuits - “Resistors, Capacitors, Switches”

Example: Determine the percent change in resistance of a 5K Polysilicon resistor as the temperature increases from 30°C to 60°C if the TCR is constant and equal to 1500 ppm/°C

$$R(T_2) \cong R(T_1)\left[1+(T_2-T_1)\frac{TCR}{10^6}\right]$$

$$R(T_2) \cong R(T_1)\left[1+\left(30^o C\right)\frac{1500}{10^6}\right]$$

$$R(T_2) \cong R(T_1)[1+.045]$$

$$R(T_2) \cong R(T_1)[1.045]$$

Thus the resistor increases by 4.5%

Did not need $R(T_1)$ to answer this question !

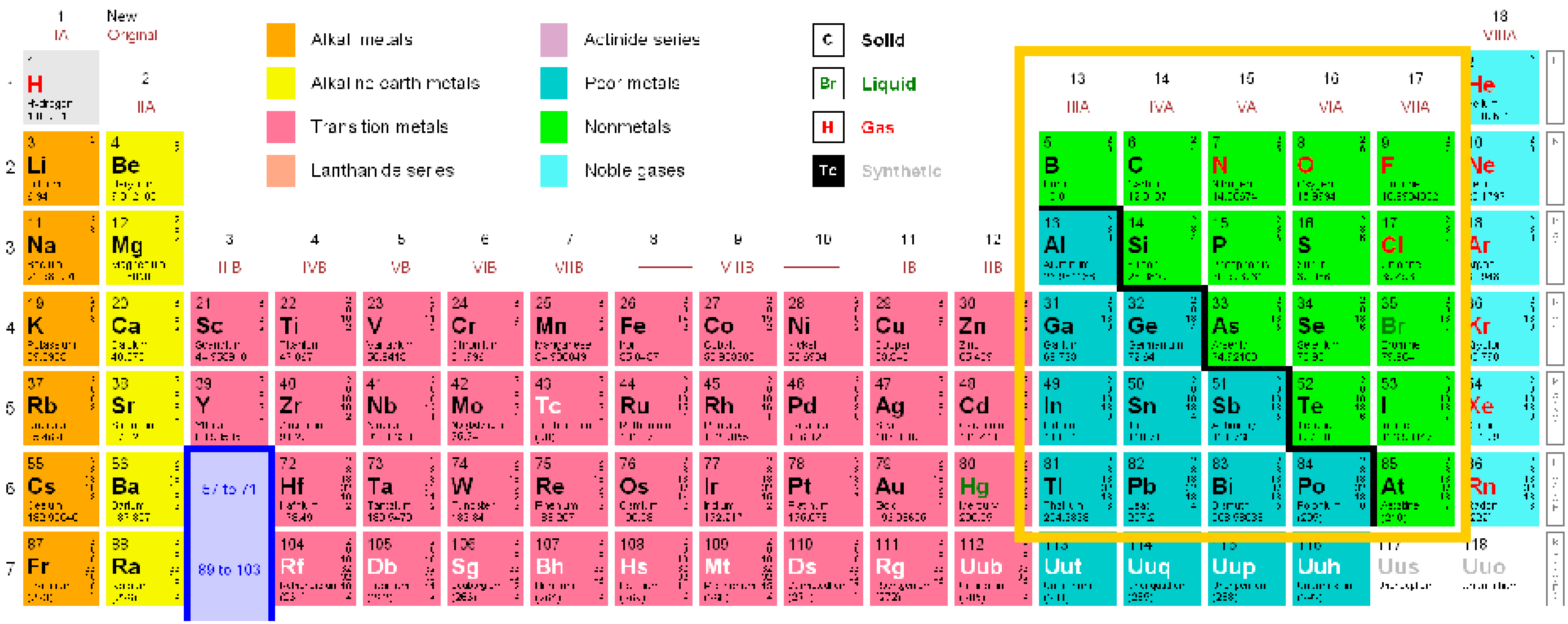
What is $R(T_1)$ as stated in this example ? 5K?

It is around 5K but if we want to be specific, would need to specify T

# Basic Devices and Device Models

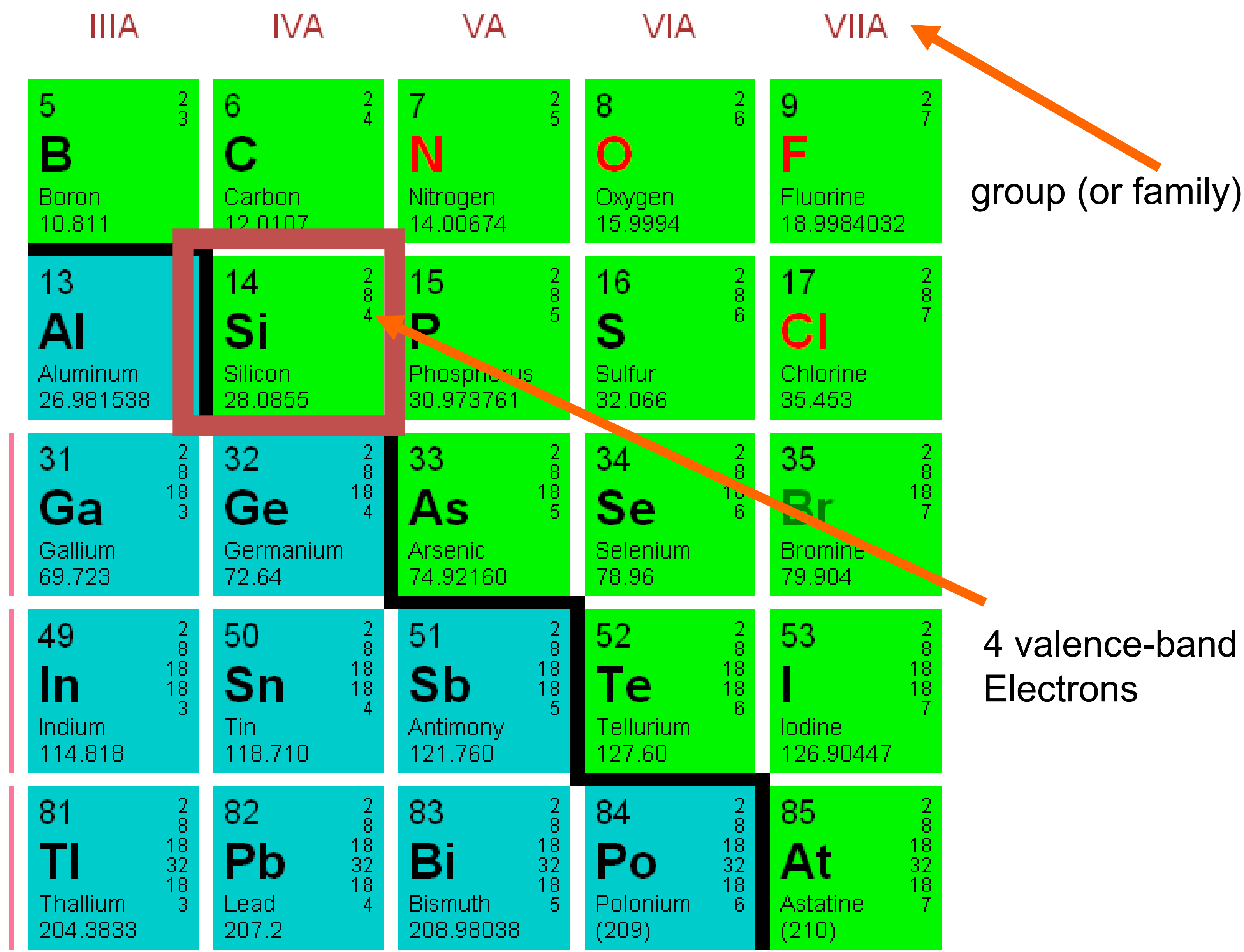
- Resistor
- ➡ Diode
- Capacitor
- MOSFET
- BJT

# Periodic Table of the Elements

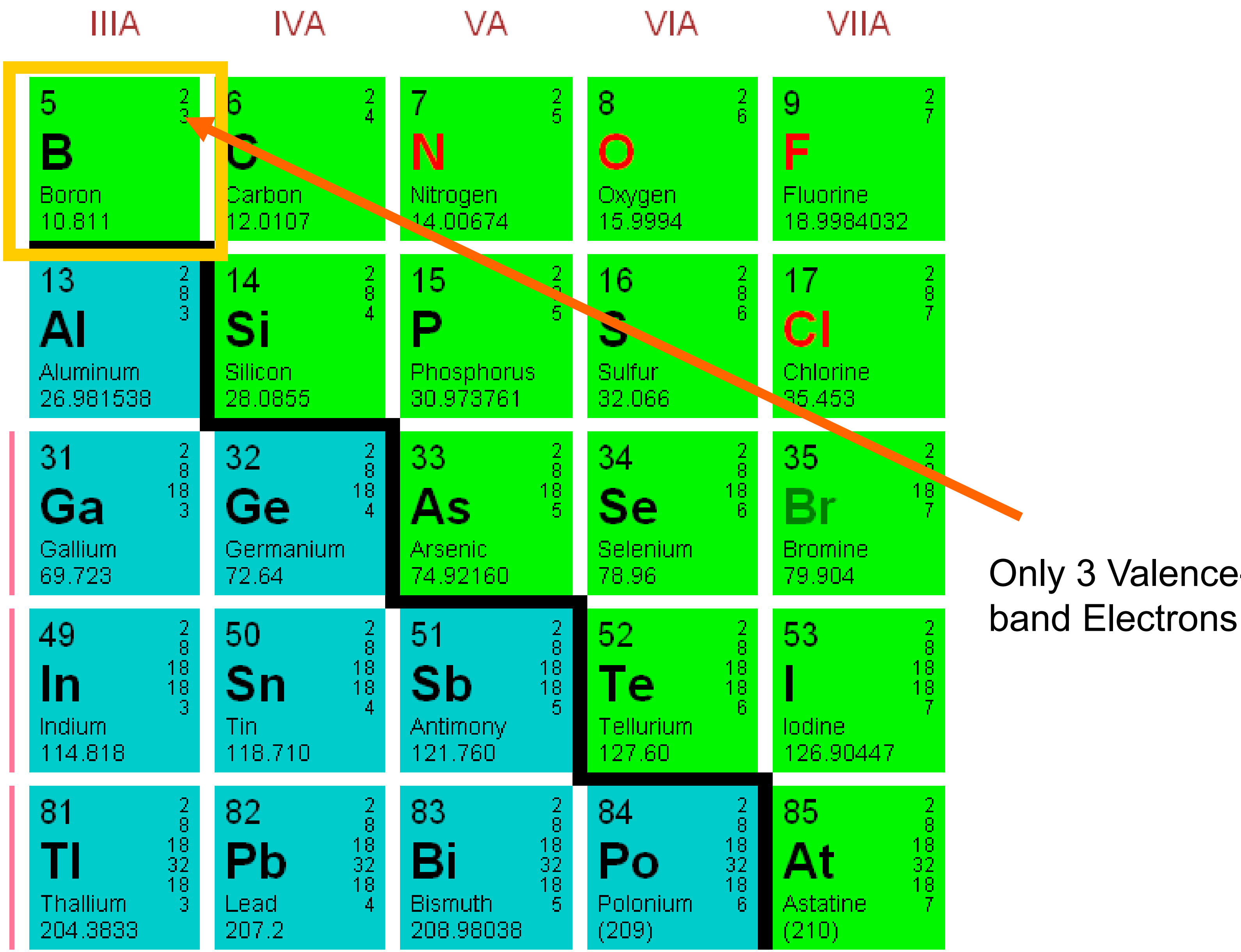



http://www.dayah.com/periodic/Images/periodic%20table.png

| IIIA | IVA | VA | VIA | VIIA |
|---|---|---|---|---|
| 5 B Boron 10.811 (2 3) | 6 C Carbon 12.0107 (2 4) | 7 N Nitrogen 14.00674 (2 5) | 8 O Oxygen 15.9994 (2 6) | 9 F Fluorine 18.9984032 (2 7) |
| 13 Al Aluminum 26.981538 (2 8 3) | 14 Si Silicon 28.0855 (2 8 4) | 15 P Phosphorus 30.973761 (2 8 5) | 16 S Sulfur 32.066 (2 8 6) | 17 Cl Chlorine 35.453 (2 8 7) |
| 31 Ga Gallium 69.723 (2 8 18 3) | 32 Ge Germanium 72.64 (2 8 18 4) | 33 As Arsenic 74.92160 (2 8 18 5) | 34 Se Selenium 78.96 (2 8 18 6) | 35 Br Bromine 79.904 (2 8 18 7) |
| 49 In Indium 114.818 (2 8 18 18 3) | 50 Sn Tin 118.710 (2 8 18 18 4) | 51 Sb Antimony 121.760 (2 8 18 18 5) | 52 Te Tellurium 127.60 (2 8 18 18 6) | 53 I Iodine 126.90447 (2 8 18 18 7) |
| 81 Tl Thallium 204.3833 (2 8 18 32 18 3) | 82 Pb Lead 207.2 (2 8 18 32 18 4) | 83 Bi Bismuth 208.98038 (2 8 18 32 18 5) | 84 Po Polonium (209) (2 8 18 32 18 6) | 85 At Astatine (210) (2 8 18 32 18 7) |



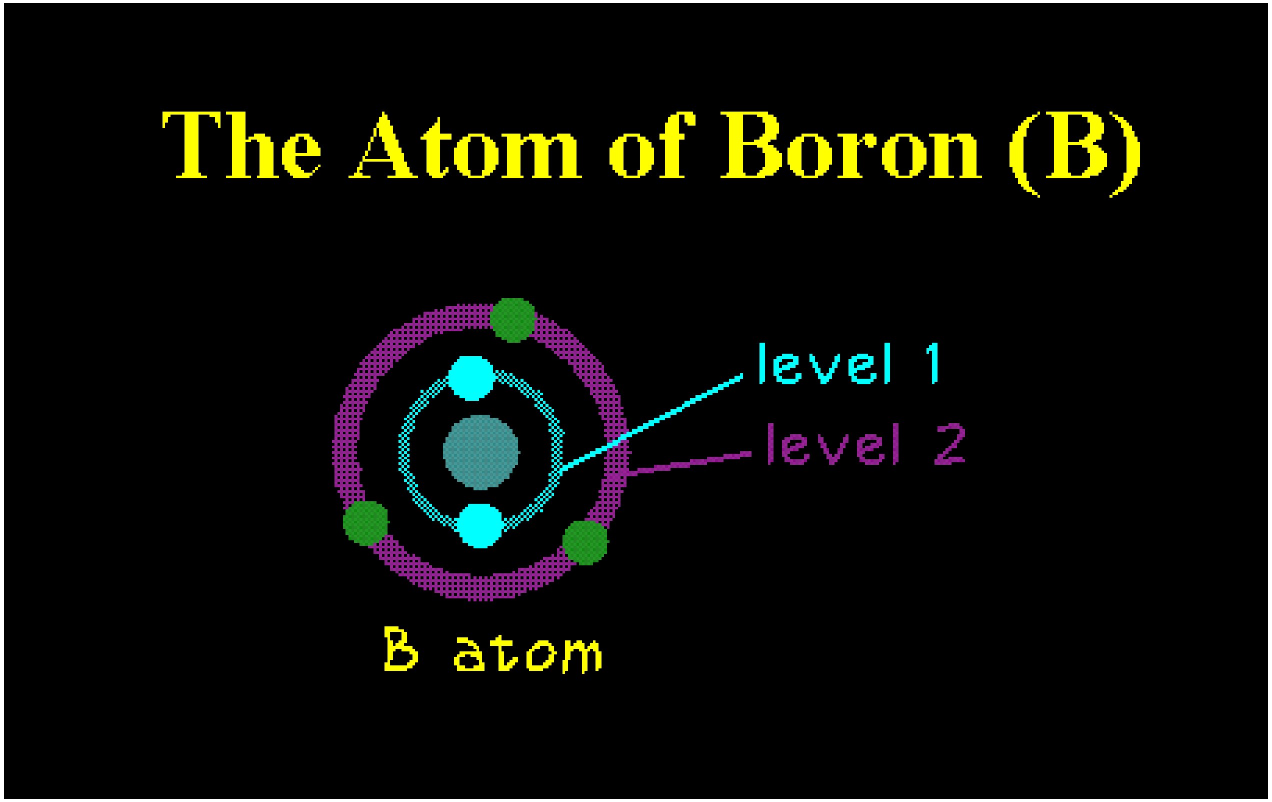

All elements in group IV have 4 valence-band electrons



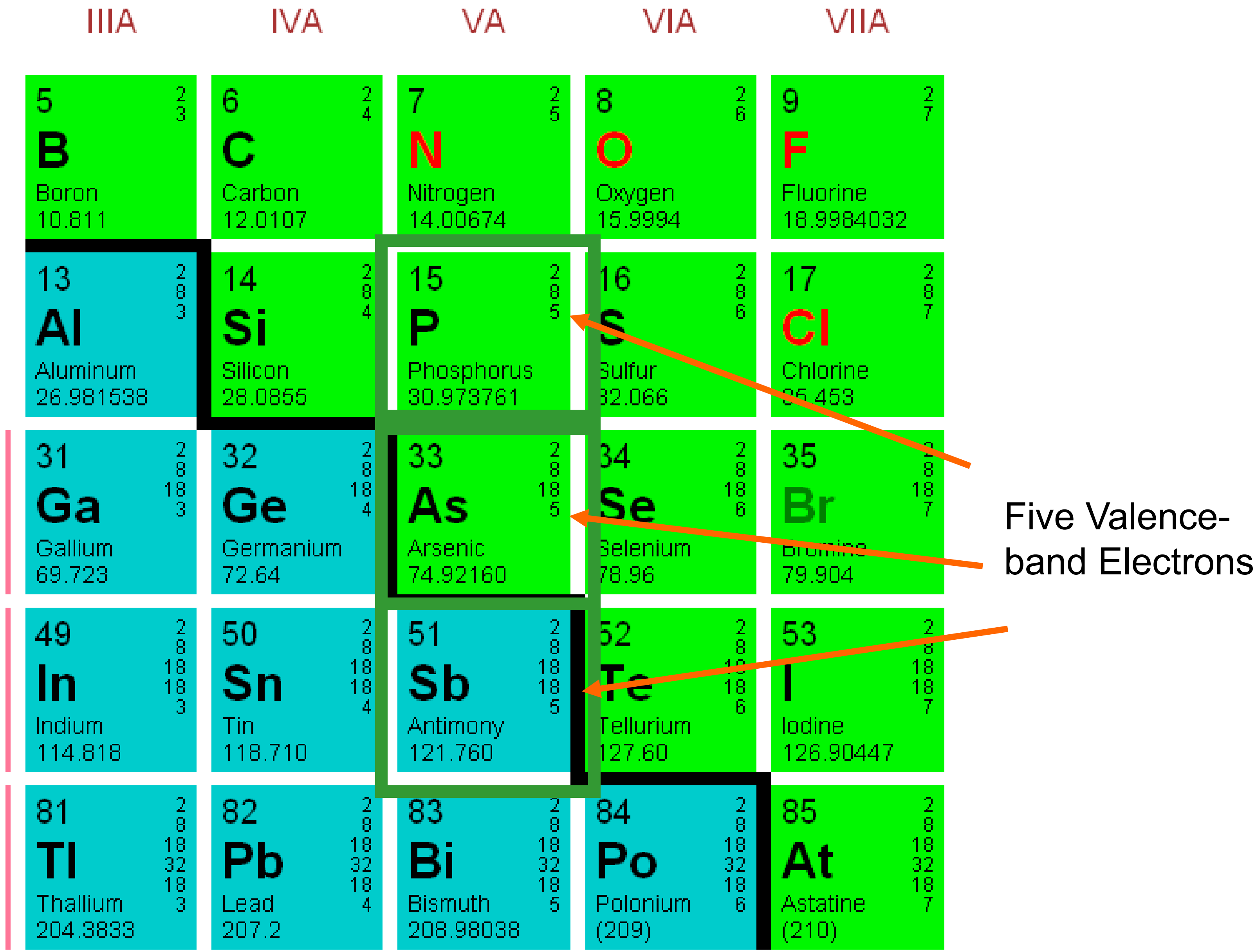

**Serves as an "acceptor" of electrons**

**Acts as a p-type impurity when used as a silicon dopant**

All elements in group III have 3 valence-band electrons




http://www.oftc.usyd.edu.au/edweb/devices/semicdev/doping4.html

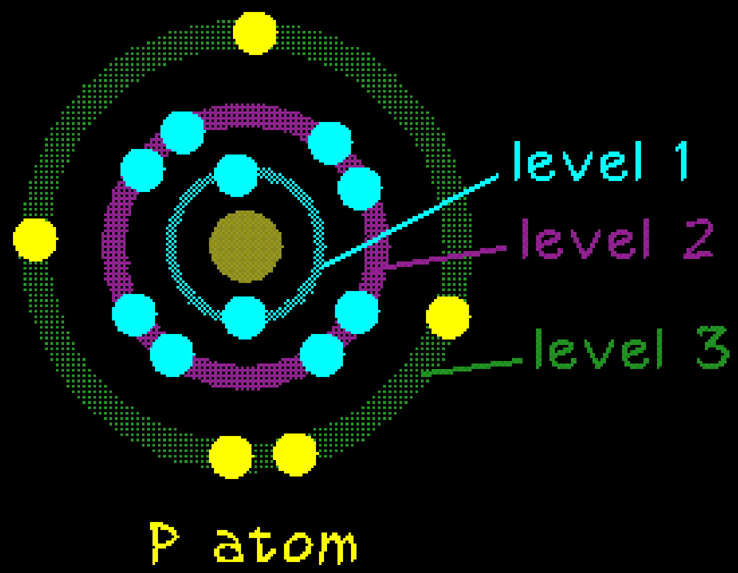



**Serves as an “donor ” of electrons**

**Acts as an n-type impurity when used as a silicon dopant**

All elements in group V have 5 valence-band electrons

# The Atom of Phosphorus (P)



15
P
Phosphorus
30.973762
2 8 5
[Ne]3s$^2$ 3p$^3$

5
B
Boron
10.811
2 3
1s$^2$ 2s$^2$ 2p$^1$

14
Si
Silicon
28.0855
2 8 4
[Ne]3s$^2$ 3p$^2$

33
As
Arsenic
74.92160
2 8 18 5
[Ar]3d$^{10}$ 4s$^2$ 4p$^3$

51
Sb
Antimony
121.760
2 8 18 18 5
[Kr]4d$^{10}$ 5s$^2$ 5p$^3$

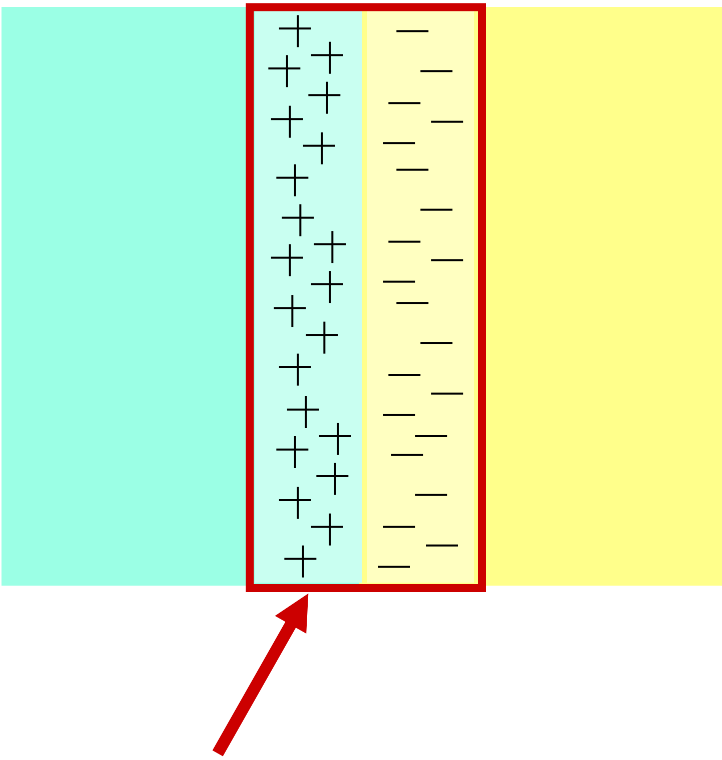
# Silicon Dopants in Semiconductor Processes

**B** (Boron) widely used dopant for creating p-type regions

**P** (Phosphorus) widely used dopant for creating n-type regions
(bulk doping, diffuses fast)

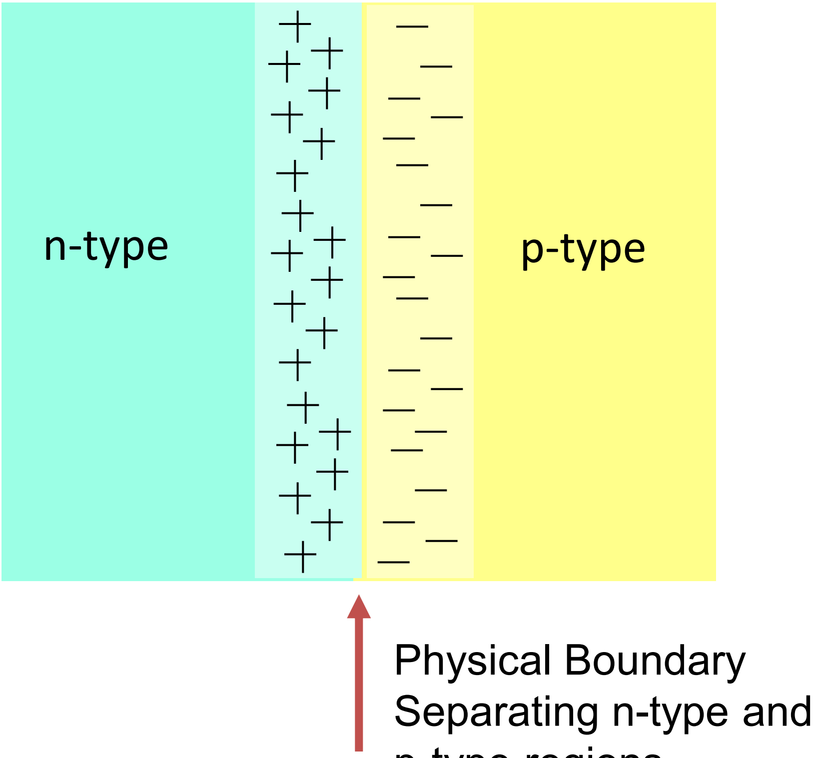
**As** (Arsenic) widely used dopant for creating n-type regions
(Active region doping, diffuses slower)

# Diodes (pn junctions)



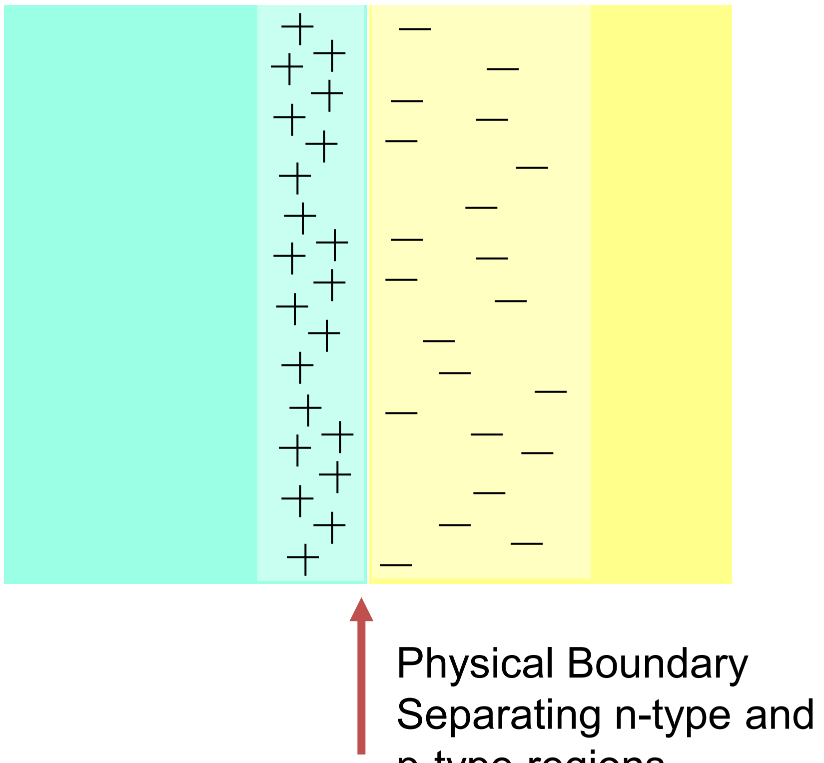
Depletion region created that is ionized but void of carriers

# pn Junctions



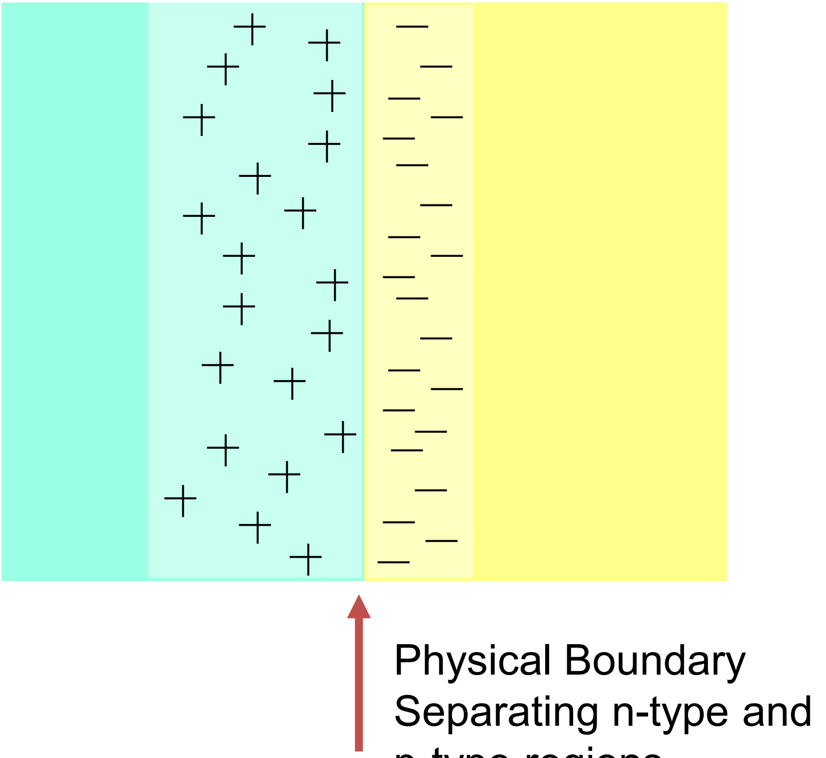

If doping levels identical, depletion region extends equally into n-type and p-type regions

# pn Junctions



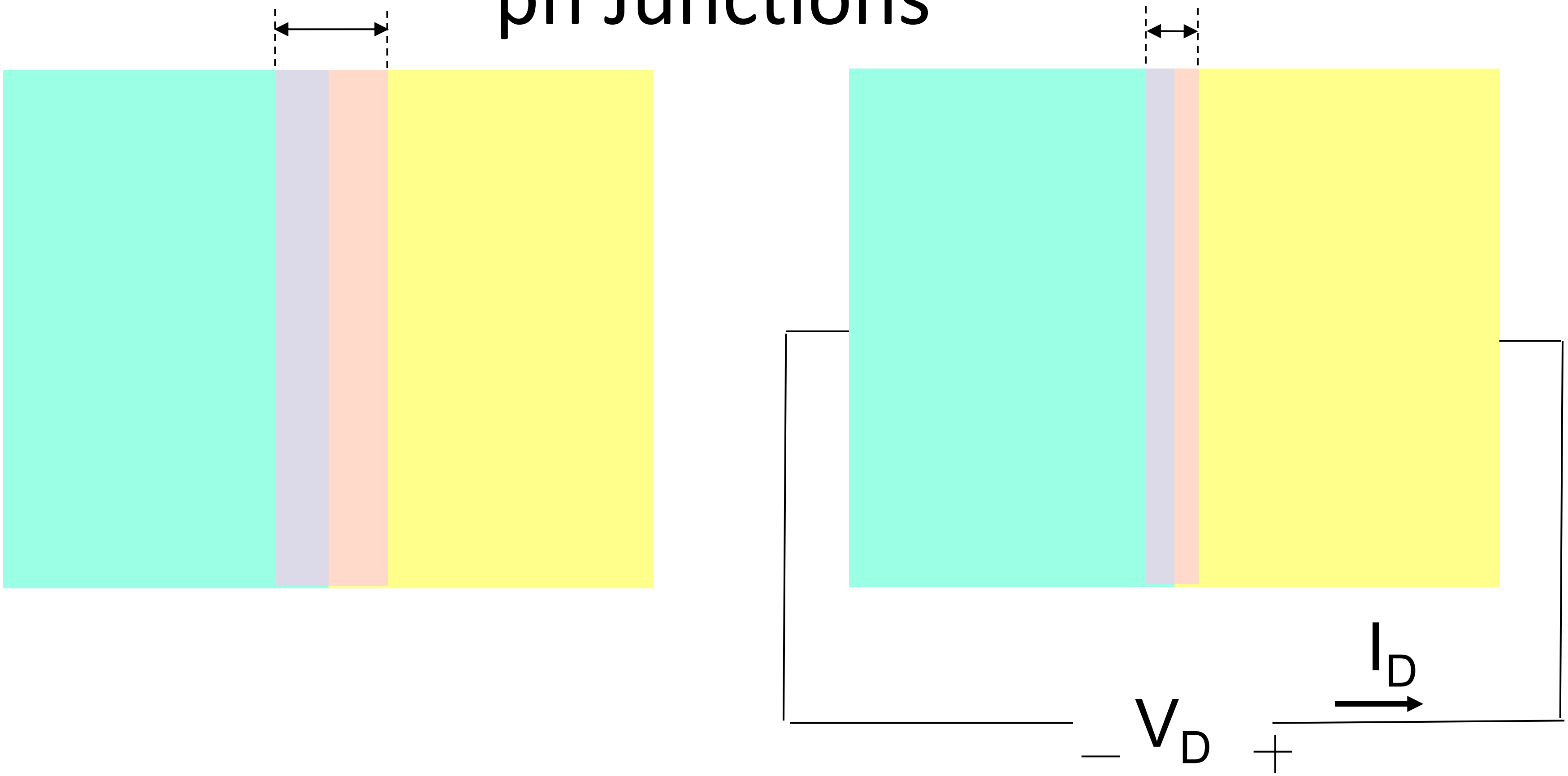

Extends farther into p-type region if p-doping lower than n-doping

# pn Junctions



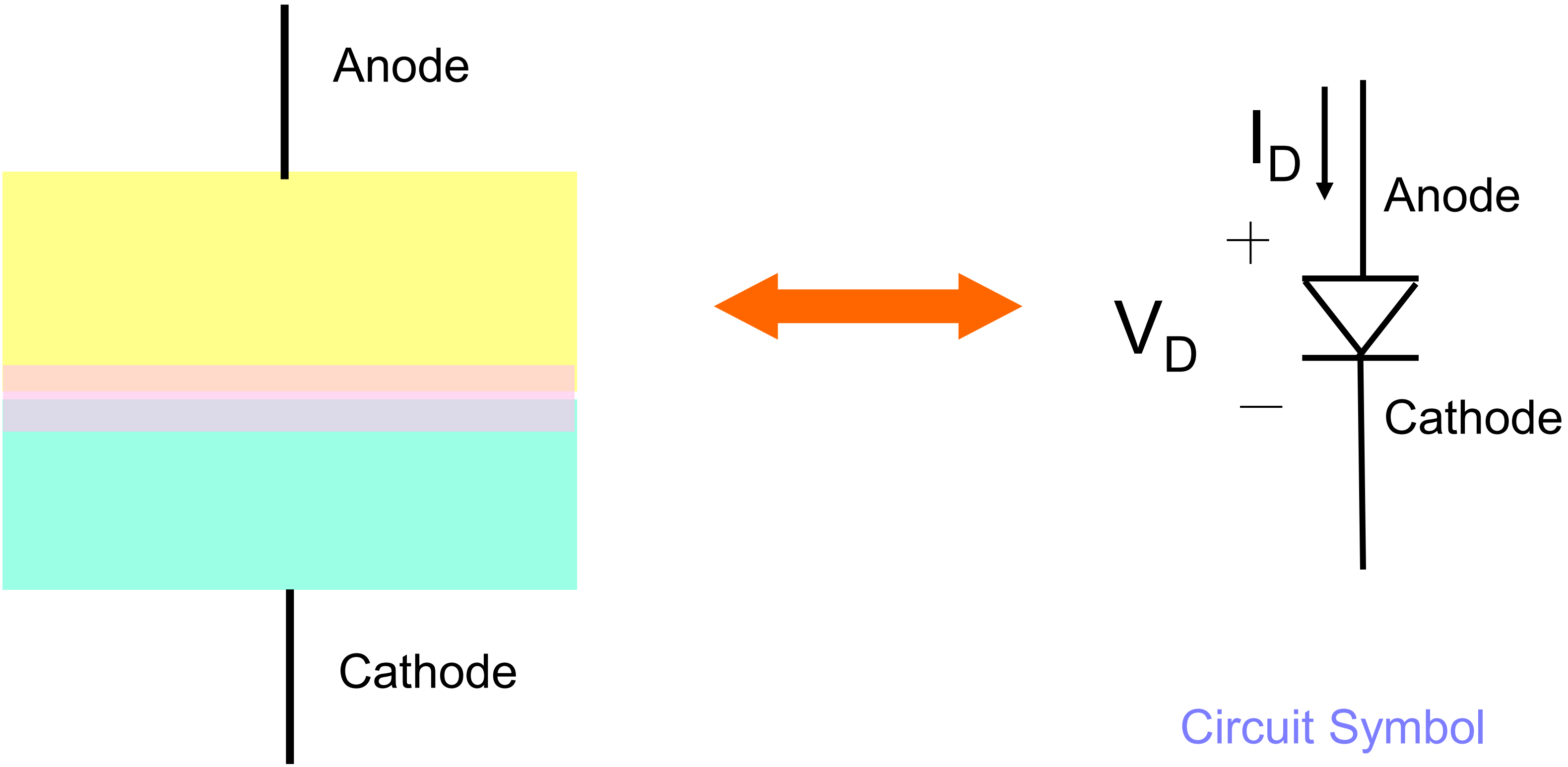

Extends farther into n-type region if n-doping lower than p-doping

# pn Junctions




- Positive voltages across the p to n junction (polarity indicated) are denoted as forward bias
- Negative voltages across the p to n junction are denoted as reverse bias
- As forward bias increases, depletion region thins and current starts to flow
- Current grows very rapidly as forward bias increases
- Current is very small under revere bias

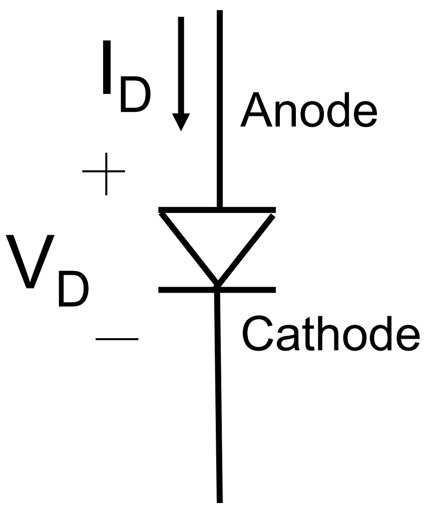
# pn Junctions




Circuit Symbol

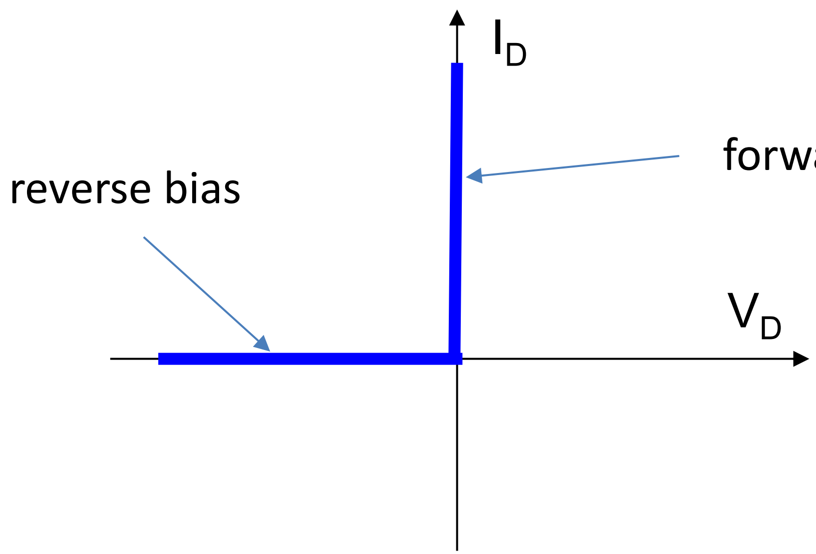
# pn Junctions

- As forward bias increases, depletion region thins and current starts to flow
- Current grows <u>very rapidly</u> as forward bias increases



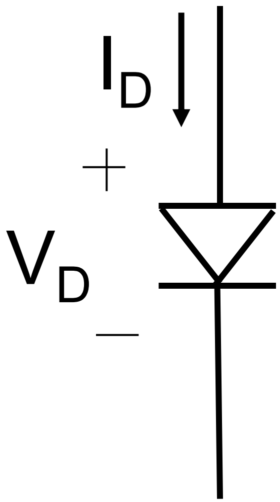

Simple Diode Model:

| | | |
|---|---|---|
| $V_D=0$ | $I_D>0$ | Forward bias |
| $I_D=0$ | $V_D<0$ | Reverse bias |

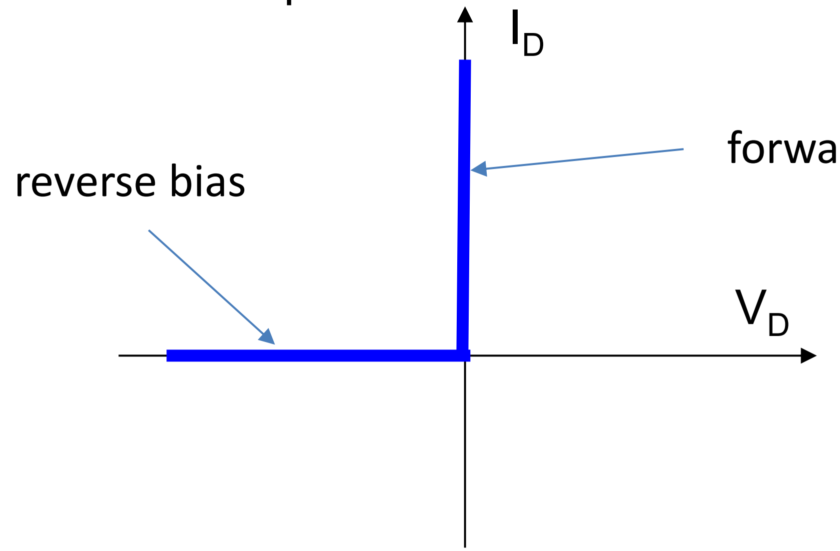



- Simple model often referred to as the “Ideal” diode model
- Termed a piecewise model

# pn Junctions

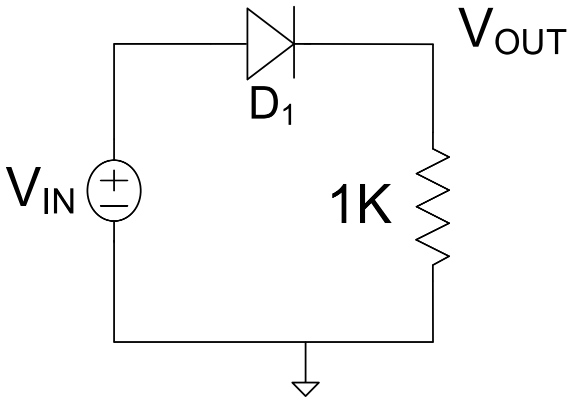


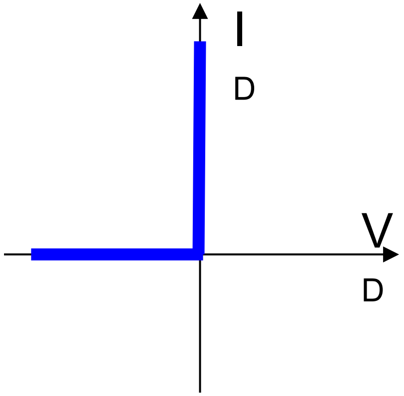

Simple Diode Model:



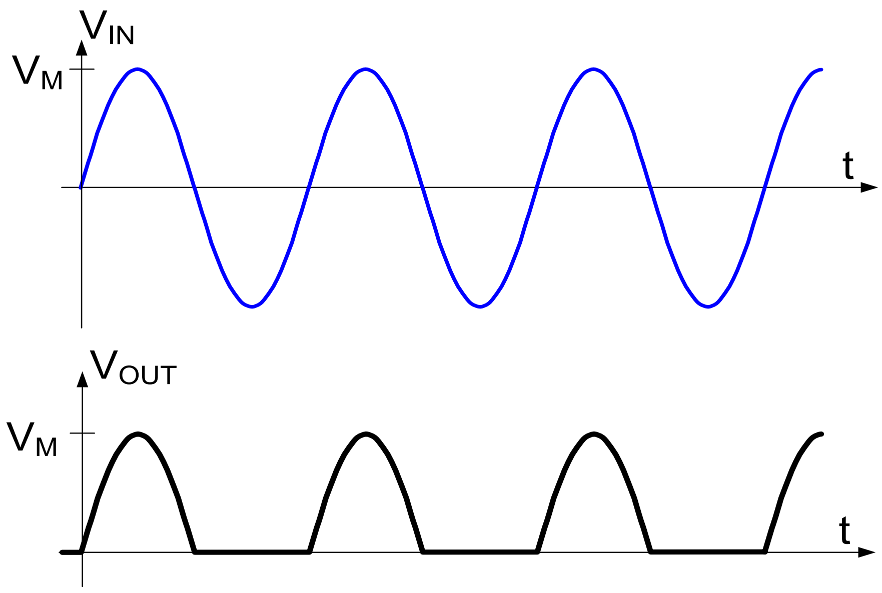

pn junction serves as a “rectifier” passing current in one direction and blocking it in the other direction

# Rectifier Application:




$$V_{IN}=V_M \sin\omega t$$

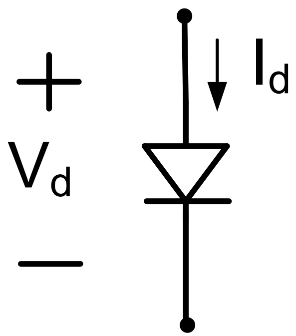



Analysis based upon “passing current” in one direction and “ blocking current” in the other direction

# I-V characteristics of pn junction

## (signal or rectifier diode)

Improved Diode Model:




$I_S$ in the 10fA to 100fA range

$I_S$ proportional to junction area

$$V_t = \frac{kT}{q}$$

k= 1.380 64852 × $10^{-23}$ $JK^{-1}$

q = −1.60217662×$10^{-19}$ C

k/q=8.62× $10^{-5}$ $VK^{-1}$

n typically about 1

Diode Equation

$$I_D = I_S\left(e^{\frac{V_d}{nV_t}} - 1\right)$$

$I_S$ and n are model parameters

What is $V_t$ at room temp?

$V_t$ is about 26mV at room temp

Diode equation due to William Shockley, inventor of BJT

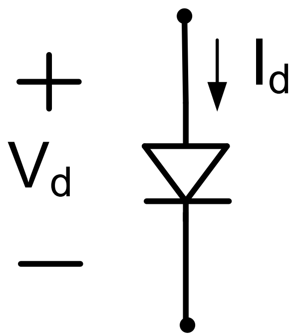
In 1919, William Henry Eccles coined the term ***diode***

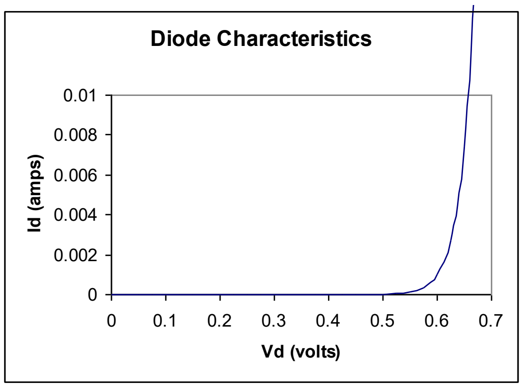
In 1940, Russell Ohl "stumbled upon" the p-n junction diode

# I-V characteristics of pn junction

## (signal or rectifier diode)

Improved Diode Model:




Diode Equation $I_D = I_S\left(e^{\frac{V_d}{nV_t}} - 1\right)$

(not a piecewise model !)

$I_S$ in 10fA -100fA range (for signal diodes)

n typically about 1

$$V_t = \frac{kT}{q}$$

$k/q = 8.62\times 10^{-5}\, VK^{-1}$

**Simplification of Diode Equation:**

Under reverse bias ($V_d$<0), $I_D \cong -I_S$

Under forward bias ($V_d$>0), $I_D = I_S e^{\frac{V_d}{nV_t}}$

$V_t$ is about 26mV at room temp

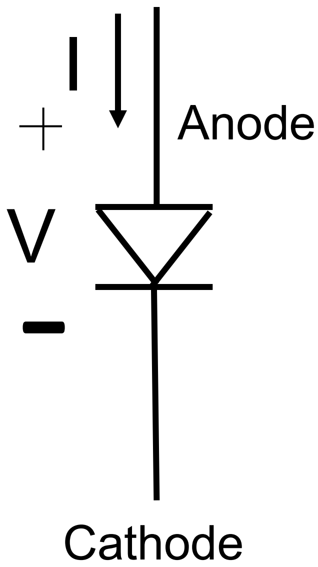
Simplification essentially identical model except for $V_d$ very close to 0

Diode Equation or forward bias simplification are unwieldy to work with analytically

# pn Junctions

**Diode Equation:**
(simplification)

$$I = \begin{cases} I_S A e^{\frac{V}{nV_T}} & V > 0 \quad \text{forward bias} \\ -I_S & V < 0 \quad \text{reverse bias} \end{cases}$$




**Diode Equation:**
(further simplification)

$$I = \begin{cases} I_S e^{\frac{V}{nV_T}} & V > 0 \quad \text{forward bias} \\ 0 & V < 0 \quad \text{reverse bias} \end{cases}$$

$I_S = J_S A$

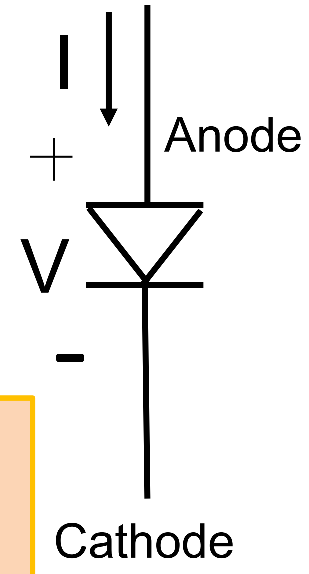
$\{J_S\}$ is model parameter (or $I_S$ is a model parameter if A is fixed)
$\{A\}$ is design parameter , A is the cross-sectional area of the junction (usually from top view in layout)

Slight discontinuity at V=0 in these models (which doesn't exist in real diodes) but of no consequence unless V is very close to 0

$I_S$ is often given in data sheets and model files

These are termed "piecewise" models

# Diode Model Summary




$I_S = J_S A$

## Ideal Diode Model

$V_D = 0 \qquad I_D > 0$ forward bias

$I_D = 0 \qquad V_D < 0$ reverse bias

## Diode Equation

$$I_D = I_S\left(e^{\frac{V_d}{nV_t}} - 1\right)$$

## Diode Equation:

(simplification)

$$I = \begin{cases} I_S e^{\frac{V}{nV_T}} & V > 0 \quad \text{forward bias} \\ -I_S & V < 0 \quad \text{reverse bias} \end{cases}$$

## Diode Equation:

(further simplification)

$$I = \begin{cases} I_S e^{\frac{V}{nV_T}} & V > 0 \quad \text{forward bias} \\ 0 & V < 0 \quad \text{reverse bias} \end{cases}$$

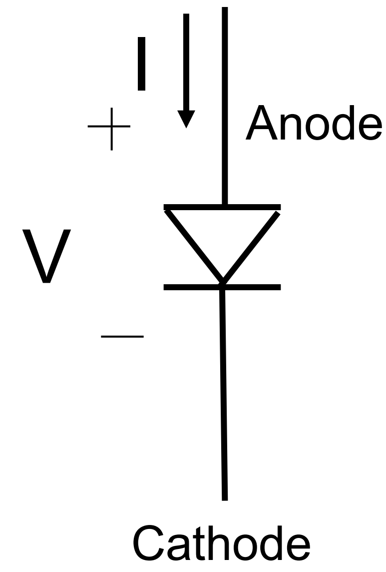
Little difference in these models, if any, in most applications. Typically, any referred to as the Diode Equation

# pn Junctions

**Diode Equation:**
(further simplification)

$$I = \begin{cases} J_S A e^{\frac{V}{nV_T}} & V > 0 \quad \text{forward bias} \\ 0 & V < 0 \quad \text{reverse bias} \end{cases}$$

$I_S = J_S A$




$J_S$ (or $I_S$) is strongly temperature dependent

With n=1, for V>0,

$$J_S = J_{SX} T^m e^{\frac{-V_{G0}}{V_t}}$$

{$J_{SX}$, m,n} are model parameters
{A} is a design parameter
{T, $V_{G0}$, k/q} are environmental parameters and physical constants

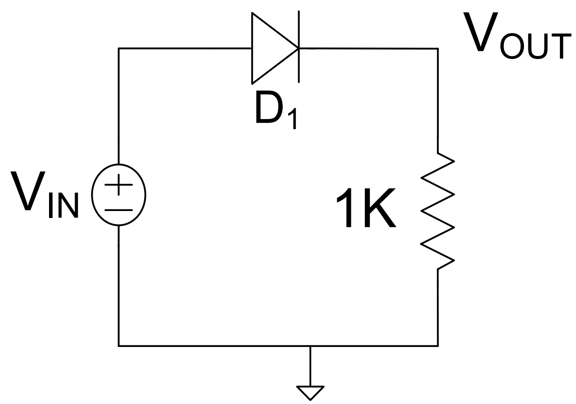
**Diode Equation:**
(further simplification showing more detail)

$$I(T) = \begin{cases} \left( J_{SX} \left[ T^m e^{\frac{-V_{G0}}{V_t}} \right] \right) A e^{\frac{V}{V_t}} & V>0 \\ 0 & V<0 \end{cases}$$

Typical values for key parameters: $J_{SX}$=0.5A/μ², $V_{G0}$=1.17V, m=2.3

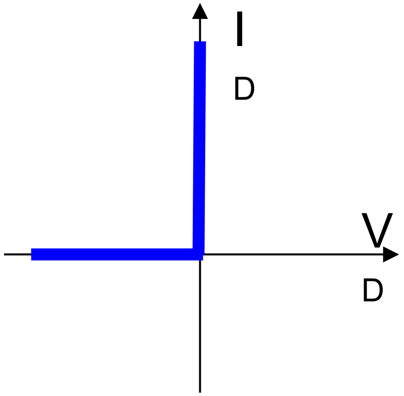
Observe this simplification is a piecewise model !

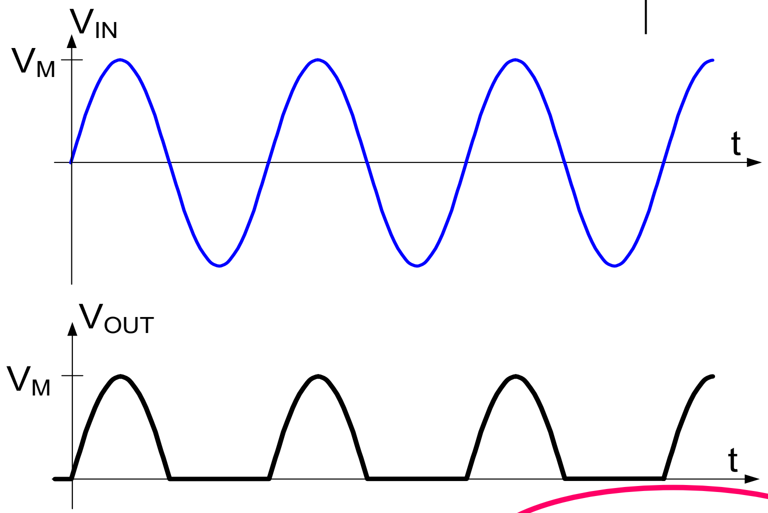
# Rectifier Application:




$V_{IN}=V_M \sin\omega t$

Simple Diode Model:



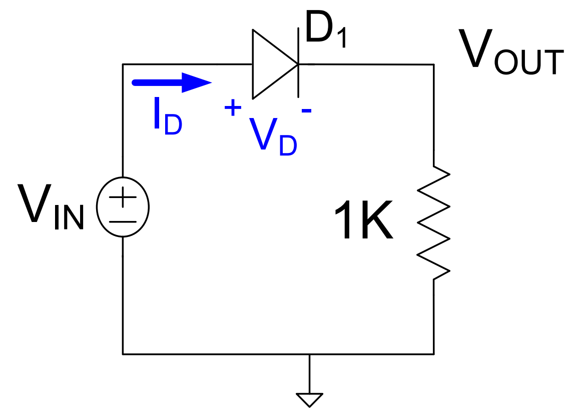

Analysis based upon "passing current" in one direction and " blocking current" in the other direction

What principle was used in this analysis?

Was this analysis rigorous ?

# Diode Equation (even simplification) unwieldly to work with analytically. Why?

## World's simplest diode circuit




## Determine $V_{OUT}$

$V_{IN}$=5V

Assume forward bias , simplified diode equation model

$$5 = V_D + V_{OUT}$$
$$V_{OUT} = I_D \bullet 1K$$
$$I_D = I_S e^{\frac{V_D}{nV_t}}$$

3 independent equations and 3 unknowns

$$V_{OUT} = I_S e^{\frac{5-V_{OUT}}{nV_t}} \bullet 1K$$

$V_{OUT}$=?

- Can obtain $V_{OUT}$ from this equation but explicit expression does not exist for $V_{OUT}$ !
- Previous analysis based upon "passing" and "blocking" currents was not rigorous !!

# I-V characteristics of pn junction

## (signal or rectifier diode)

Diode Equation

$$I_D = I_S\left(e^{\frac{V_d}{nV_t}} - 1\right)$$

$I_S$ often in the 10fA to 100fA range

$I_S$ proportional to junction area

$V_t$ is about 26mV at room temp

Simplification of Diode Equation:

$$I_D = \begin{cases} I_S e^{\frac{V_D}{nV_T}} & V > 0 \\ -I_S & V < 0 \end{cases}$$

How much error is introduced using the simplification for $V_d$ > 0.5V ? (assume n=1)

$$\varepsilon = \frac{I_S\left(e^{\frac{V_d}{V_t}} - 1\right) - I_S e^{\frac{V_d}{V_t}}}{I_S\left(e^{\frac{V_d}{V_t}} - 1\right)}$$

$$\varepsilon < \frac{1}{e^{\frac{0.5}{.026}}} = 4.4 \bullet 10^{-9}$$

How much error is introduced using the simplification for $V_d$ < - 0.5V?

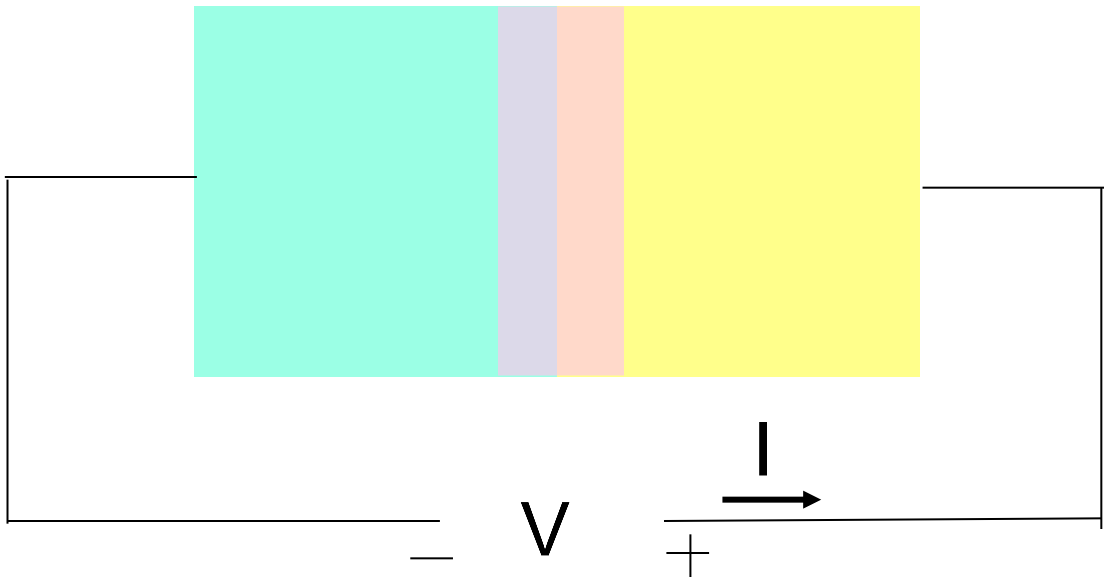
$$\varepsilon < e^{\frac{-0.5}{.026}} = 4.4 \bullet 10^{-9}$$

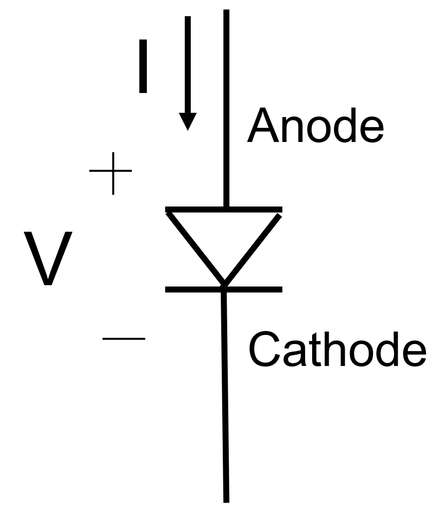
**Simplification almost never introduces any significant error**

Will you impress your colleagues or your boss if you use the more exact diode equation when $V_d < -0.5V$ or $V_d > +0.5V$ ?

Will your colleagues or your boss be unimpressed if you use the more exact diode equation when $V_d < -0.5V$ or $V_d > +0.5V$ ?

# pn Junctions




Note: $I_S = J_s A$

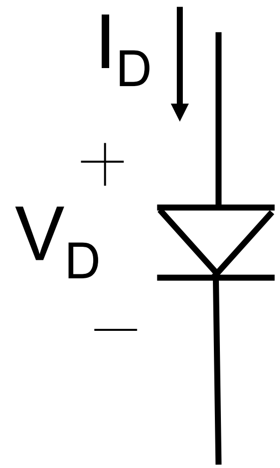
"Diode Equation":
(good enough for most applications
when ideal diode model is inadequate)

$$I = \begin{cases} J_S A e^{\frac{V}{nV_T}} & V > 0 \\ 0 & V < 0 \end{cases}$$

$J_S$= Sat Current Density (in the 1aA/u$^2$ to 1fA/u$^2$ range)
A= Junction Cross Section Area
$V_T$=kT/q (k/q=1.381x10$^{-23}$V•C/°K/1.6x10$^{-19}$C=8.62x10$^{-5}$V/°K)
n is approximately 1

# $I_S$ highly temperature dependent

Example: Consider diode operating under forward bias




$$I_D(T) = \left(J_{SX}\left[T^m e^{\frac{-V_{G0}}{V_t}}\right]\right) A e^{\frac{V_D}{V_t}}$$

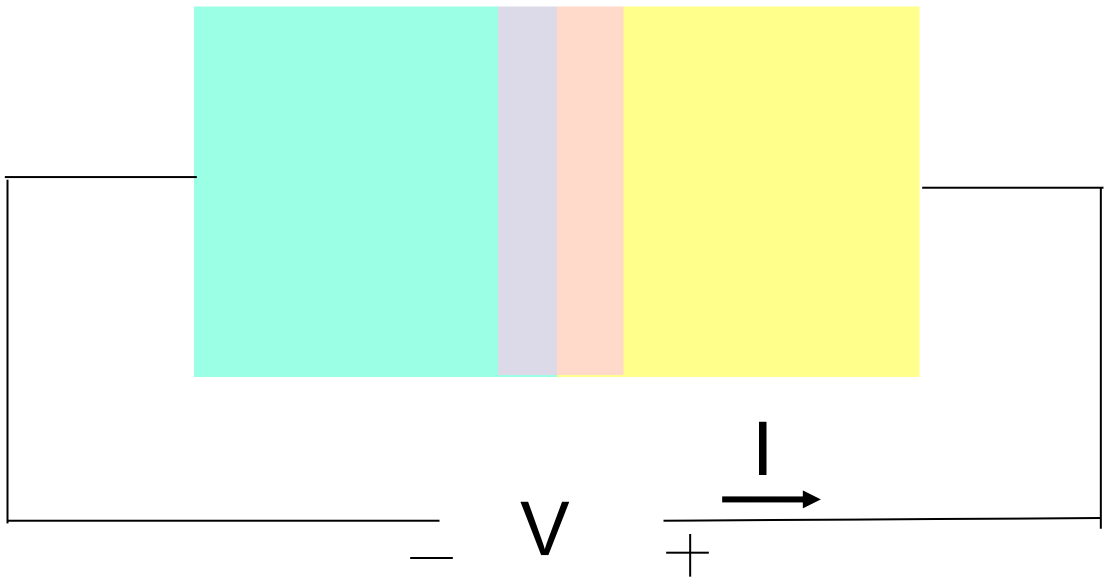
What percent change in $I_S$ will occur for a 1°C change in temperature at room temperature?

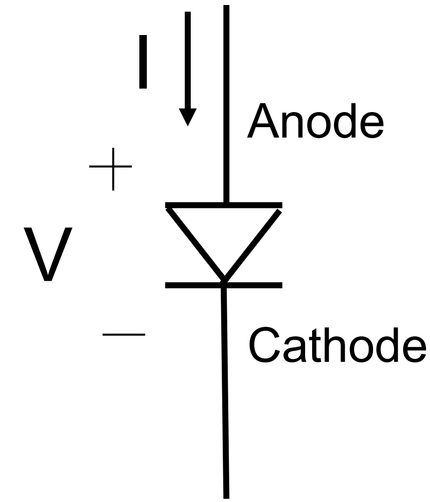
$$\frac{\Delta I_S}{I_S} = \frac{\left(J_{SX}\left[T_{T_2}^m e^{\frac{-V_{G0}}{V_t(T_2)}}\right]\right)A - \left(J_{SX}\left[T_{T_1}^m e^{\frac{-V_{G0}}{V_t(T_1)}}\right]\right)A}{\left(J_{SX}\left[T_{T_1}^m e^{\frac{-V_{G0}}{V_t(T_1)}}\right]\right)A} = \frac{\left(\left[T_{T_2}^m e^{\frac{-V_{G0}}{V_t(T_2)}}\right]\right) - \left(\left[T_{T_1}^m e^{\frac{-V_{G0}}{V_t(T_1)}}\right]\right)}{\left(\left[T_{T_1}^m e^{\frac{-V_{G0}}{V_t(T_1)}}\right]\right)}$$

$$\frac{\Delta I_S}{I_S} = \frac{\left(1.240x10^{-15}\right) - \left(1.025x10^{-15}\right)}{\left(1.025x10^{-15}\right)} 100\% = 21\%$$

- Attempts to measure $I_S$ in our laboratories can result in large errors !
- Most circuits whose performance depends upon precise value for $I_S$ are not practical

# pn Junctions



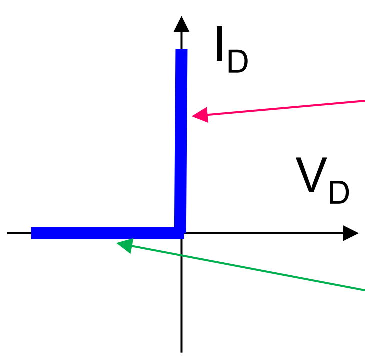

## Diode Equation:

(good enough for most applications)

$$I = \begin{cases} J_S A e^{\frac{V}{nV_T}} & V > 0 \\ 0 & V < 0 \end{cases}$$

$I_S = J_s A$

Simple Diode Model:

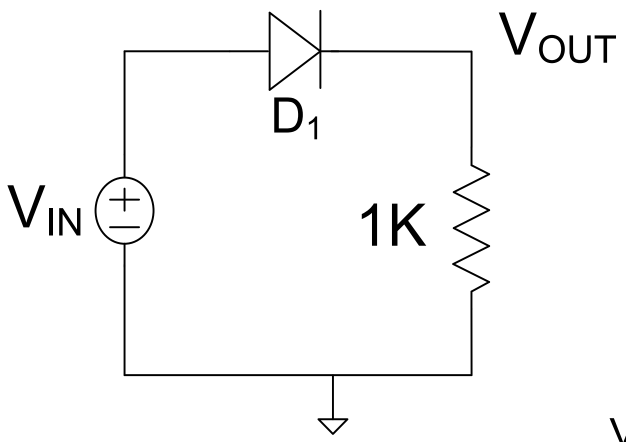



Often termed the “conducting” or “ON” state

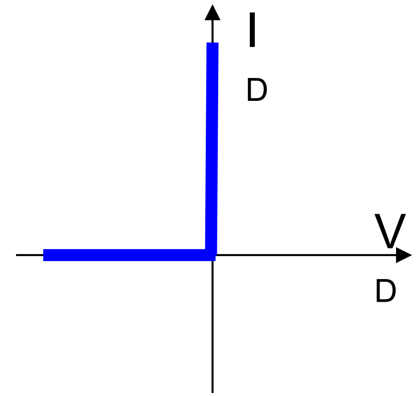
Often termed the “nonconducting” or “OFF” state

**What basic circuit analysis principles were used to analyze this circuit?**

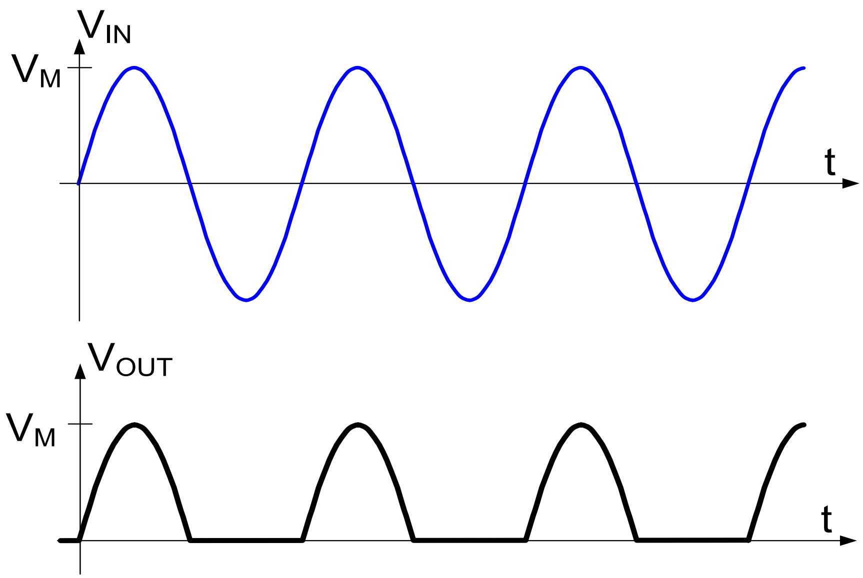
# Rectifier Application:




Simple Diode Model:

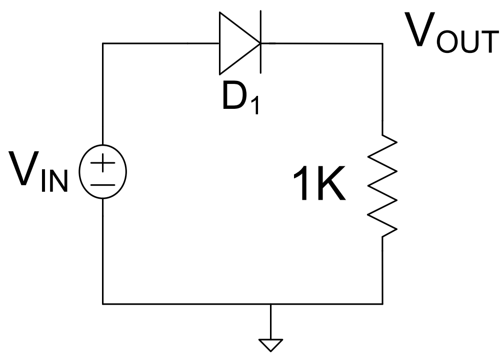



$V_{IN}=V_M \sin\omega t$



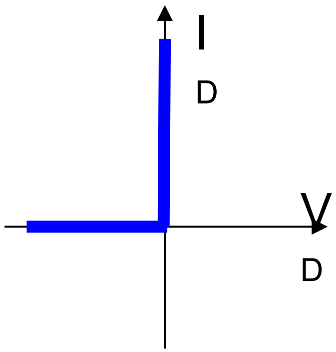

Analysis based upon "passing current" in one direction and " blocking current" in the other direction

# Rectifier Application:




$V_{IN}=V_M\sin\omega t$

Simple Diode Model:

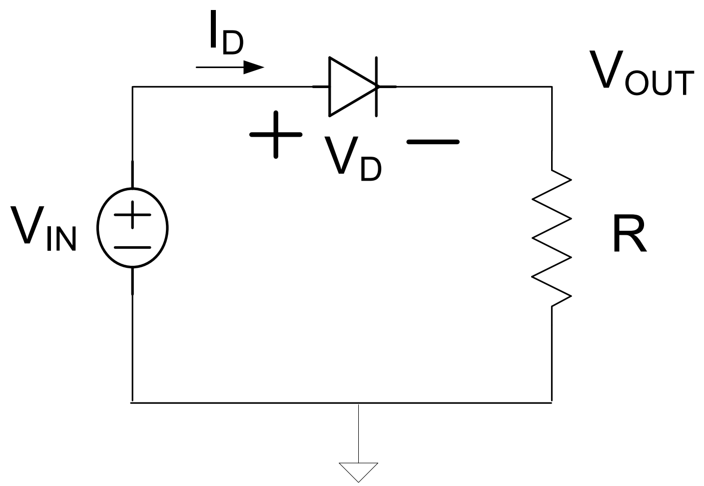


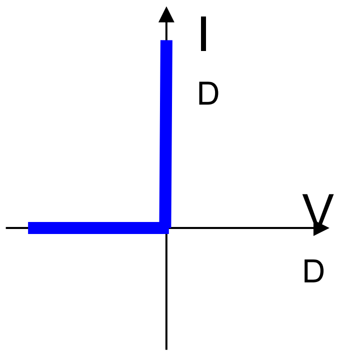

Analysis based upon "passing current" in one direction and " blocking current" in the other direction

**Was the previous analysis rigorous?**

**Is use of simple diode model justifiable?**

# Consider again the basic rectifier circuit

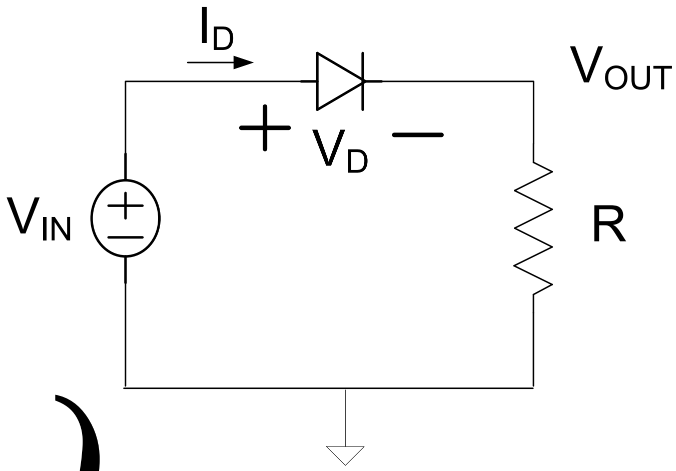



- Previously considered sinusoidal excitation
- Previously gave "qualitative" analysis
- **Rigorous analysis method is essential**

$$V_{OUT} = \ ?$$

# Consider again the basic rectifier circuit




$$\left.\begin{aligned} V_{IN} &= V_D + I_D R \\ V_{OUT} &= I_D R \\ I_D &= I_S\left(e^{\frac{V_D}{V_t}} - 1\right) \end{aligned}\right\}$$

$$V_{OUT} = I_S R\left(e^{\frac{V_{IN} - V_{OUT}}{V_t}} - 1\right)$$

This analysis is rigorous (using only KVL and device models)

Even the simplest diode circuit does not have a closed-form explicit solution when diode equation is used to model the diode !!

Due to the nonlinear nature of the diode equation

**Simplifications of diode model are essential if analytical results are to be obtained !**

Stay Safe and Stay Healthy !

End of Lecture 13