EE 330
Lecture 13

Devices in Semiconductor Processes

- Diodes
- Capacitors
- MOSFETs

Exam 1 Friday Sept 27

- Students may bring 1 page of notes
- HW assignment for week of Sept 23 due on Wed Sept 25 at beginning of class
- No 5:00 p.m extension so solutions can be posted
- Scientific calculators will be provided – no use of any personal electronic devices of any kind
- Those with special accommodation needs, please send me an email message or contact me so arrangements can be made
- Review session – to be determined

Review from Last Lecture

Temperature Coefficients

Used for indicating temperature sensitivity of resistors & capacitors

For a resistor:

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

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

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

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

Identical Expressions for Capacitors

Voltage Coefficients

Used for indicating voltage sensitivity of resistors & capacitors

For a resistor:

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

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

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

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

Identical Expressions for Capacitors

Temperature and Voltage Coefficients

- Temperature and voltage coefficients often quite large for diffused resistors
- Temperature and voltage coefficients often quite small for poly and metal resistors

Type of layer	Sheet Resistance $\Omega/\square$	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

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

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

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

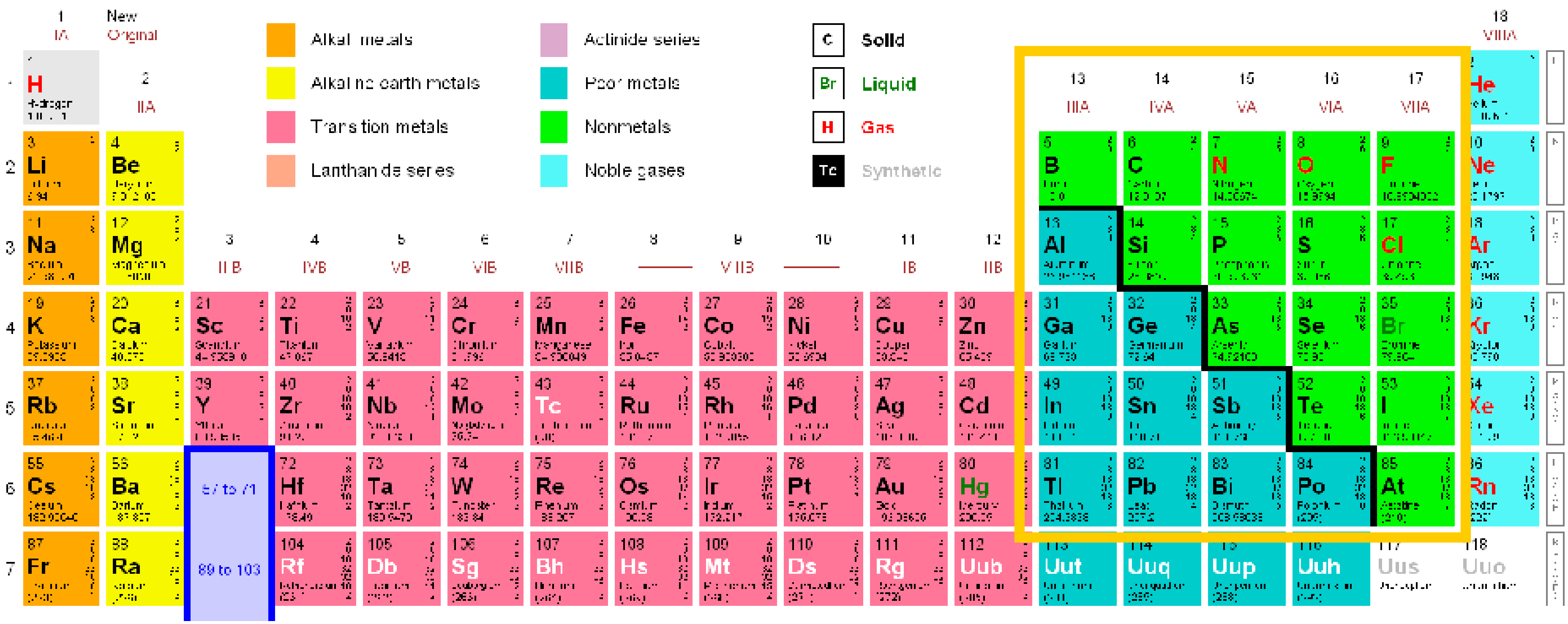
$$R(T_2) \cong R(T_1)[1.045]$$

Thus the resistor increases by 4.5%

Basic Devices and Device Models

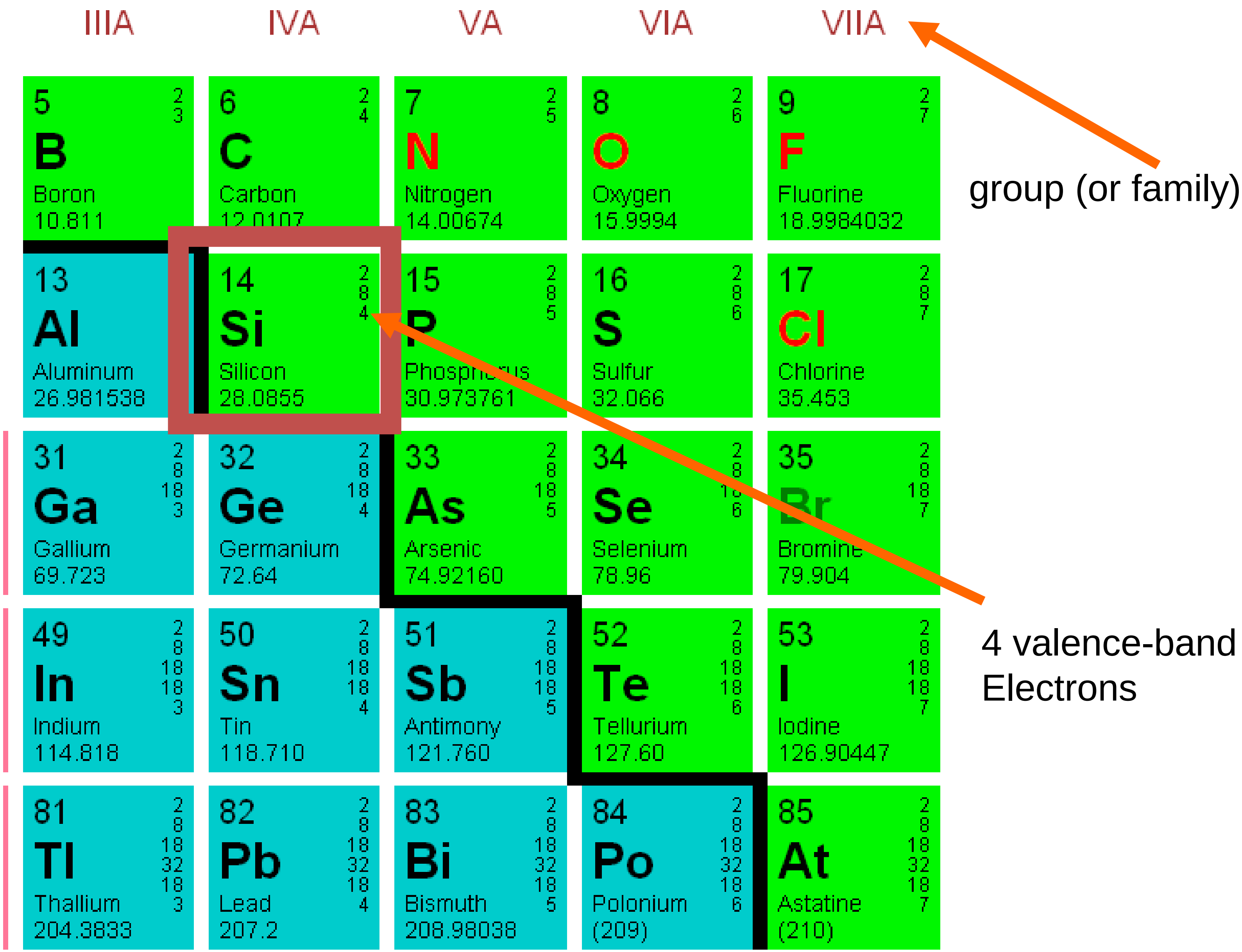
- Resistor
- Diode
- Capacitor
- MOSFET
- BJT

Periodic Table of the Elements



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

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



All elements in group IV have 4 valence-band electrons

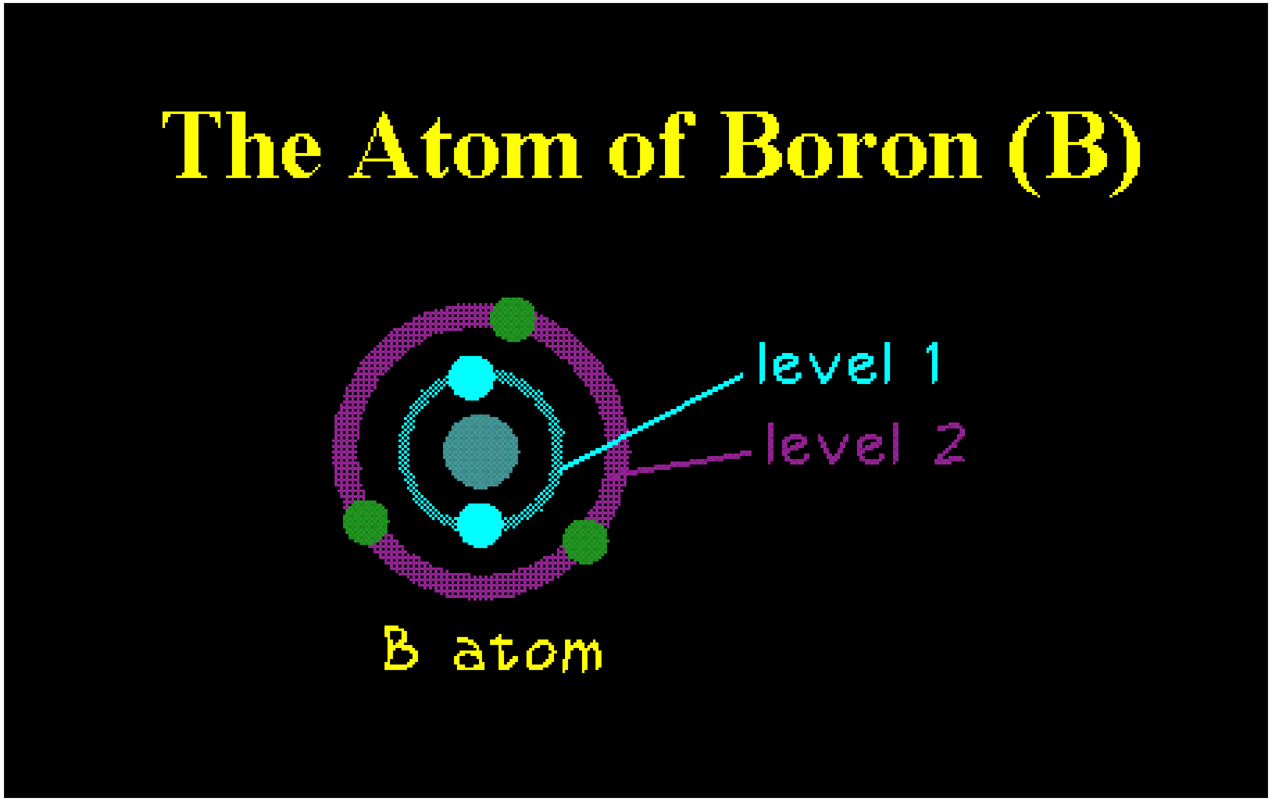
IIIA	IVA	VA	VIA	VIIA
5 **B** Boron 10.811 (2, 3)	6 **C** Carbon 12.0107 (2, 4)	7 **N** Nitrogen 14.00674 (2, 5)	8 **O** Oxygen 15.9994 (2, 6)	9 **F** Fluorine 18.9984032 (2, 7)
13 **Al** Aluminum 26.981538 (2, 8, 3)	14 **Si** Silicon 28.0855 (2, 8, 4)	15 **P** Phosphorus 30.973761 (2, 8, 5)	16 **S** 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)

Only 3 Valence-band Electrons

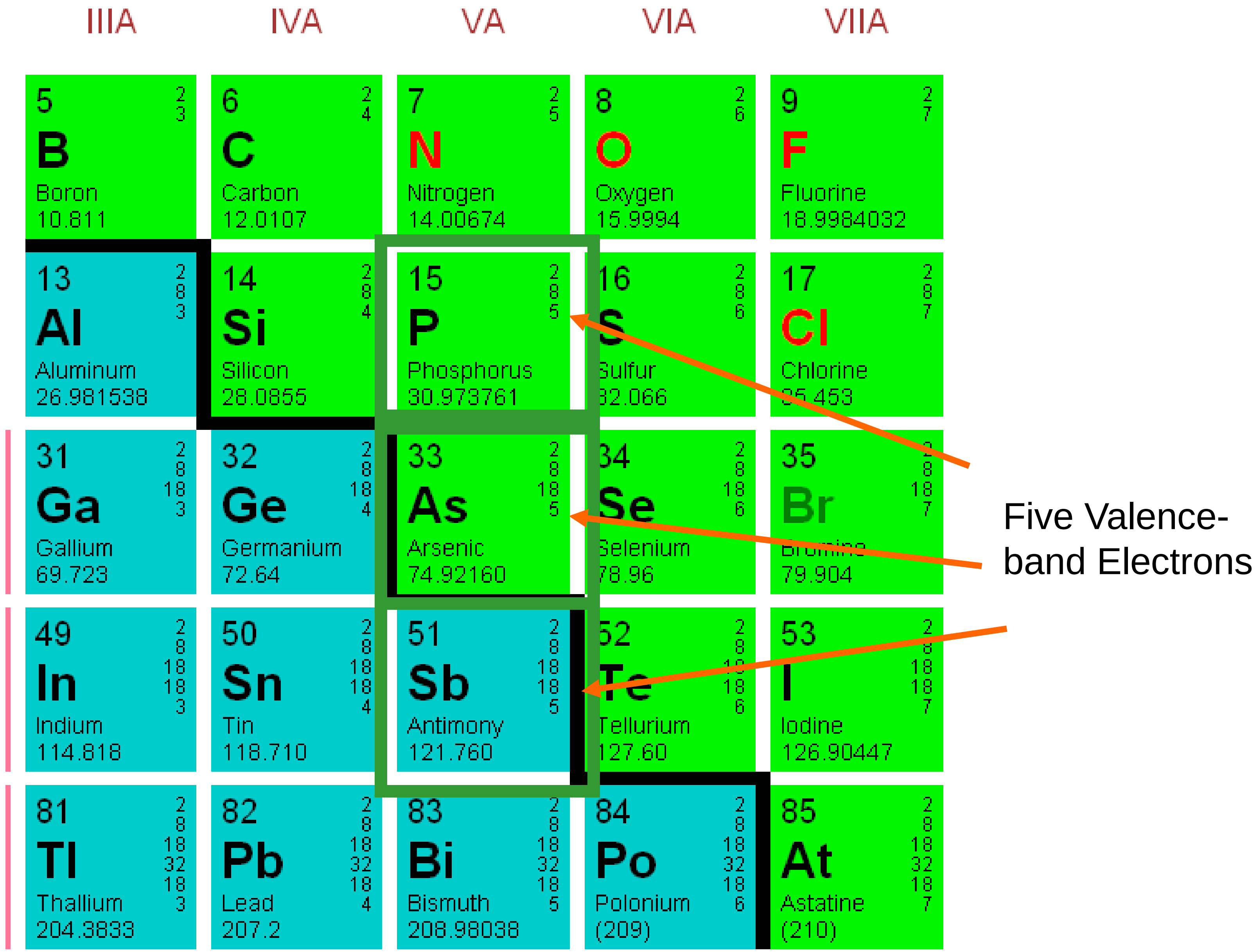
Serves as an "acceptor" of electrons

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

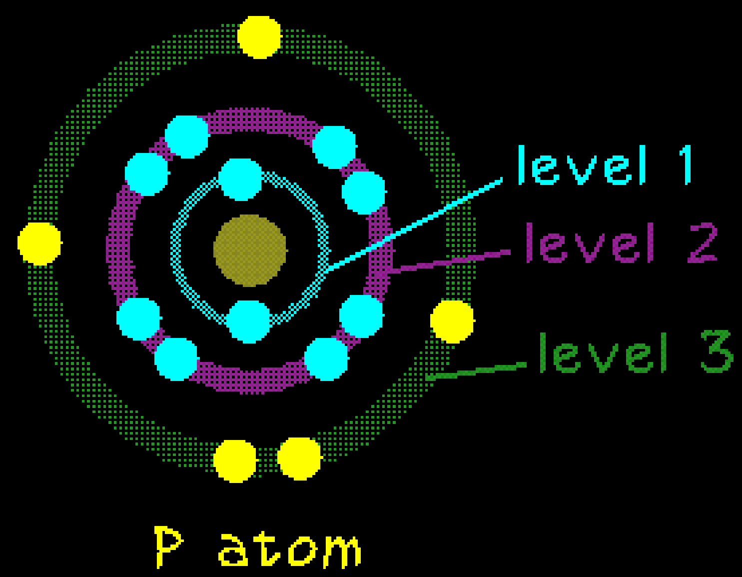


Serves as an “donor ” of electrons

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

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

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

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

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

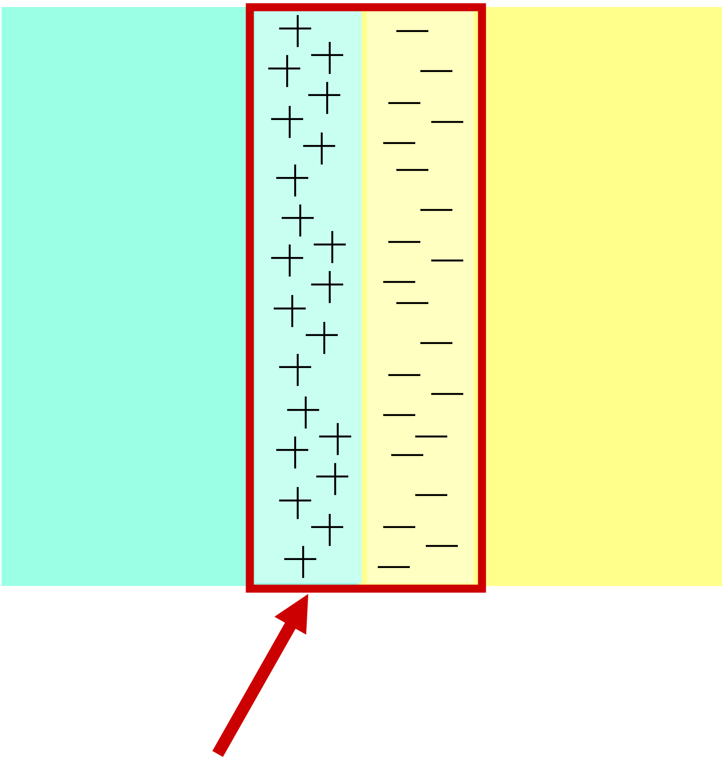
Silicon Dopants in Semiconductor Processes

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

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

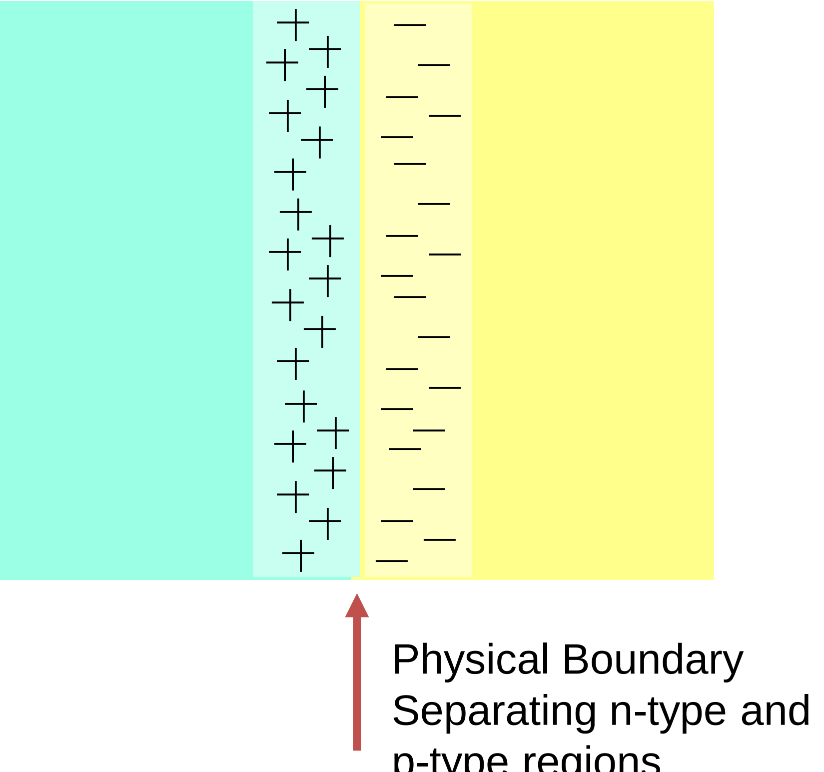
As (Arsenic) widely used a dopant for creating n-type regions
(Active region doping, diffuses slower)

Diodes (pn junctions)



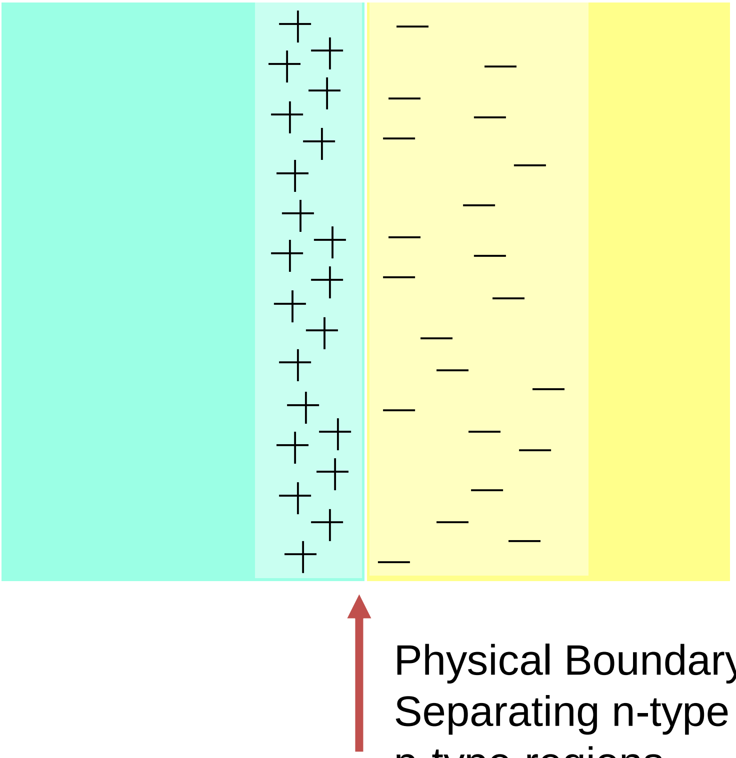
Depletion region created that is ionized but void of carriers

pn Junctions



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

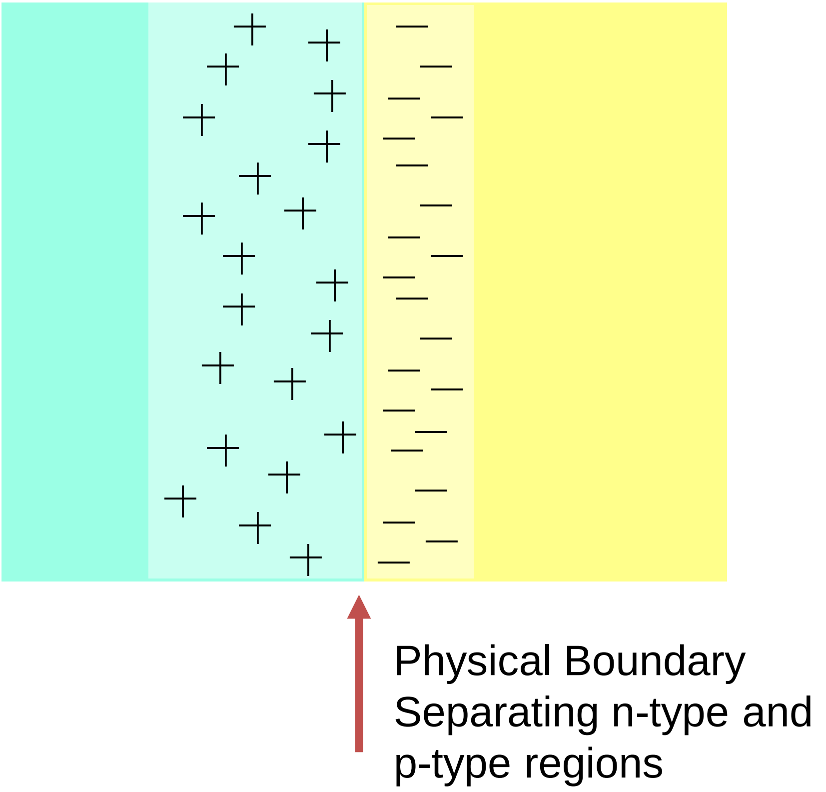
pn Junctions



Physical Boundary Separating n-type and p-type regions

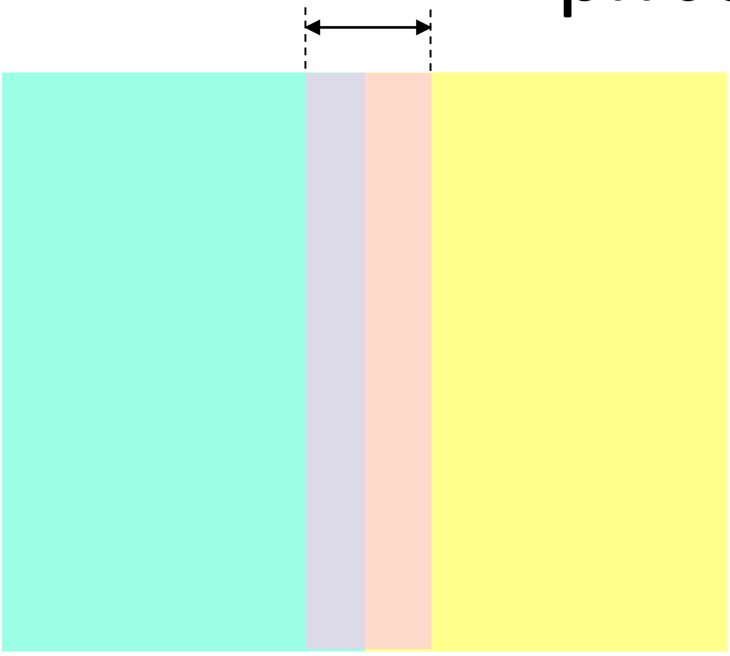
Extends farther into p-type region if p-doping lower than n-doping

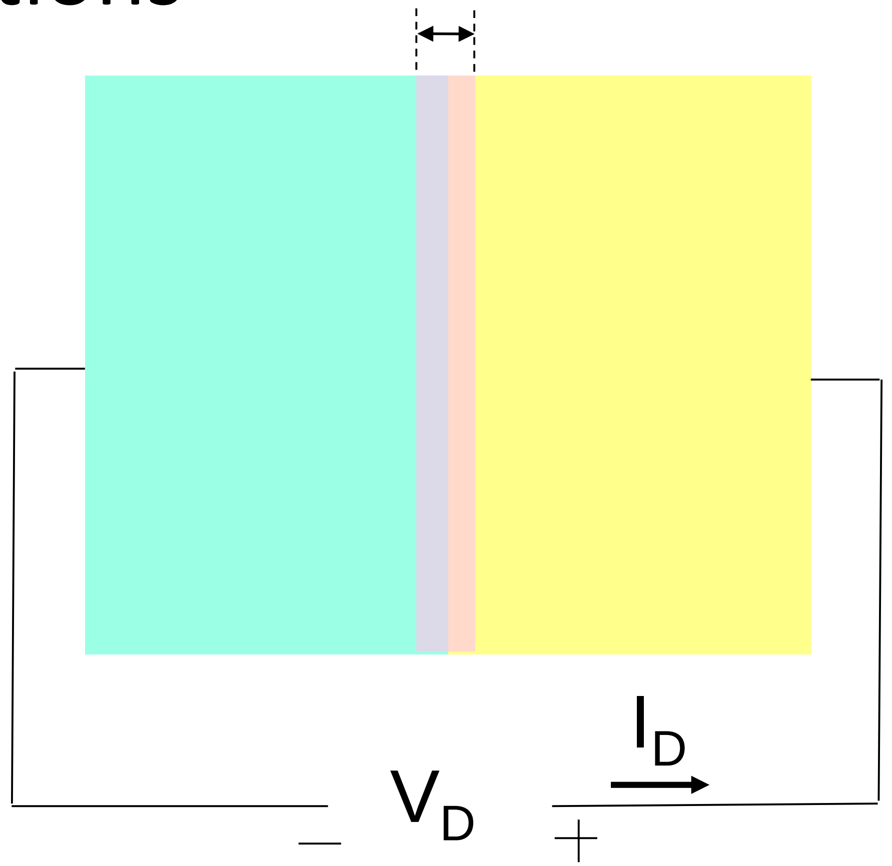
pn Junctions



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

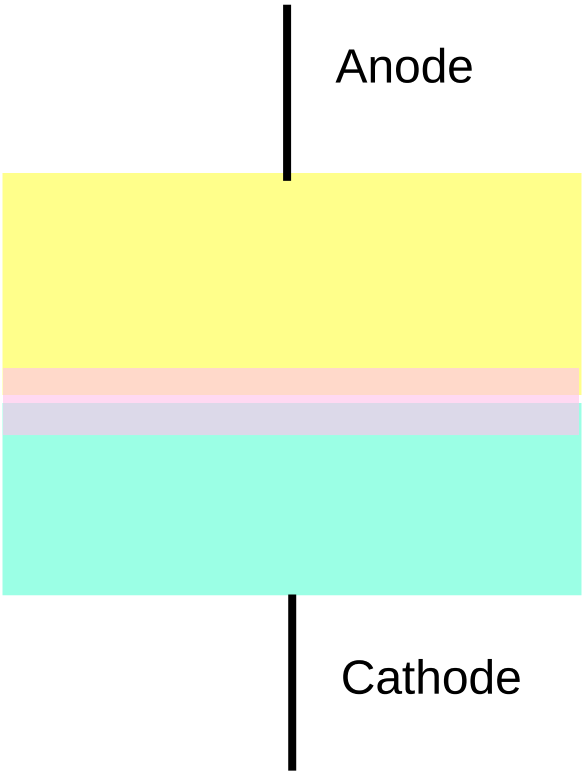
pn Junctions

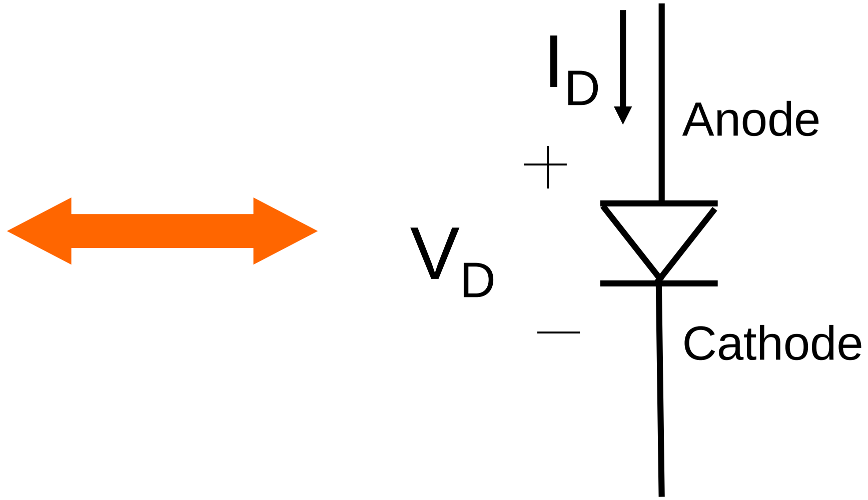




- Positive voltages across the p to n junction are referred to forward bias
- Negative voltages across the p to n junction are referred to reverse bias
- As forward bias increases, depletion region thins and current starts to flow
- Current grows <u>very rapidly</u> as forward bias increases
- Current is very small under revere bias

pn Junctions

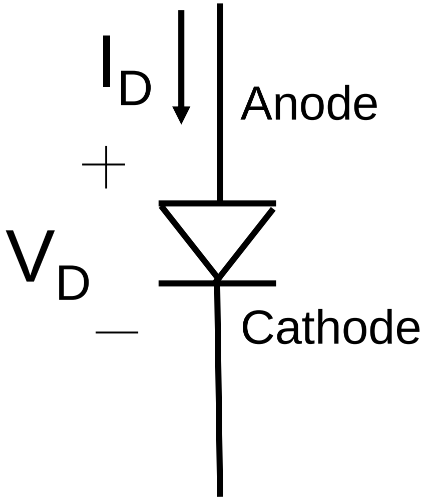




Circuit Symbol

pn Junctions

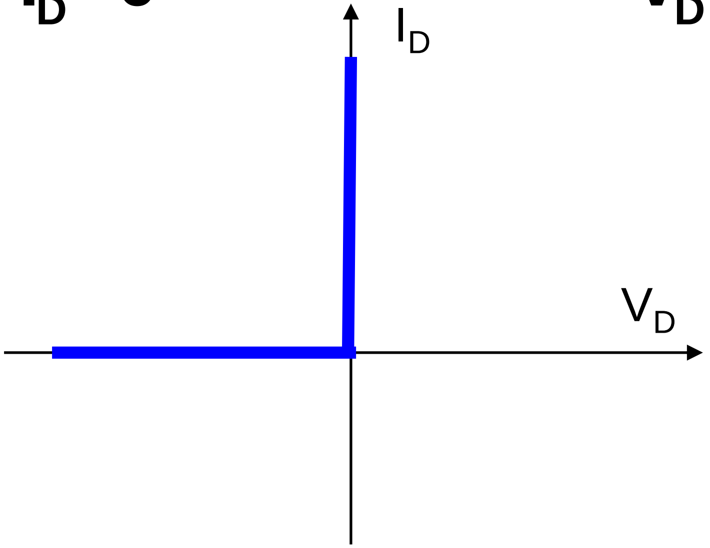
- As forward bias increases, depletion region thins and current starts to flow
- Current grows very rapidly as forward bias increases



Simple Diode Model:

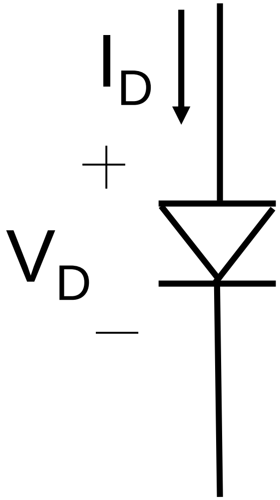
$V_D = 0$ **$I_D > 0$**

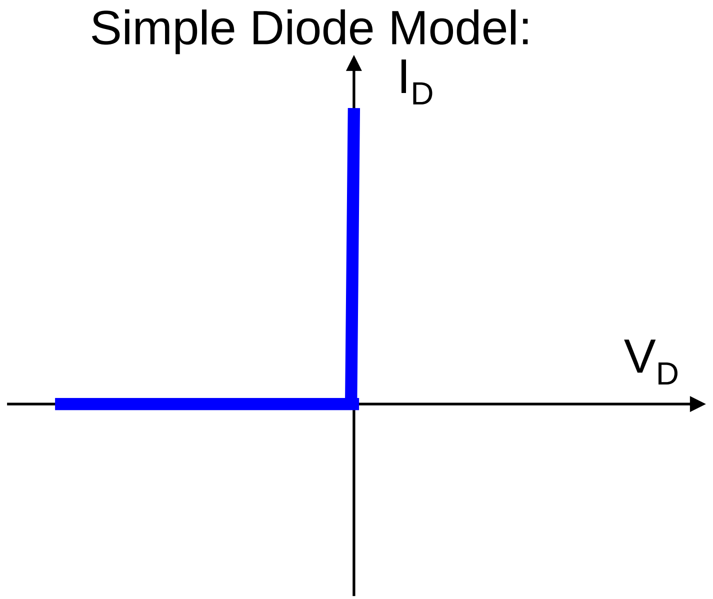
$I_D = 0$ **$V_D < 0$**



Simple model often referred to as the “Ideal” diode model

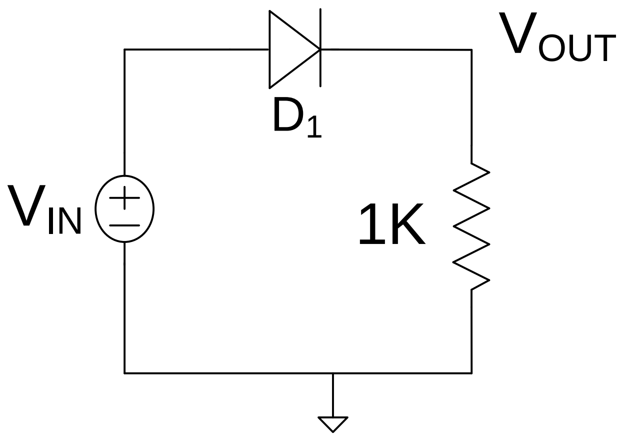
pn Junctions



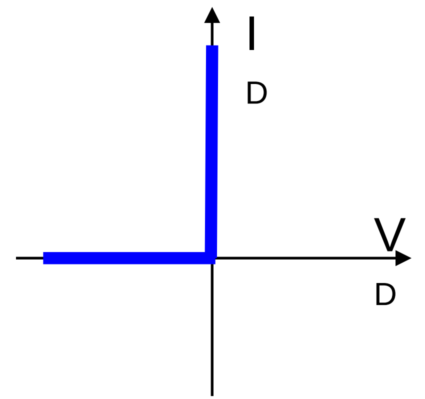


pn junction serves as a "rectifier" passing current in one direction and blocking it in the other direction

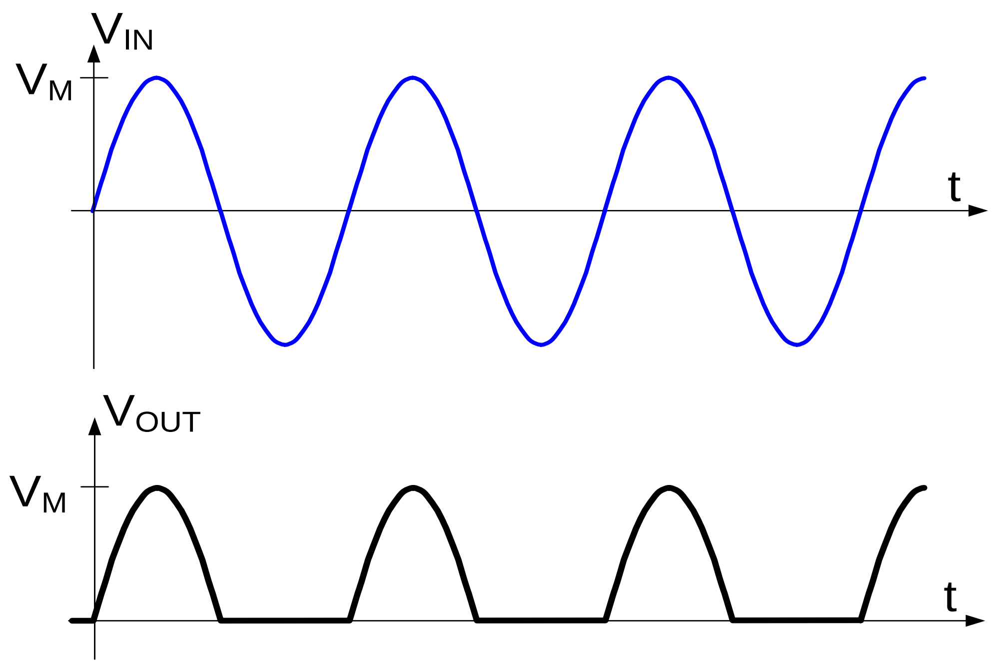
Rectifier Application:



Simple Diode Model:



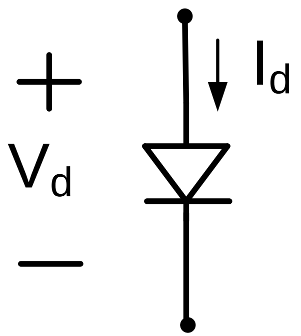
$V_{IN}=V_M \sin\omega t$



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}

Diode Equation

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

What is V_t at room temp?

V_t is about 26mV at room temp

Diode equation due to William Shockley, inventor of BJT

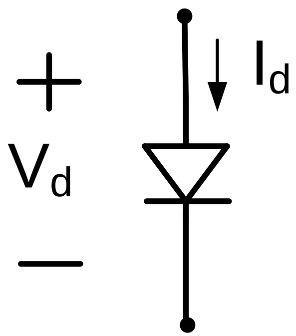
In 1919, William Henry Eccles coined the term ***diode***

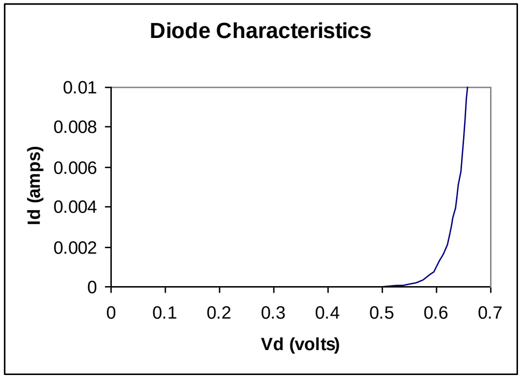
In 1940, Russell Ohl “stumbled upon” the p-n junction diode

I-V characteristics of pn junction

(signal or rectifier diode)

Improved Diode Model:





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

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

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

$k = 1.380\,6504(24) \times 10^{-23} JK^{-1}$

$q = -1.602176487(40)\times 10^{-19}$ C

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

Simplification of Diode Equation:

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

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

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 is unwieldy to work with analytically

I-V characteristics of pn junction

(signal or rectifier diode)

Improved Diode Model:

Diode Equation

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

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:

Under reverse bias, $I_D \cong -I_S$

Under forward bias, $I_D = I_S e^{\frac{V_d}{V_t}}$

How much error is introduced using the simplification for V_d > 0.5V?

$$\varepsilon = \frac{I_S\left(e^{\frac{V_d}{V_t}} - 1\right) - I_S e^{\frac{V_d}{V_t}}}{I_S\left(e^{\frac{V_d}{V_t}} - 1\right)} \qquad \varepsilon < \frac{1}{e^{\frac{0.5}{.026}}} = 4.4 \bullet 10^{-9}$$

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

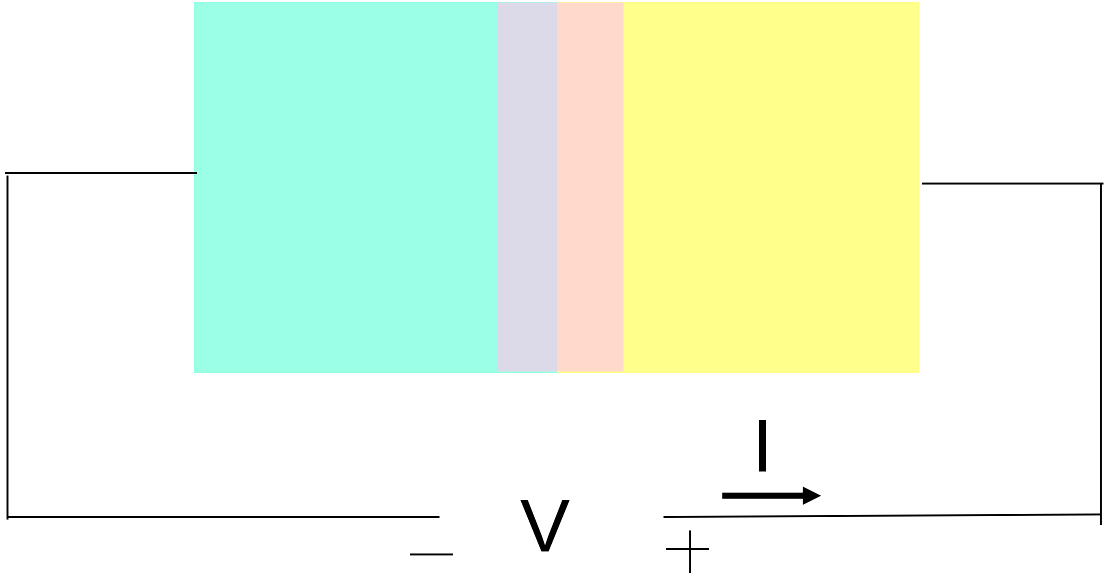
$$\varepsilon < e^{\frac{-0.5}{.026}} = 4.4 \bullet 10^{-9}$$

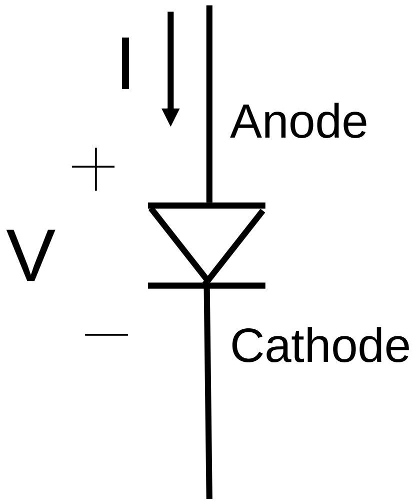
Simplification almost never introduces any significant error

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





Diode Equation:
(good enough for most applications)

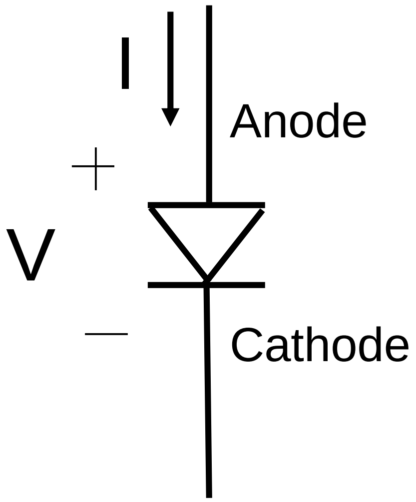
$$I = \begin{cases} J_S A e^{\frac{V}{nV_T}} & V > 0 \\ 0 & V < 0 \end{cases}$$

Note: $I_S = J_s A$

J_S= Sat Current Density (in the 1aA/u² to 1fA/u² range)
A= Junction Cross Section Area
V_T=kT/q (k/q=1.381×10^{-23}V•C/°K/1.6×10^{-19}C=8.62×10^{-5}V/°K)
n is approximately 1

pn Junctions

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



J_S is strongly temperature dependent

With n=1, for V>0,

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

Typical values for key parameters: J_{SX}=0.5A/μ^2, V_{G0}=1.17V, m=2.3

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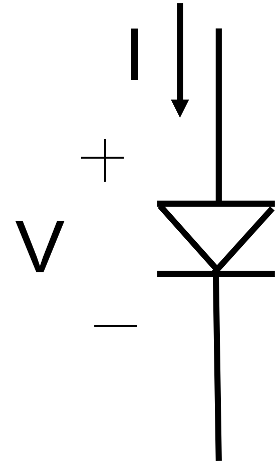
Example:

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



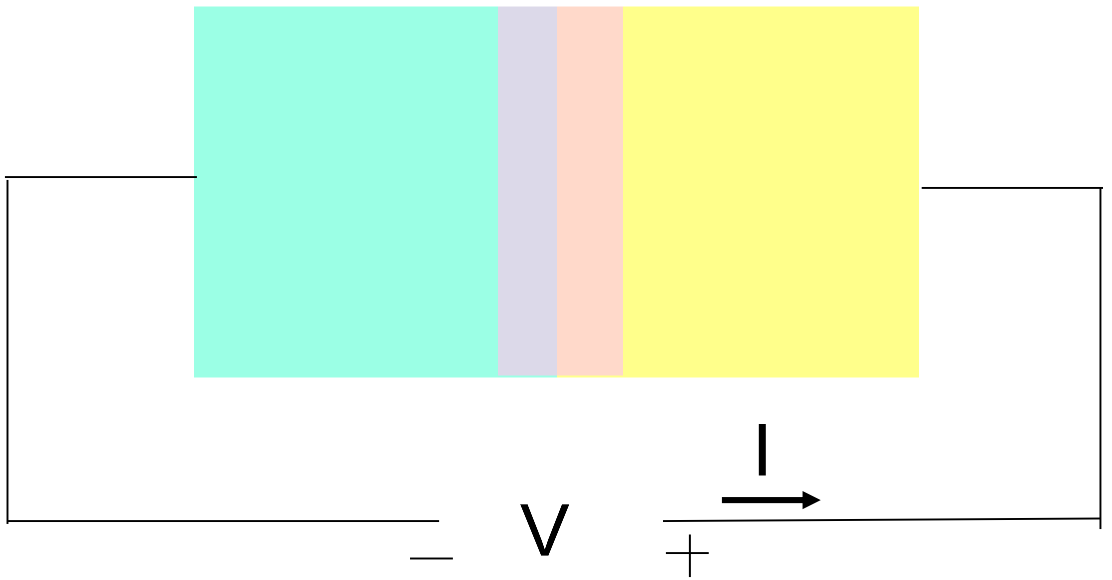
What percent change in I_S will occur for a 1°C change in temperature at room temperature?

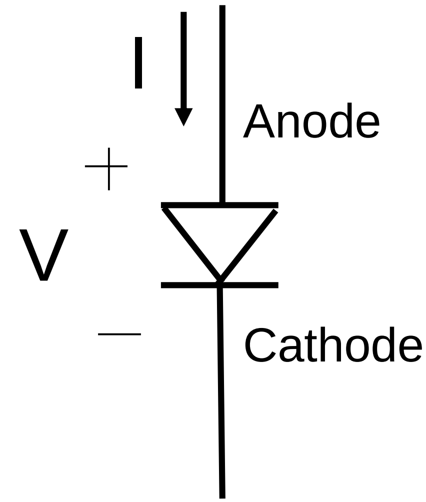
$$\frac{\Delta I_S}{I_S} = \frac{\left(J_{SX} \left[T_{T_@}^m e^{\frac{-V_{G0}}{V_t(T_2)}} \right] \right) A e^{\frac{V_D}{V_t}} - \left(J_{SX} \left[T_{T_1}^m e^{\frac{-V_{G0}}{V_t(T_1)}} \right] \right) A e^{\frac{-V_{G0}}{V_t(T_2)}}}{\left(J_{SX} \left[T_{T_1}^m e^{\frac{-V_{G0}}{V_t(T_1)}} \right]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

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

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

pn Junctions



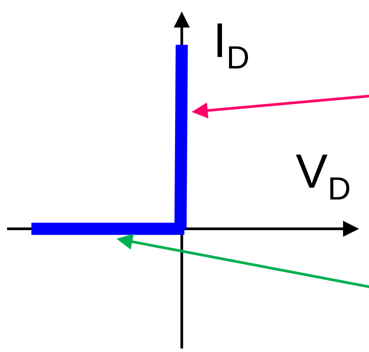


Diode Equation:
(good enough for most applications)

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

$I_S = J_s A$

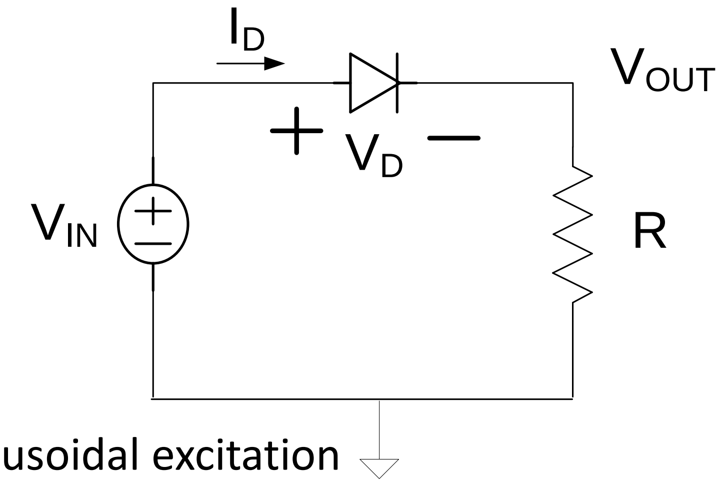
Simple Diode Model:



Often termed the "conducting" or "ON" state

Often termed the "nonconducting" or "OFF" state

Consider again the basic rectifier circuit



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

$$V_{OUT} = ?$$

Analysis of Nonlinear Circuits

(Circuits with one or more nonlinear devices)

What analysis tools or methods can be used?

KCL ?

KVL?

~~Superposition?~~

~~Voltage Divider ?~~

~~Current Divider?~~

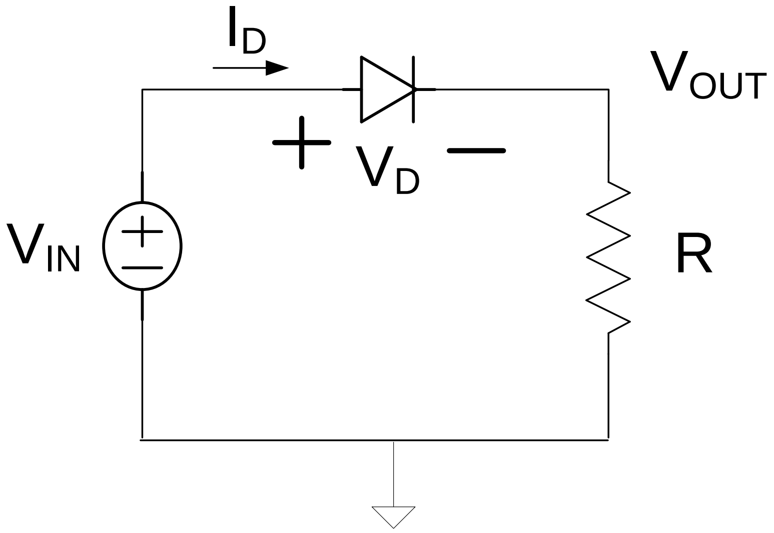
~~Thevenin and Norton Equivalent Circuits?~~

Nodal Analysis ?

Mesh Analysis ?

Two-Port Subcircuits ?

Consider again the basic rectifier circuit



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

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

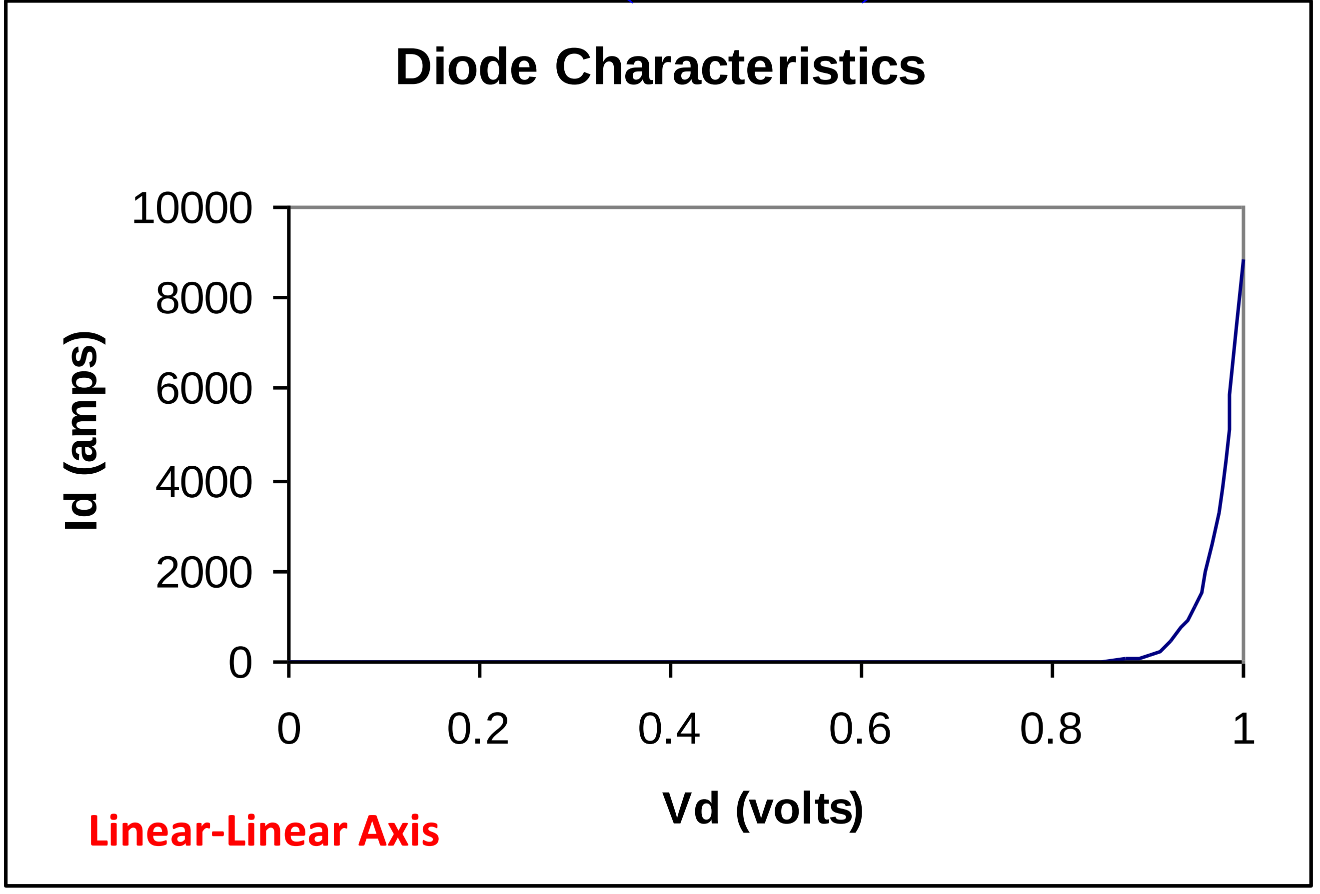
Even the simplest diode circuit does not have a closed-form solution when diode equation is used to model the diode !!

Due to the nonlinear nature of the diode equation

Simplifications are essential if analytical results are to be obtained

Lets study the diode equation a little further

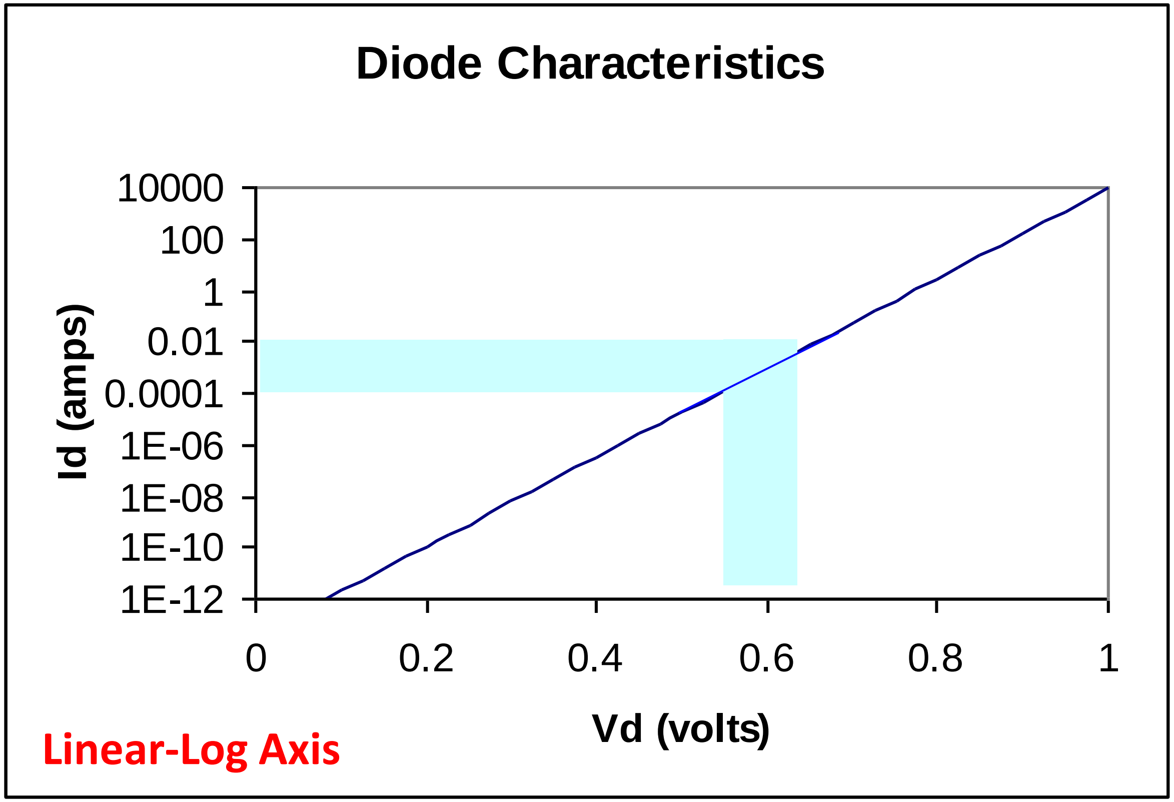
$$I_d = I_S\left(e^{\frac{V_d}{V_t}} - 1\right)$$



Power Dissipation Becomes Destructive if Vd > 0.85V (actually less)

Lets study the diode equation a little further

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

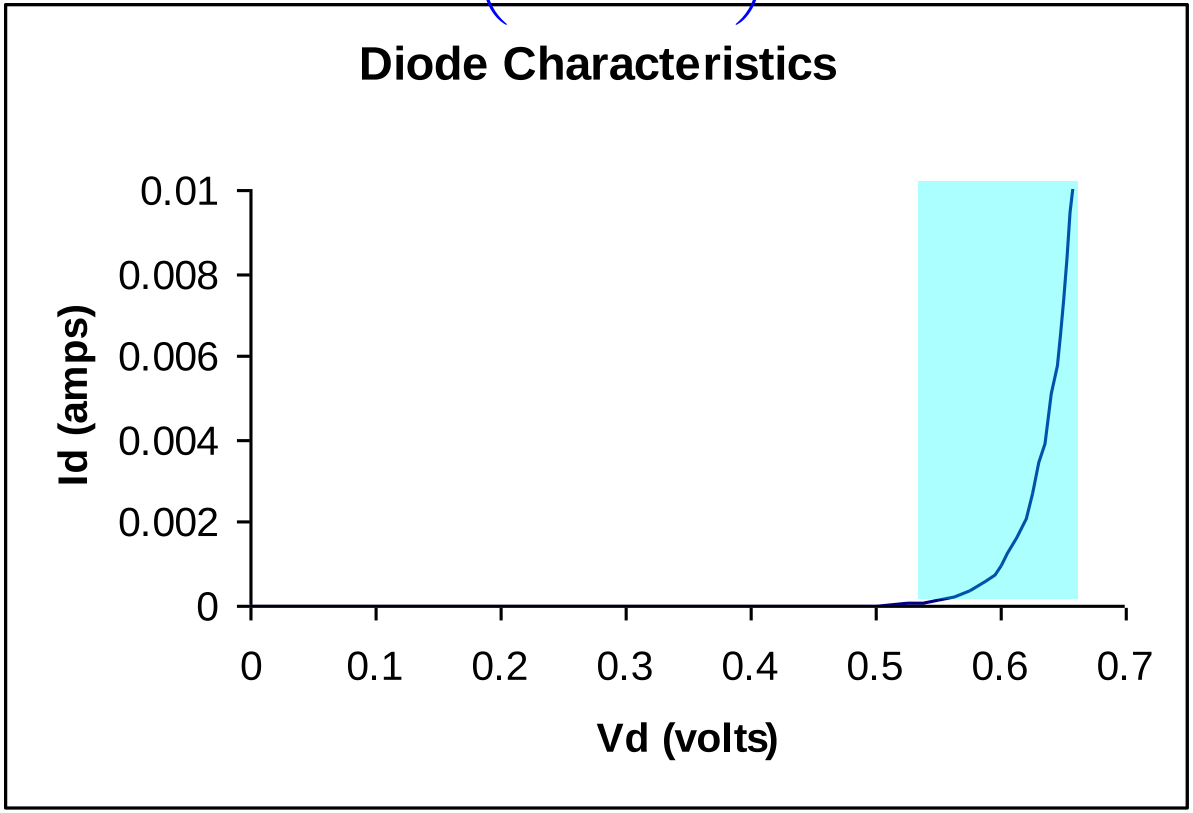


For two decades of current change, Vd is close to 0.6V

This is the most useful conducting current range for many applications

Lets study the diode equation a little further

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



For two decades of current change, Vd is close to 0.6V

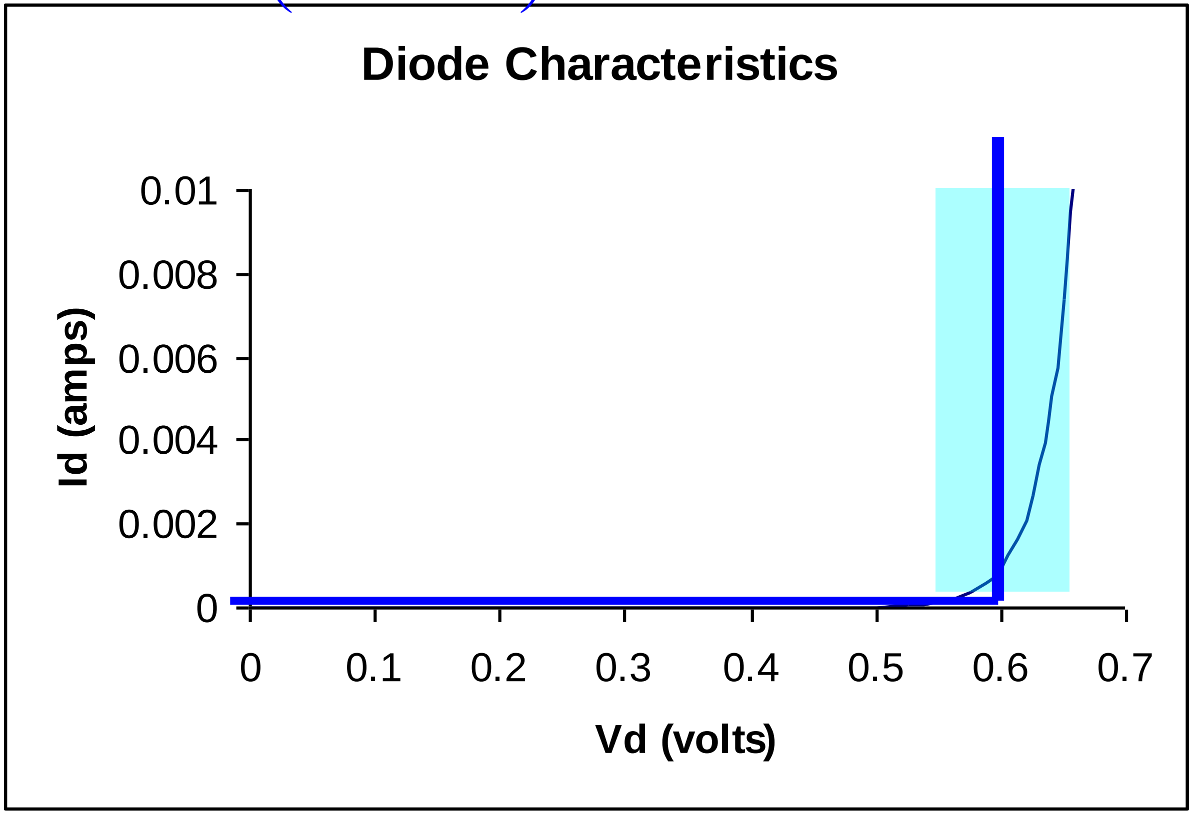
This is the most useful current range when conducting for many applications

Lets study the diode equation a little further

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

$I_d = 0 \qquad V_d < 0.6V$

$V_d = 0.6V \qquad I_d > 0$



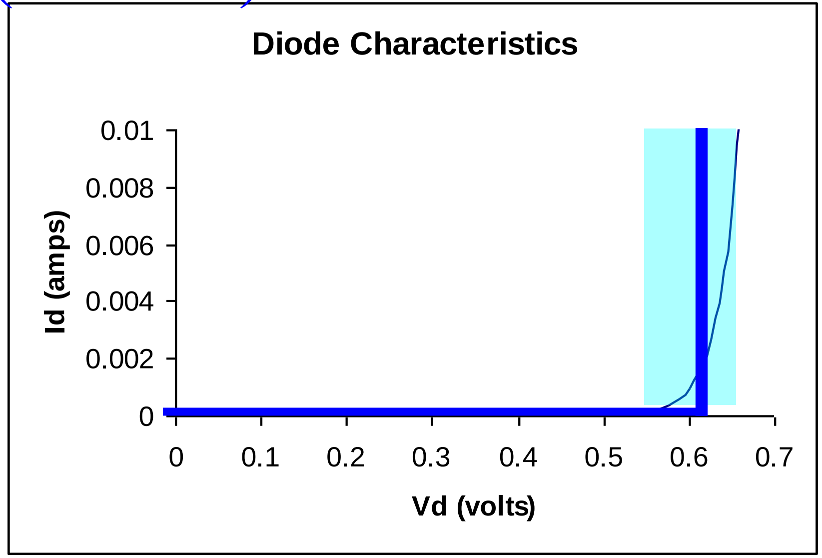
Widely Used **<u>Piecewise Linear</u>** Model

Lets study the diode equation a little further

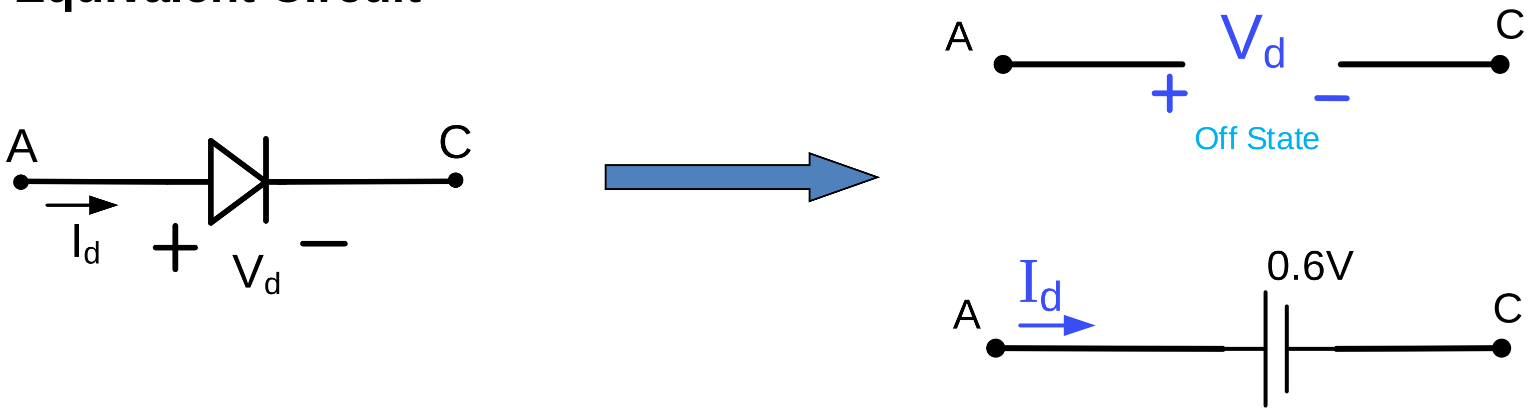
$$I_d = I_S\left(e^{\frac{V_d}{V_t}} - 1\right)$$

$$I_d = 0 \qquad V_d < 0.6V$$

$$V_d = 0.6V \qquad I_d > 0$$

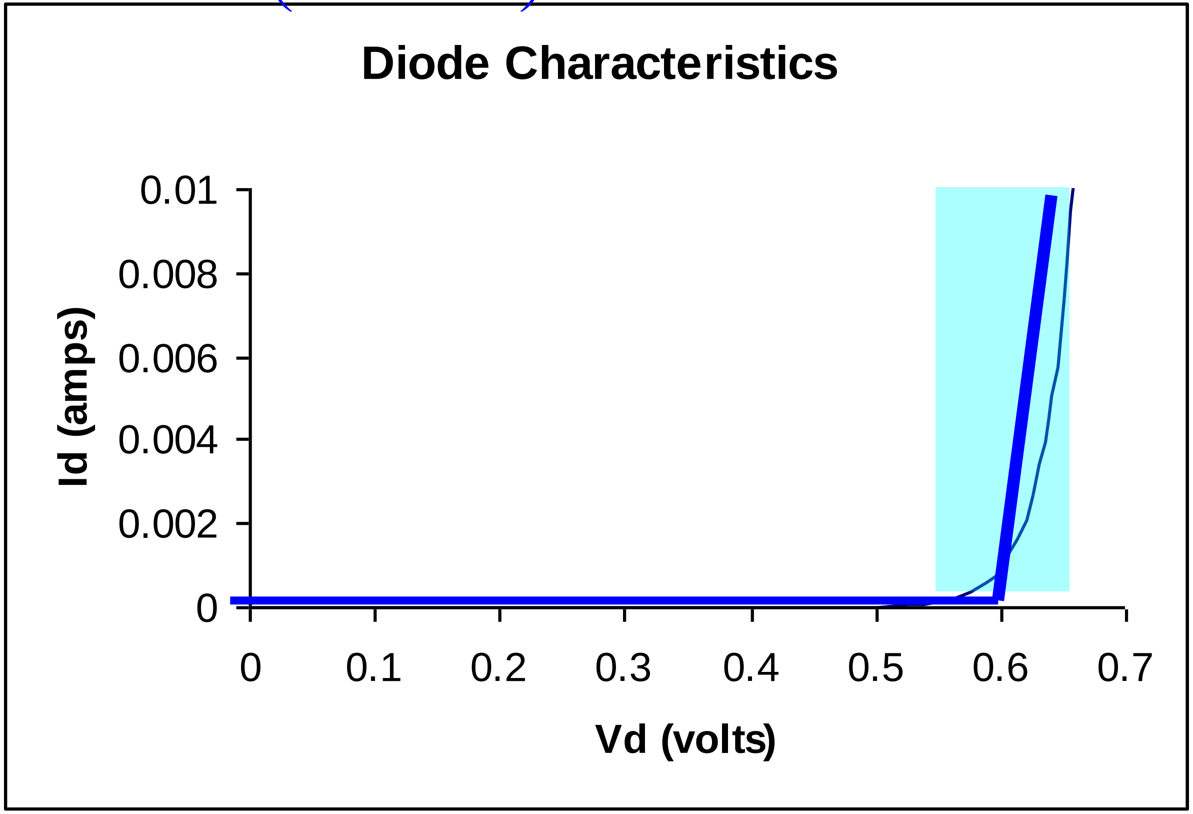


Equivalent Circuit



Lets study the diode equation a little further

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



Better model in “ON” state though often not needed

Includes Diode “ON” resistance

Lets study the diode equation a little further

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

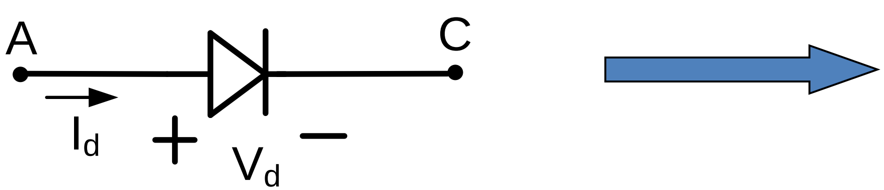
Piecewise Linear Model with Diode Resistance

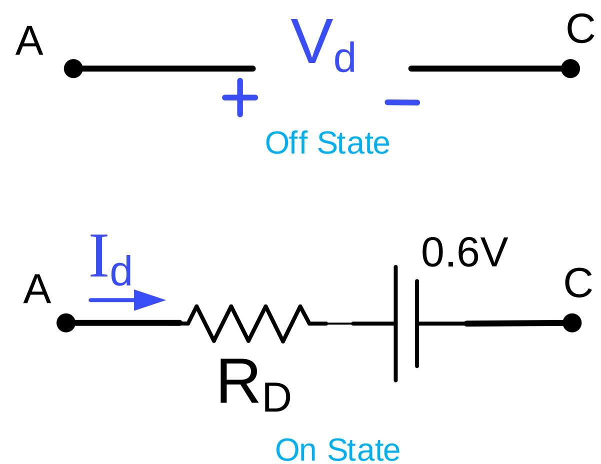
$$I_d = 0 \qquad \text{if } V_d < 0.6V$$

$$V_d = 0.6V + I_d R_D \qquad \text{if } I_d > 0$$

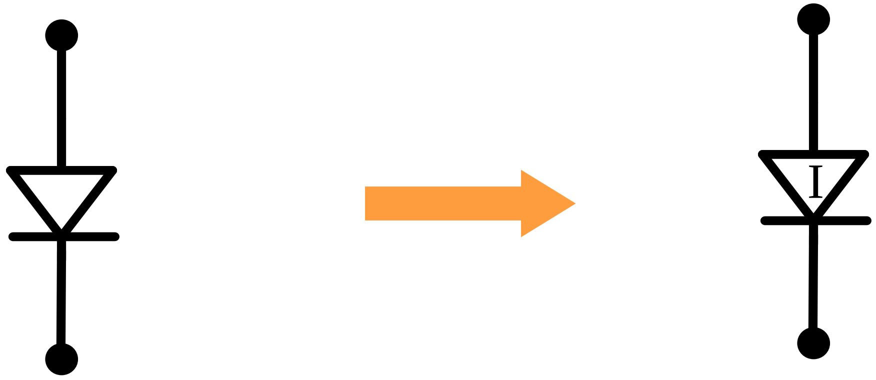
(R_D is rather small: often in the 20Ω to 100Ω range):

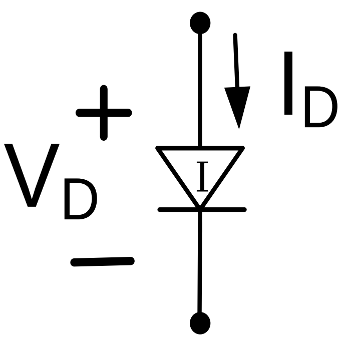
Equivalent Circuit

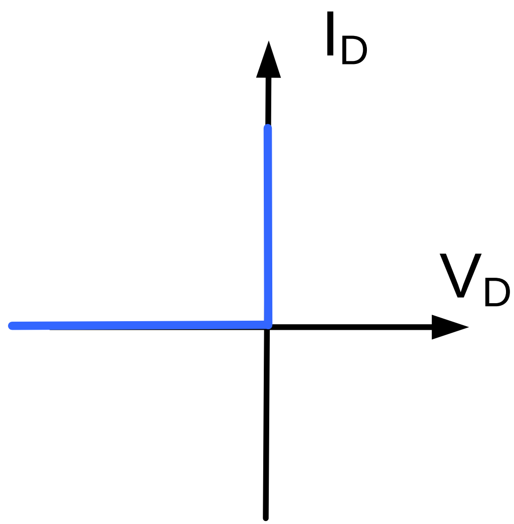




The Ideal Diode



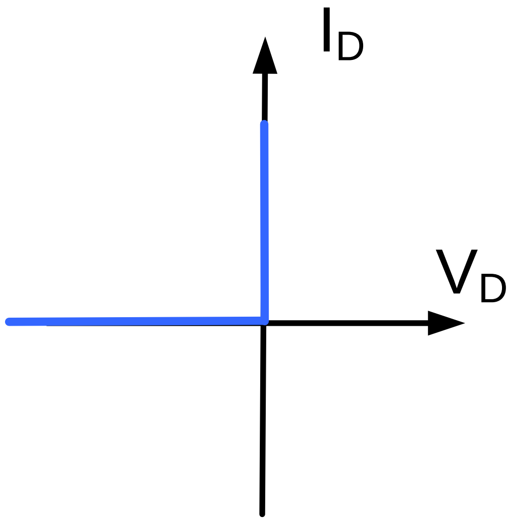




$I_D = 0 \quad \text{if} \quad V_D \le 0$

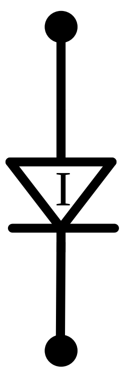
$V_D = 0 \quad \text{if} \quad I_D > 0$

The Ideal Diode

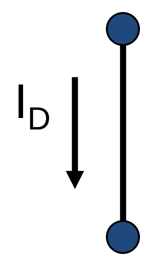


$I_D = 0$ if $V_D \leq 0$ “OFF”

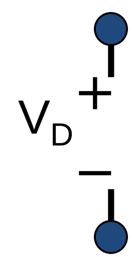
$V_D = 0$ if $I_D > 0$ “ON”



“ON”

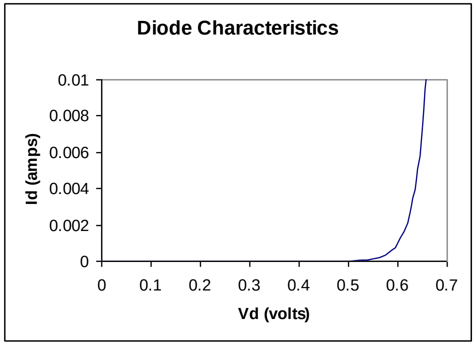


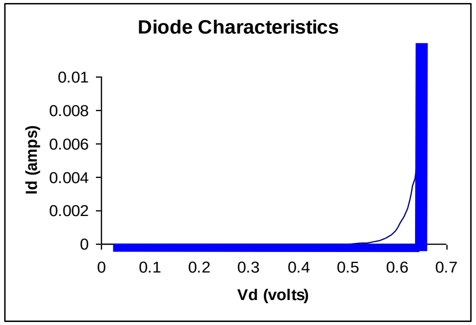
“OFF”

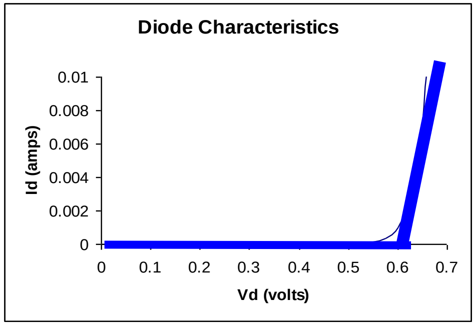


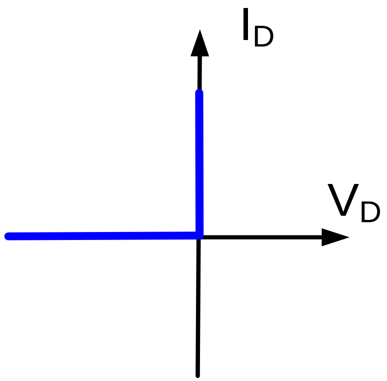
Valid for $I_D > 0$ $V_D \leq 0$

Diode Models









Which model should be used?

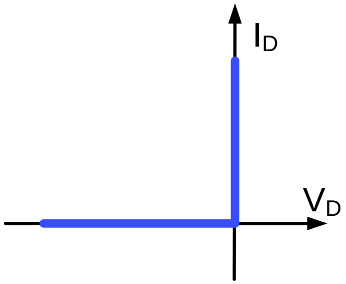
The simplest model that will give acceptable results in the analysis of a circuit

Diode Model Summary

Piecewise Linear Models

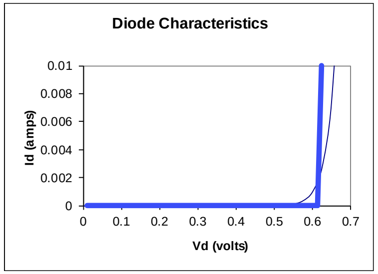
$I_d = 0$ if $V_d < 0$

$V_d = 0$ if $I_d > 0$



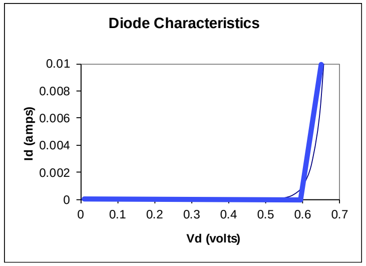
$I_d = 0$ if $V_d < 0.6V$

$V_d = 0.6V$ if $I_d > 0$



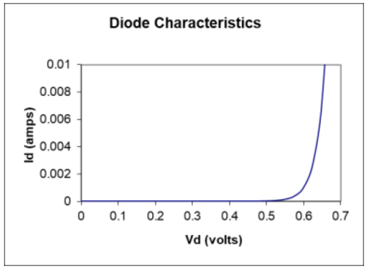
$I_d = 0$ if $V_d < 0.6$

$V_d = 0.6 + I_d R_d$ if $I_d > 0$



Diode Equation

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



Diode Model Summary

Piecewise Linear Models

$I_d = 0$ if $V_d < 0$

$V_d = 0$ if $I_d > 0$

$I_d = 0$ if $V_d < 0.6V$

$V_d = 0.6V$ if $I_d > 0$

$I_d = 0$ if $V_d < 0.6$

$V_d = 0.6 + I_d R_d$ if $I_d > 0$

Diode Equation

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

When is the ideal model adequate?

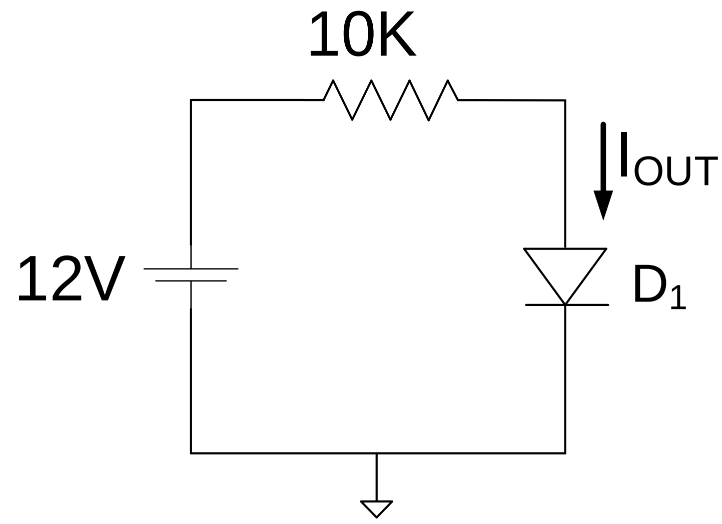
When it doesn't make much difference whether V_d=0V or V_d=0.6V

When is the second piecewise-linear model adequate?

When it doesn't make much difference whether V_d=0.6V or V_d=0.7V

Example:

Determine I_{OUT} for the following circuit



Solution:

Strategy:

1. Assume PWL model with V_D=0.6V, R_D=0
2. Guess state of diode (ON)
3. Analyze circuit with model
4. Validate state of guess in step 2 (verify the "if" condition in model)

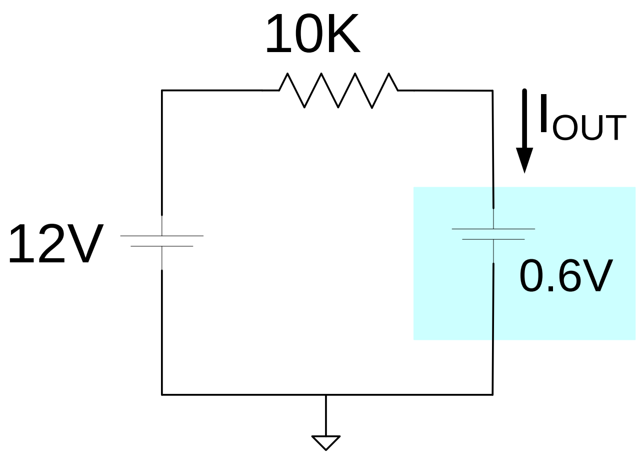
Select Model

5. Assume PWL with V_D=0.7V
6. Guess state of diode (ON)
7. Analyze circuit with model
8. Validate state of guess in step 6 (verify the "if" condition in model)
9. Show difference between results using these two models is small
10. If difference is not small, must use a different model

Validate Model

Solution:

1. Assume PWL model with V_D=0.6V, R_D=0
2. Guess state of diode (ON)



3. Analyze circuit with model

$$I_{OUT} = \frac{12V-0.6V}{10K} = 1.14mA$$

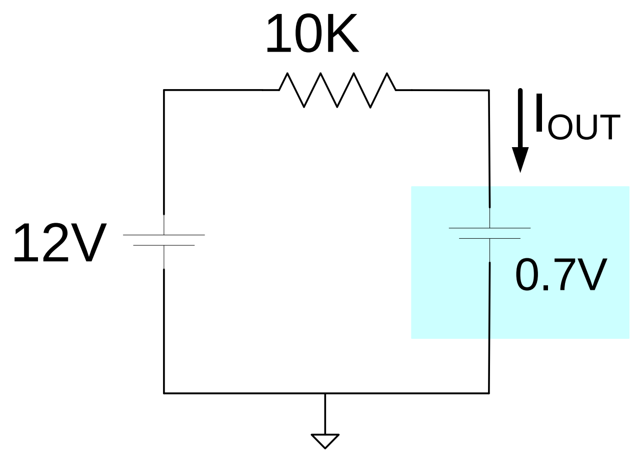
4. Validate state of guess in step 2

To validate state, must show I_D>0

$$I_D = I_{OUT} = 1.14mA > 0$$

Solution:

5. Assume PWL model with V_D=0.7V, R_D=0
6. Guess state of diode (ON)



7. Analyze circuit with model

$$I_{OUT} = \frac{12V-0.7V}{10K} = 1.13mA$$

8. Validate state of guess in step 6

To validate state, must show I_D>0

$$I_D = I_{OUT} = 1.13mA > 0$$

Solution:

9. Show difference between results using these two models is small

I_{OUT} =1.14mA and I_{OUT} =1.13 mA are close

Thus, can conclude $\boxed{I_{OUT} \cong 1.14\text{mA}}$

End of Lecture 13