Review

- What we have covered.
  - Circuits Devices Review
    - Characterizing a device i-v equation & plot.
    - Solving circuits and transfer functions.
  - The Ideal Diode
    - A new “non-linear” device.
    - Characteristics, i-v eq. & plot, models (short or open).
    - Solving circuits and transfer functions.

Forward

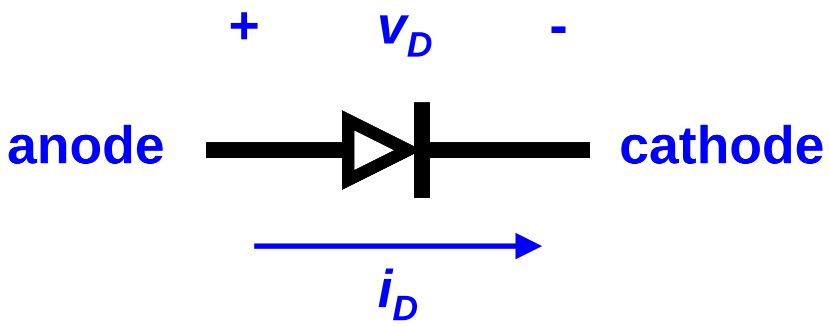
- What we will cover.
  - Application of diodes.
    - Simple digital logic (and-gates, or-gates).
  - The Junction Diode.
    - Characteristics, i-v equation and plots.
    - Solving circuits.
    - Modeling the Junction Diode.
    - Applications: Voltage Regulator.

The Junction Diode

Junction Diodes:

- An implementation of a diode using semiconductor tech.

A) The Junction Diode Symbol



- Similar to the ideal diode.

Why is it called the junction diode?

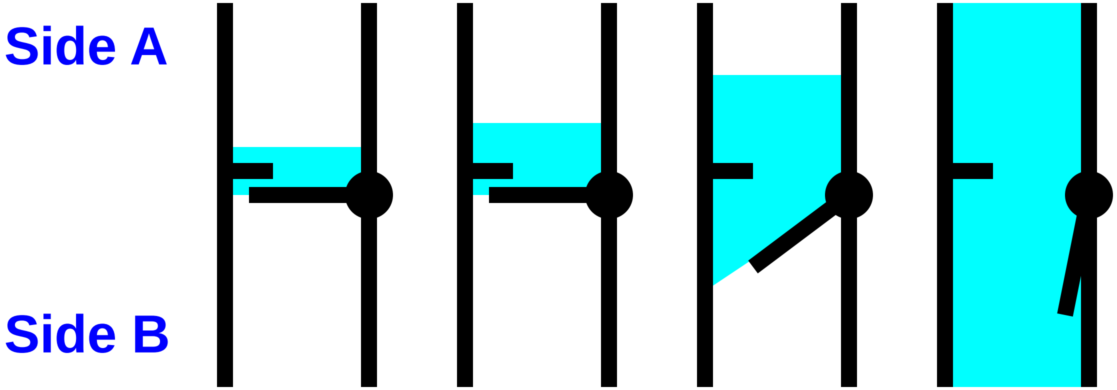
- It is made by joining two different materials.

How is the Junction Diode different than the Ideal Diode?

- Look at the i-v characteristic.
- Relate to our mechanical valve.

The Junction Diode

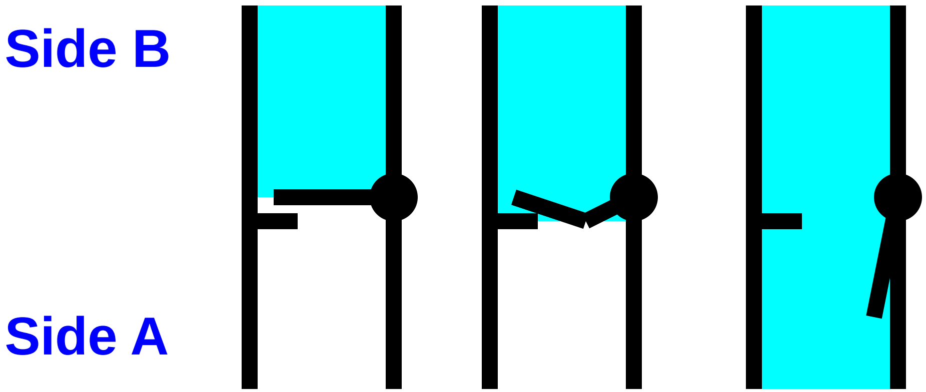
- A real valve will not open unless there is a certain amount of pressure.



- This is not **IDEAL**.
- It finally opens with a significantly positive pressure.
- This transition is not instantaneous.

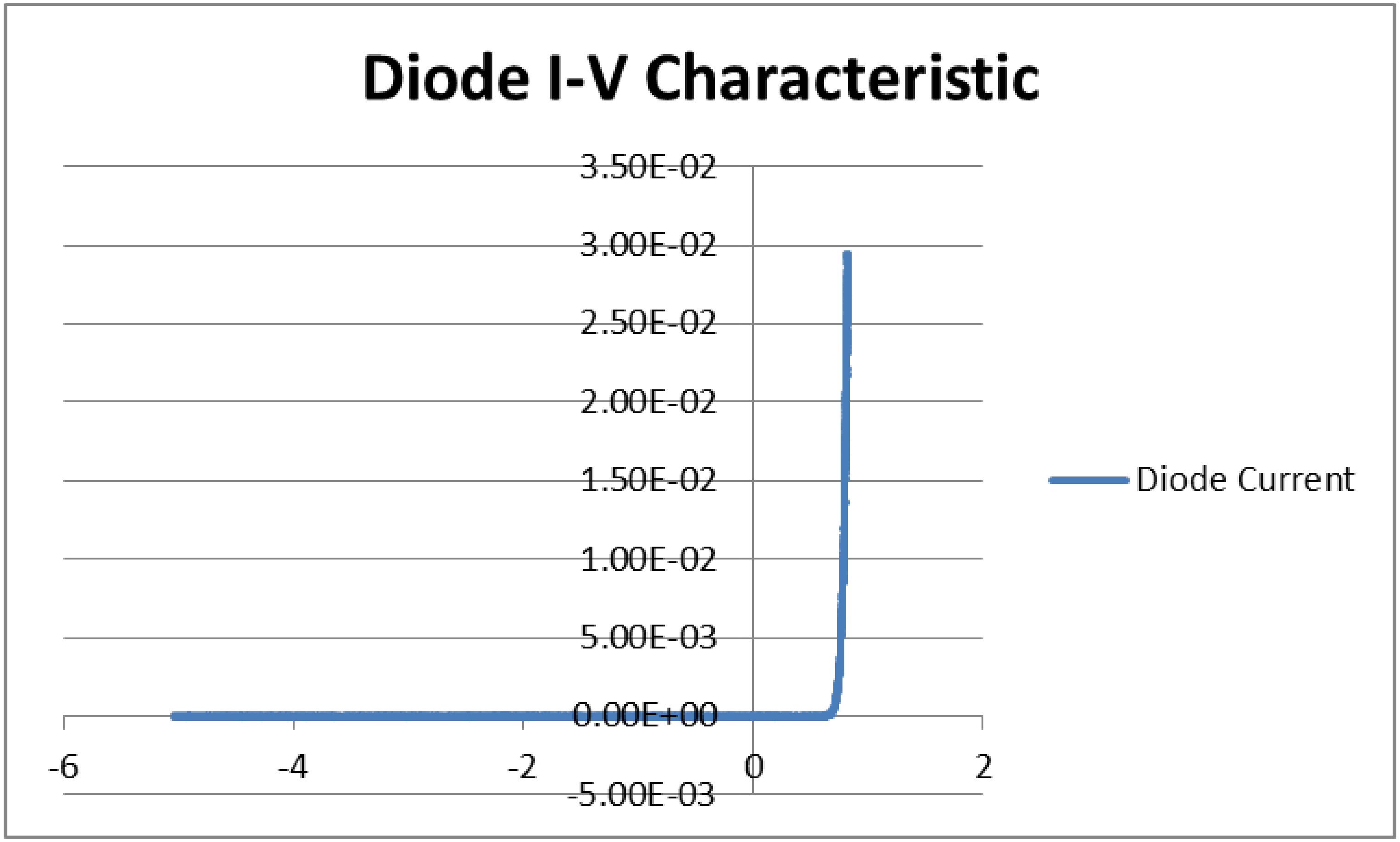
The Junction Diode

- A real valve will fail if there is too much pressure in the reverse direction.



- This is not **IDEAL**.
- This transition is “almost” instantaneous … at least compared to the previous slide.
- Is this behavior useful???

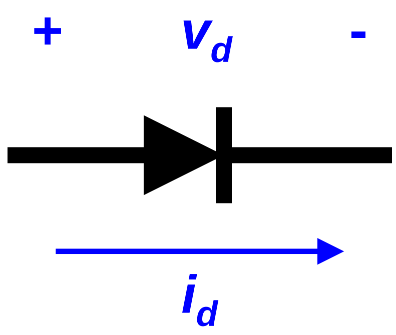
The Junction Diode

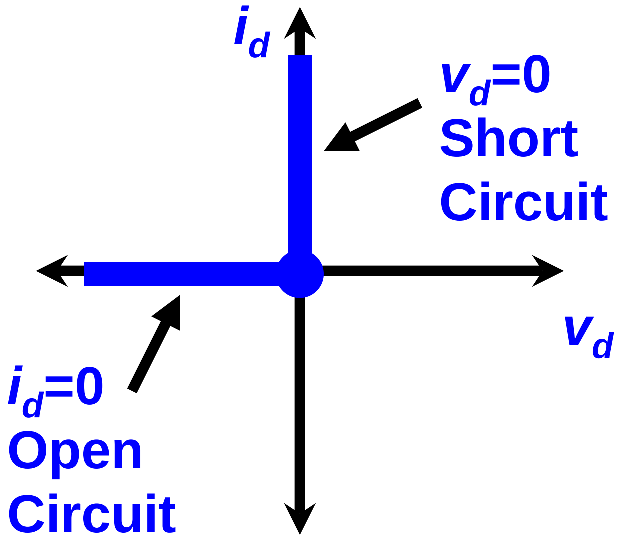


The Junction Diode

B) The Junction Diode *i-v* Relationship

- First let's review the Ideal Diode curve.





- What did we learn from the previous i-v plot and real valve?

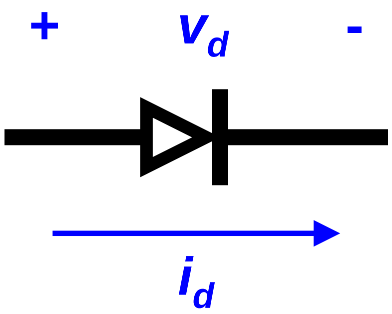
    a) The diode does not start conducting at v=0.

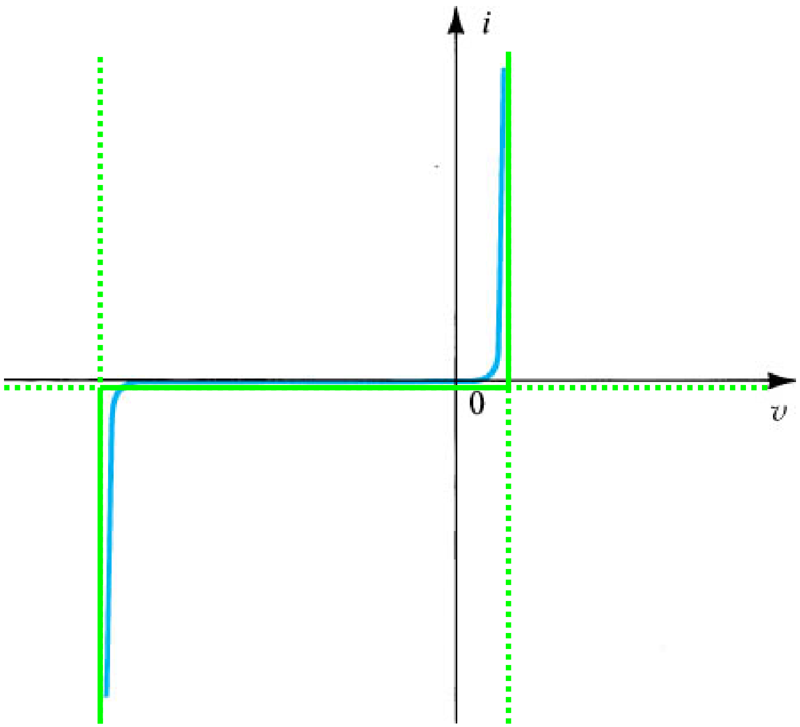
    b) The diode will eventually break down in the reverse bias region.

    c) The transitions are not instantaneous.

The Junction Diode

B) The Junction Diode *i-v* Relationship





- There are 3 distinct regions of operation.
  (Ideal diode only had 2)

- Transitions are smooth.
  (Ideal diode changes are instantaneous)

- Boundaries are ambiguous.
  (The curve has "knees")

We know that the curve v=0 is a short, but, what does v=C represent?

The Junction Diode

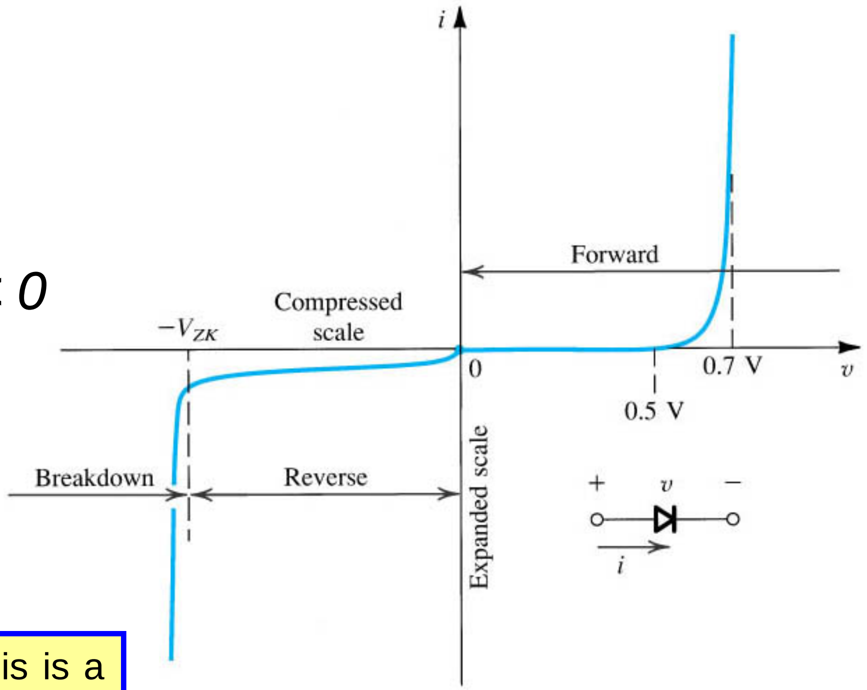
B) The Junction Diode *i-v* Relationship

- In comparison to the real diode, the junction diode has three regions of operation:

1) Forward Bias: $v_d > 0$
This is related to the ideal diode acting as a short.

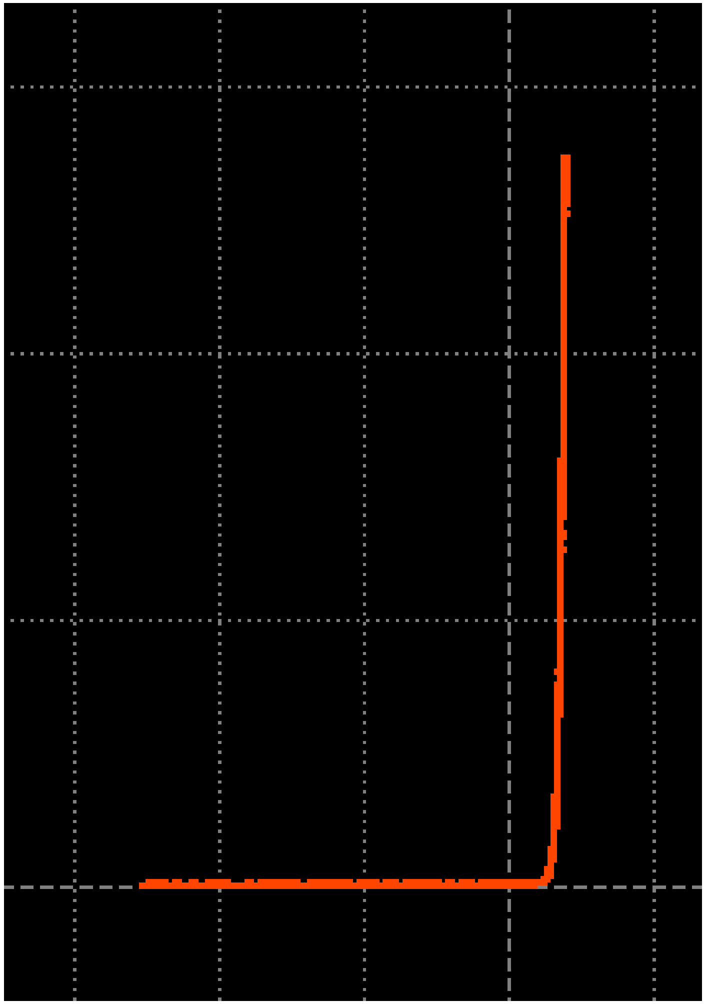
2) Reverse Bias: $-V_{ZK} < vd < 0$
This is related to the ideal diode acting as an open.

3) Breakdown: $v_d < -V_{ZK}$
This is a new mode not apparent in the ideal diode.

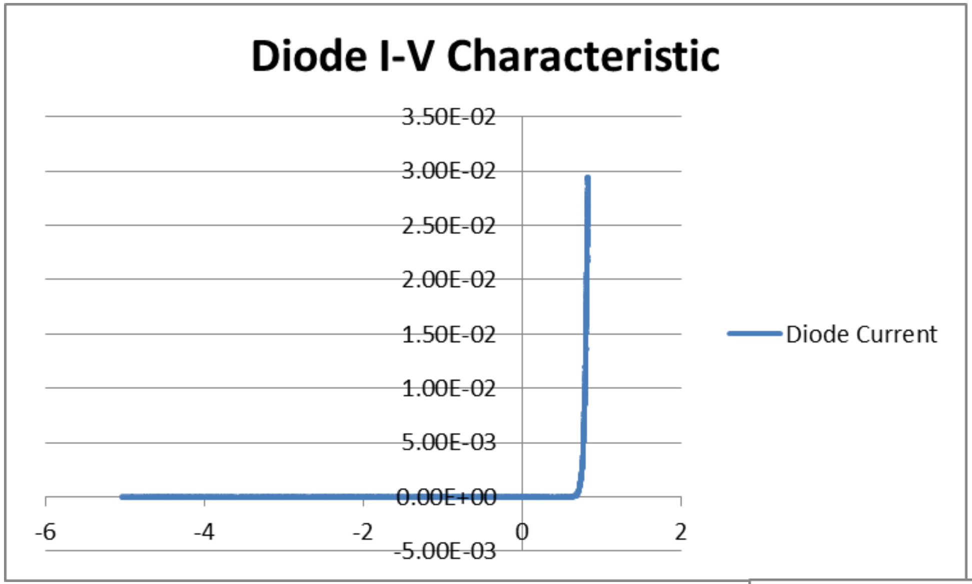


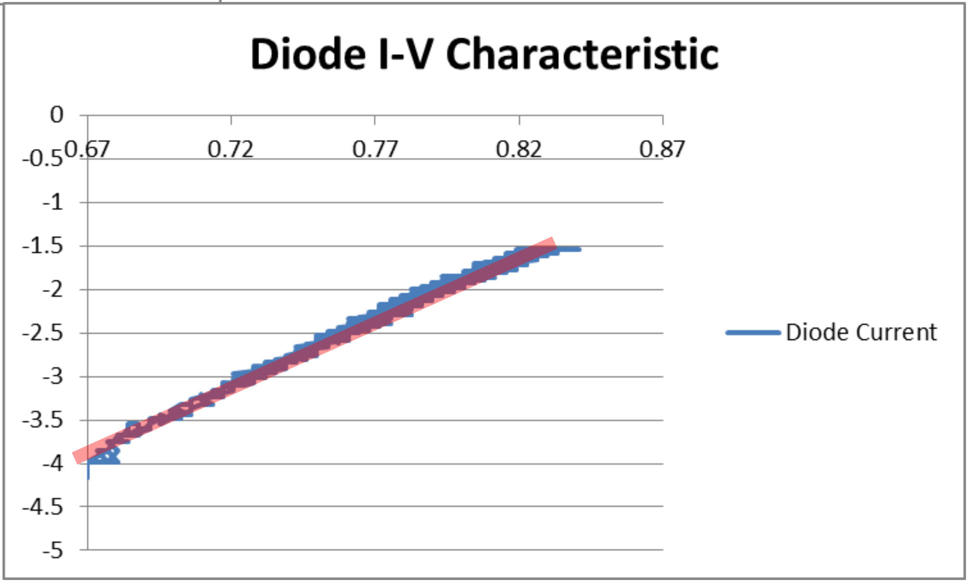
Breakdown occurs when $v_D < -V_{ZK}$. This is a predictable behavior of junction diodes. The value V_{ZK} is known as the **zener breakdown voltage**, and is a fundamental performance parameter of any **junction** diode .

The Junction Diode (FB and RB)



The Junction Diode (FB and RB)





The Junction Diode

B) The Junction Diode *i-v* Relationship

- The Junction diode *i-v* relationship in the forward and reverse bias regions **(not in breakdown)** can be modeled using semiconductor physics! Therefore, we can express this relationship as a **single** function for both these regions.

$$i_D = I_S\left(e^{v_D / nV_T} - 1\right) \qquad for \qquad v_D > -V_{ZK}$$

I_S: Scale Current (or Saturation Current):

- Depends on diode physical properties – material, size, and temperature.
- Proportional to junction area (remember a resistor).
- Units – Amps.
- Typical values range from 10^{-8} to 10^{-15} Amps (tiny).

The Junction Diode

B) The Junction Diode *i-v* Relationship

$$i_D = I_S\left(e^{v_D/nV_T} - 1\right) \qquad for \qquad v_D > -V_{ZK}$$

<u>V_T:Thermal Voltage, $V_T = kT/q$:</u>

k: Boltzman's Constant: 1.38e-23
T: Temperature in kelvins: 273+ºC
q: electron charge: 1.6e-19 coulomb

- At room temperature ~20º C, V_T is approximately 25 mV.
- Unless stated otherwise, we assume this value (**<u>V_T = 25 mV</u>**).

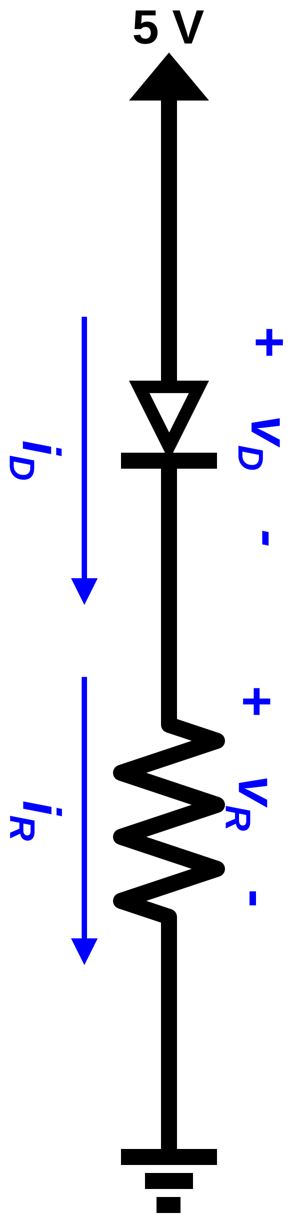
n: Ideality Factor (emission coefficient).

- Fudge factor to make the equation match reality.
- Usually between 1 and 2.

- Great, now that we know this eq. that works for both F.B. and R.B., we don't need to guess the state of the diode???

The Junction Diode

Let's try: A Junction Diode Example



The Junction Diode

Let's try: A Junction Diode Example

$i_D = i_R$

$i_R = (5 - v_D)/R$

$i_D = I_S(\exp(v_D/nV_T) - 1)$

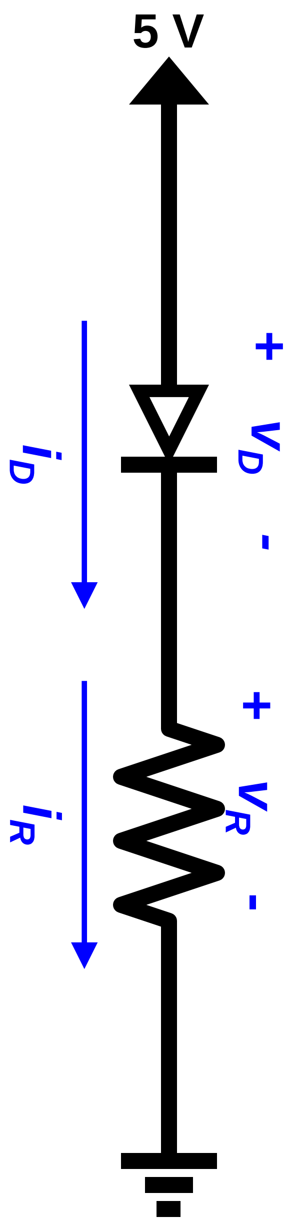
$(5 - v_D)/R = I_S(\exp(v_D/nV_T) - 1)$

$5 - v_D = RI_S\exp(v_D/nV_T) - RI_S$

$5 - v_D + RI_S = RI_S\exp(v_D/nV_T)$

$(5 - v_D + RI_S)/RI_S = \exp(v_D/nV_T)$

$\ln(5 - v_D + RI_S) - \ln(RI_S) = (v_D/nV_T)$



The Junction Diode

C) Forward Bias Region

$$i_D = I_S\left(e^{v_D/nV_T} - 1\right) \qquad \mathit{for} \qquad v_D > -V_{ZK}$$

- When $v_D >> nV_T$ this equation can be simplified.

$$v_D >> nV_T \qquad \text{then} \qquad e^{v_D/nV_T} >> 1$$

$$i_D \cong I_S e^{v_D/nV_T} \qquad \text{for} \qquad v_D >> nV_T$$

- In the forward bias region there is an exponential relationship between v_D and i_D.
- Solving for v_D gives.

$$v_D = nV_T \ln\left(i_D/I_S\right)$$

The Junction Diode

$$i_1 = I_S e^{v_1/nV_T} \qquad \text{and} \qquad i_2 = I_S e^{v_2/nV_T}$$

Then

$$\frac{i_2}{i_1} = \frac{I_S e^{v_2/nV_T}}{I_S e^{v_1/nV_T}} = e^{v_2/nV_T} e^{-v_1/nV_T} = e^{(v_2 - v_1)/nV_T}$$

Or equivalently

$$v_2 - v_1 = nV_T \ln\left(i_2/i_1\right)$$

$$v_2 - v_1 = 2.3nV_T \log_{10}\left(i_2/i_1\right)$$

$$v_2 - v_1 = 0.69nV_T \log_2\left(i_2/i_1\right)$$

What does this mean?

- Every time the current increases by a factor of 10, the voltage increases by 2.3nV_T. (60mV for n=1, and 120mV for n=2).
- Every time the voltage increases by ~60mV, the current is multiplied by 10.
- Every time the voltage increases by ~17mV, the current doubles.

The Junction Diode

C) Forward Bias Region

$$i_D = I_S e^{v_D / nV_T} \qquad \text{for} \qquad v_D >> nV_T$$

I_S=10^{-12}, V_T=25mV, n=1				
	v_d	I_d	R_{EFF}	Power
	0.4 V	8.89 μA	45 kΩ	3.55 μW
Cut-in voltage →	**0.5 V**	485 μA	1.03 kΩ	242 mW
	0.6 V	26.5 mA	22.7 Ω	15.9 mW
	0.7 V	1.45 A	484 mΩ	1.01 W
	0.8 V	79 A	10.1 mΩ	63.2 W
	0.9 V	4.31 kA	209 μΩ	3.88 kW

Rows 0.4 V – 0.6 V: Too much resistance. Not really Forward Biased.

Row 0.7 V: Typical F.B. operating point.

Rows 0.8 V – 0.9 V: Way too much current. Diode would be destoryed.

The Junction Diode

C) Forward Bias Region

$$i_D = I_S e^{v_D / nV_T} \qquad \text{for} \qquad v_D >> nV_T$$

Q. How are diodes specified (given a diode how do we find I_S, n, and V_T)?

- V_T is a function of temperature (~25mV at 20ºC).

1) Manufacturer specifications for n and I_S.

2) Given a value of n, a statement such as 1mA at 0.7V can be used to determine I_S. (If just the current is given, can assume 0.7V as a standard reference for that current).

3) If no values are given, a simple experiment can be used.

The Junction Diode

C) Forward Bias Region

A silicon diode is a 1mA device. Find the values for the scaling constant, I_S, if n=1 and n=2.

Exercises:
n=1.5. Find the change in voltage from 0.1mA to 10mA.

n=1 is a 1mA device. Find v_d at 0.1 mA and 10mA.

The Junction Diode

C) Forward Bias Region

A silicon diode is a 1mA device. Find the values for the scaling constant, I_S, if n=1 and n=2.

$0.001 = I_S * \exp(0.7/(0.025))$, $I_S = 6.91 \times 10^{-16}$A

$0.001 = I_S * \exp(0.7/(0.050))$, $I_S = 8.32 \times 10^{-10}$A

Exercises:

n=1.5. Find the change in voltage from 0.1mA to 10mA.

$\Delta V = nV_T \ln(i_2/i_1) = 0.0375 * \ln(100) = 0.172$V

n=1 is a 1mA device. Find v_d at 0.1 mA and 10mA.

$\Delta V = nV_T \ln(i_2/i_1) = 0.0375 * \ln(10) = 0.058$V

$V(0.0001) = 0.7 - 0.058 = 0.642$V

$V(0.0100) = 0.7 + 0.058 = 0.758$V

The Junction Diode

C) Forward Bias Region

Temperature variations.

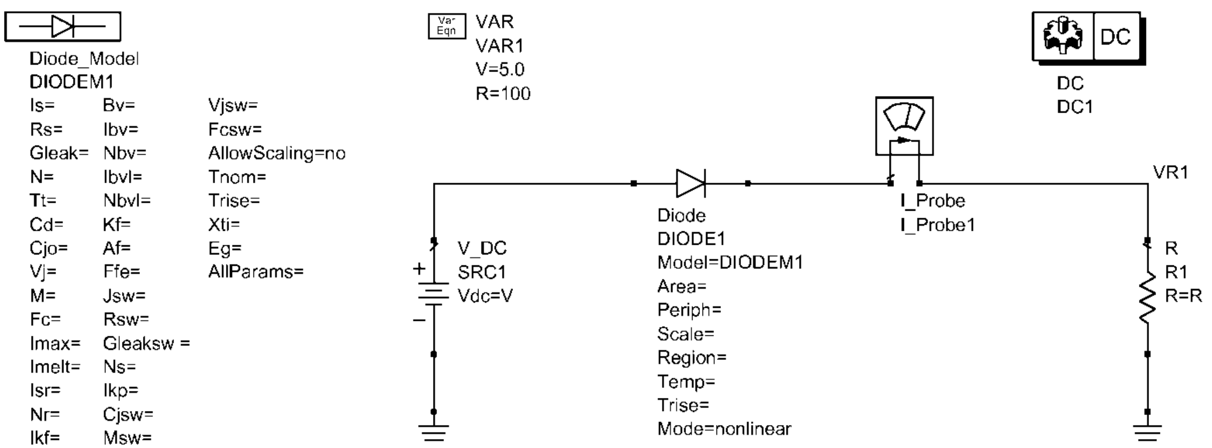
- V_T varies directly with temperature (previous slide).
- I_S also varies with temperture by increasing by 15% for every 1ºC rise in temperature.

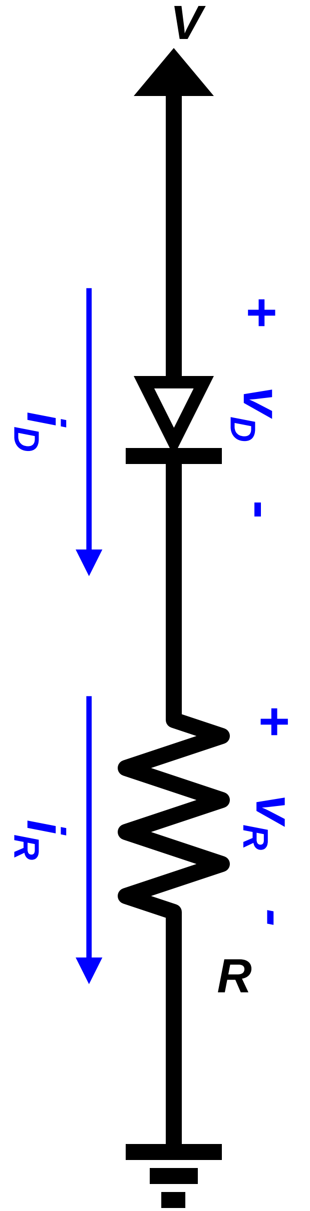
$$I_{S2}=I_{S1}*1.15^{(T2-T1)}$$

- For every ~5ºC rise in temperature I_S will double.

A Junction Diode Example: Forward Bias

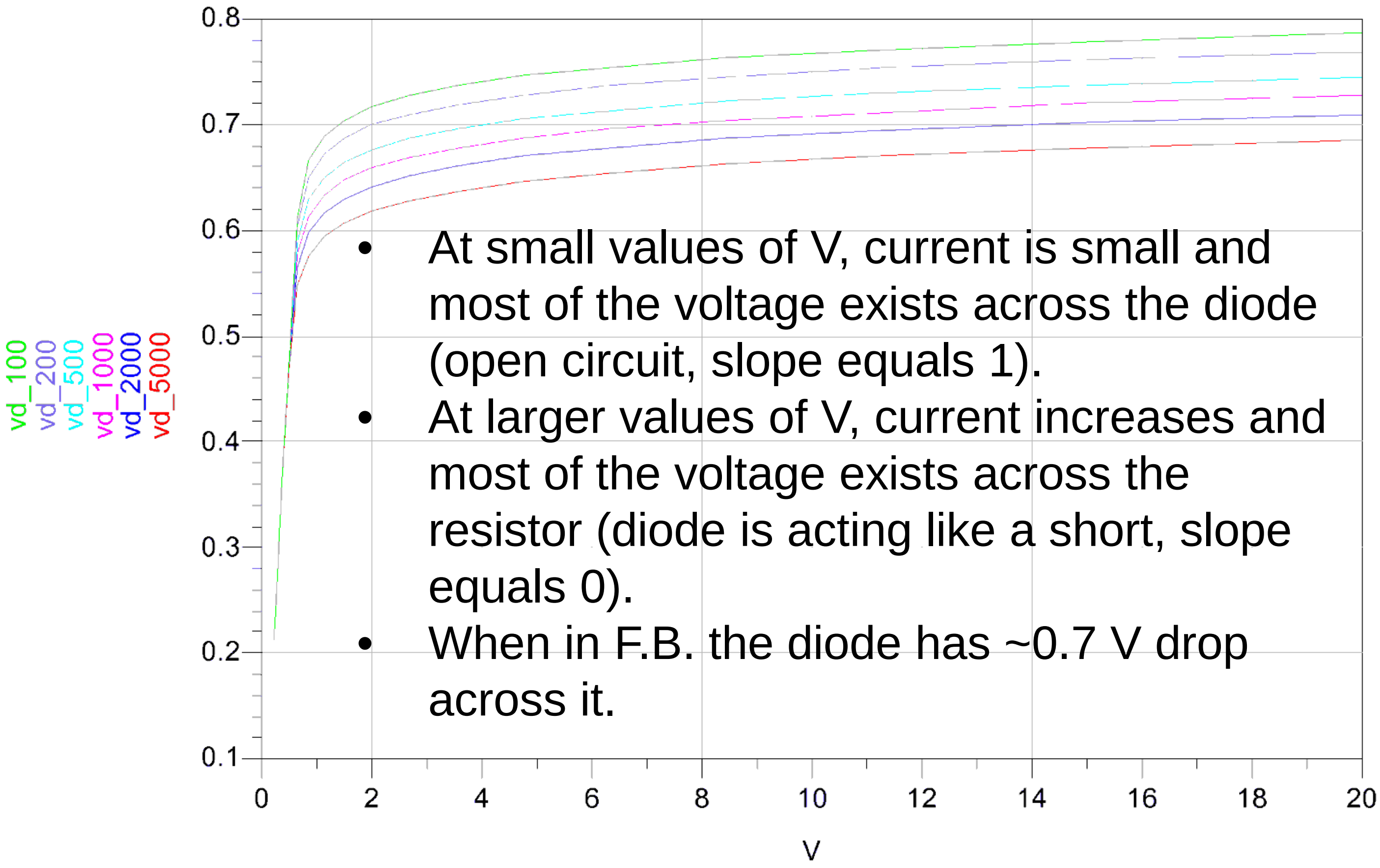
- Solve using a computer (ADS) for values of *R* and *V*.



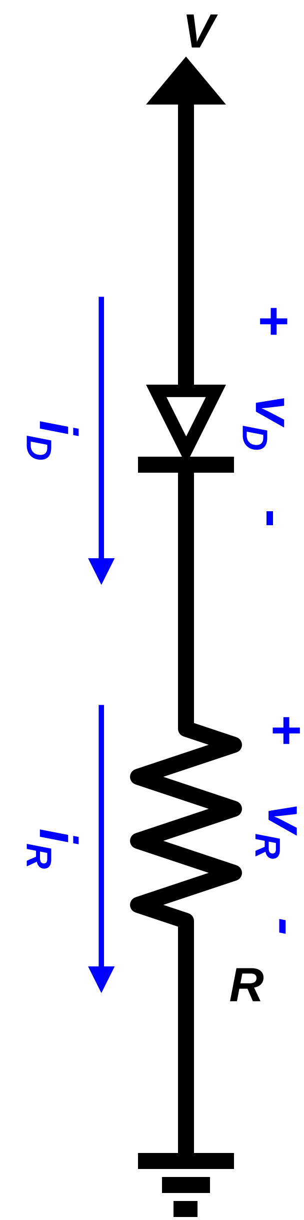


The Junction Diode

A Junction Diode Example: Forward Bias

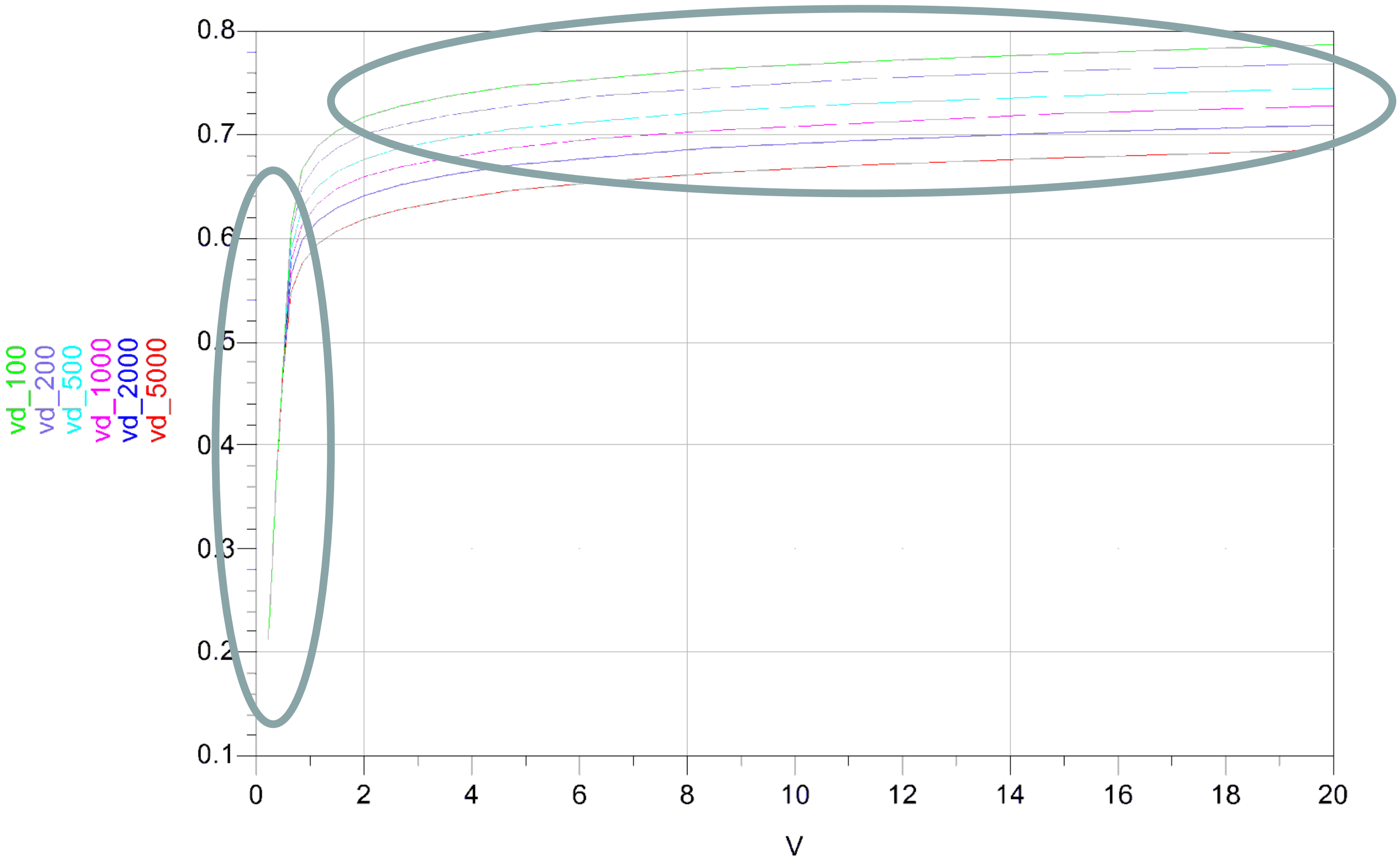


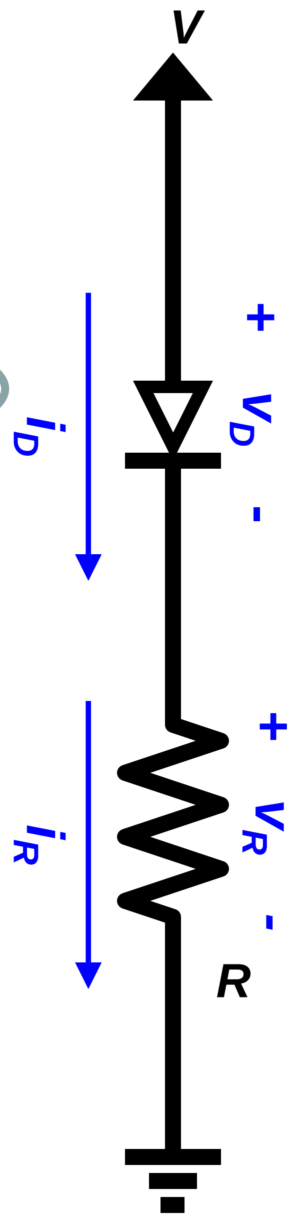
- At small values of V, current is small and most of the voltage exists across the diode (open circuit, slope equals 1).
- At larger values of V, current increases and most of the voltage exists across the resistor (diode is acting like a short, slope equals 0).
- When in F.B. the diode has ~0.7 V drop across it.



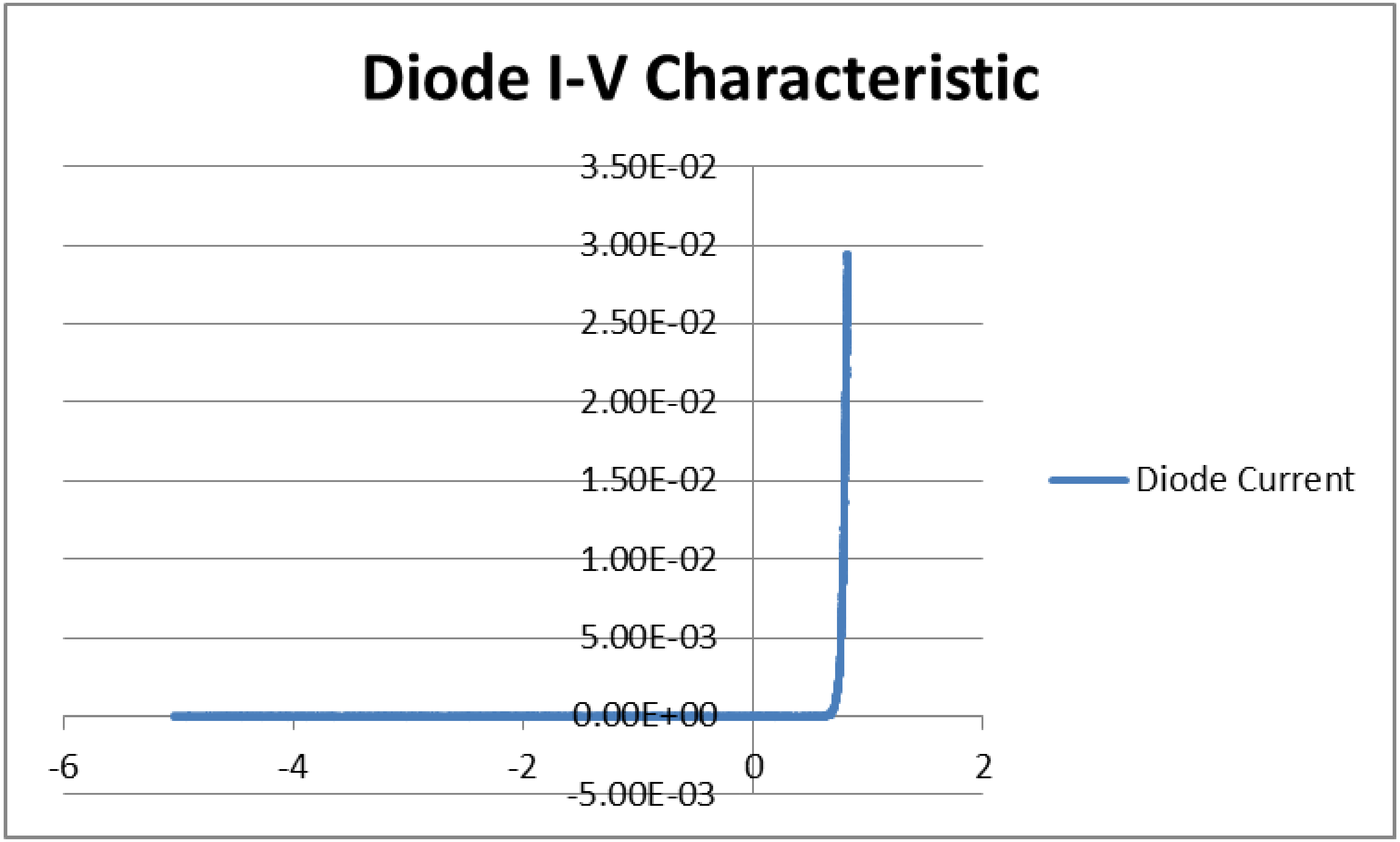
The Junction Diode

A Junction Diode Example: Forward Bias

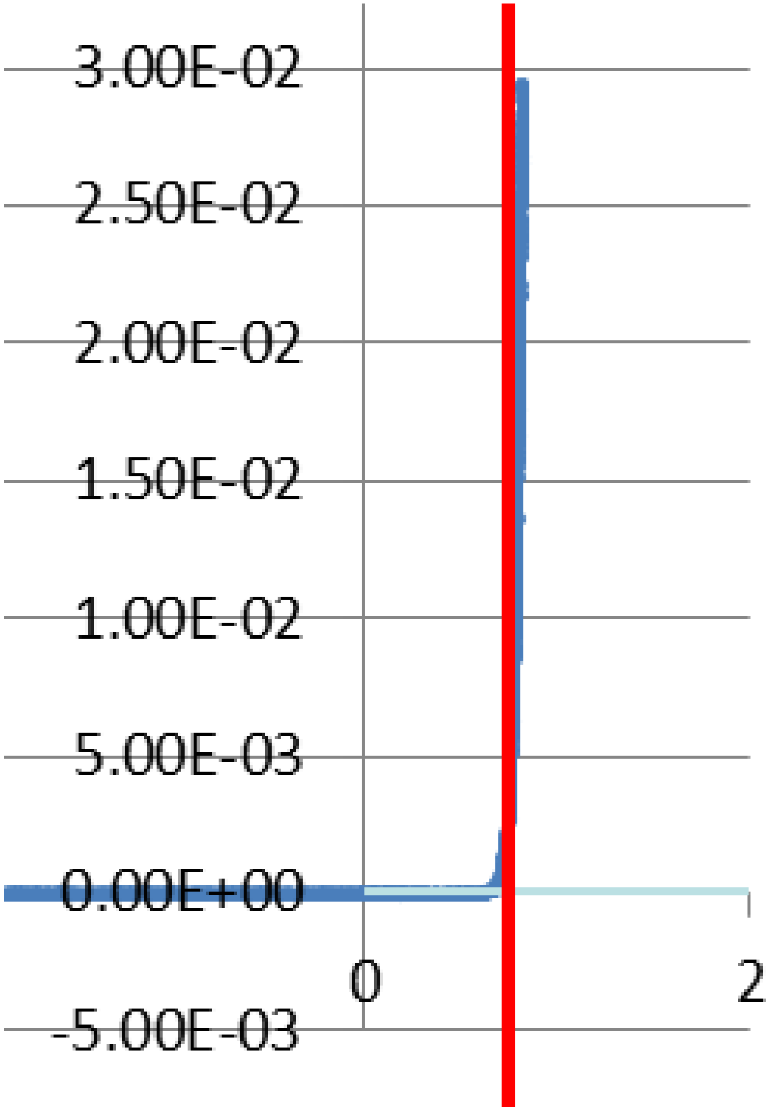




The Junction Diode



The Junction Diode



- From approximately 1mA to 30mA, the voltage across the diode is very close to 0.7V.
- A vertical line is a voltage source.
- For this diode in FB, a very good guess (or model) for the diode would be a 0.7V voltage source.

The Junction Diode

C) Reverse Bias Region

$$i_D = I_S\left(e^{v_D/nV_T} - 1\right) \qquad \text{for} \qquad v_D > -V_{ZK}$$

- When $v_d << -nV_T$ this equation can be simplified.

$$v_D << -nV_T \qquad \text{then} \qquad e^{v_D/V_T} \cong 0$$

$$\boxed{i_D \cong -I_S \qquad \text{for} \qquad v_D << -nV_T}$$

- In the reverse bias region there is a constant value for i_d.
- Thus the name saturation current.
- Real diodes also exhibit a leakage currents that are typically much larger than I_S. These currents tend to dominate
- Temperture Dependence: Whereas I_S double for every 5ºC, the R.B. current doubles for every 10ºC.

The Junction Diode

C) Breakdown Region

- Occurs when the magnitude of the reverse voltage exceeds a certain threshold value specific to the particular diode.
- This value is denoted as V_{ZK}: Zener-Knee Voltage.
  Typically around 25V.
- Fall-off in this region is steep.
- Mechanism for breakdown is non-destructive; however, diode breakdown can result in a significant amount of power dissipated within the diode, and this can be destructive.

$P_{R.B.} = I_S * v_D$ very small
$P_{F.B.} = 0.7 * i_D$ moderate
$P_{B.D.} = V_{ZK} * i_D$ potentially destructive