The pn Junction

ECE 320 Electronics I (Digital Electronics)

Jake Glower - Lecture #5

PN Junction

Dope silicon with boron and you get p-type silicon

- Almost all of the charge carriers are holes

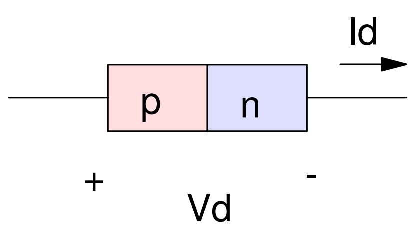
$$p_p \approx 10^{16} \qquad n_p = \left(\frac{n_i^2}{p}\right) = 2.25 \cdot 10^4$$

Dope silicon with phosphorus and you get n-type silicon

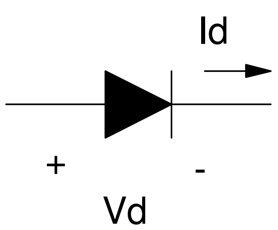
- Almost all of the charge carriers are electrons

$$n_n \approx 10^{16} \qquad p_n = 2.25 \cdot 10^4$$

- Put p-type next to n-type and you get a pn junction (a diode)



Diode pn junction



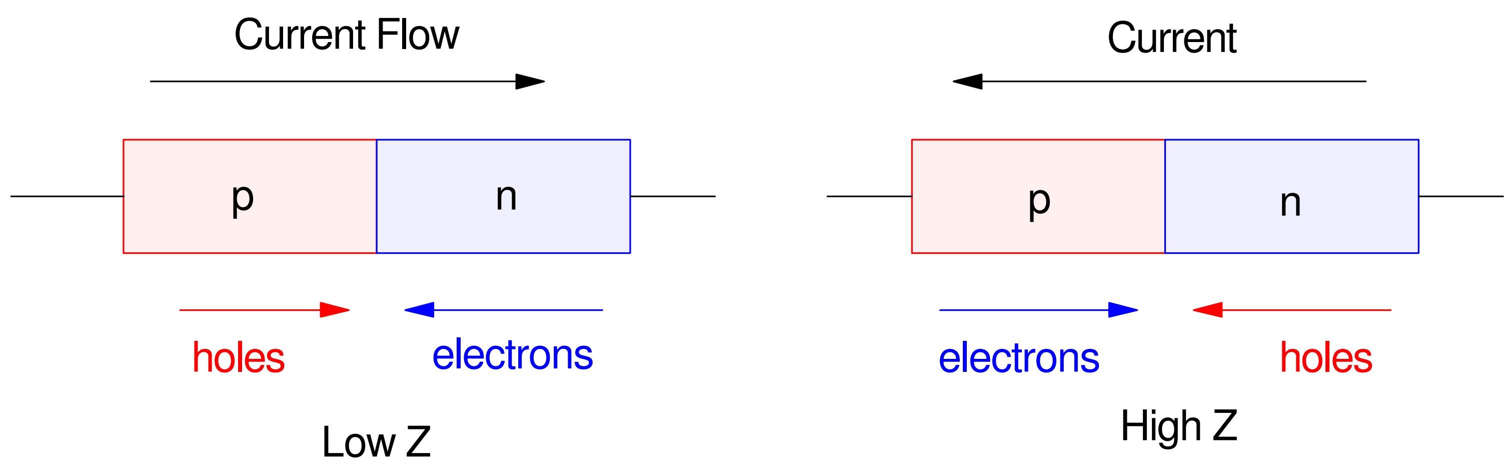
Diode symbol

Diodes are Valves

- pn junctions only allow current to flow p to n

Assume no electron / hole pairs are created at the pn junction

- p to n: Uses majority carriers (low resistance)
- n to p: Uses minority carriers (high resistance)



Diodes are Valves (take 2)

A depletion is created at the pn junction

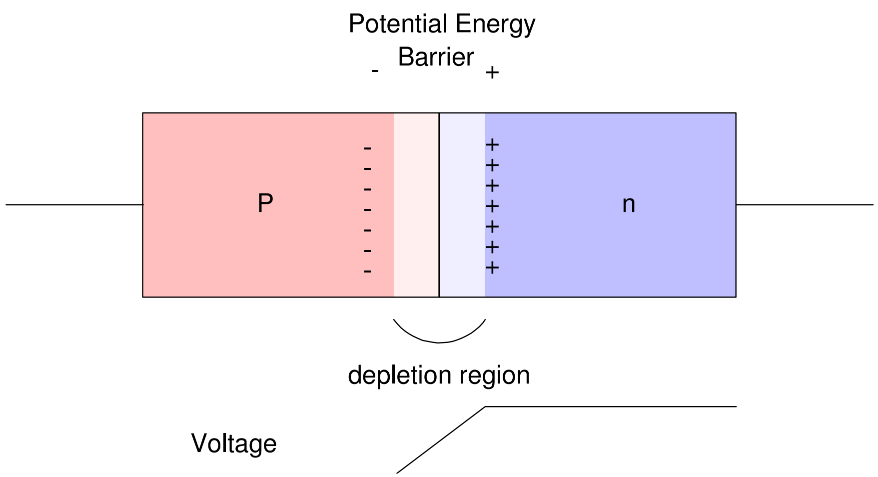
- Holes on the p-side diffuse to the n-side and are not replaced
- Electrons on the n-side diffuse to the p-side and are not replaced

This creates a zone with no charge carriers

- No carriers means no current flow

Voltage p to n squeezes the deplation zone down to zero.

- Once the depletion zone is gone, current flows



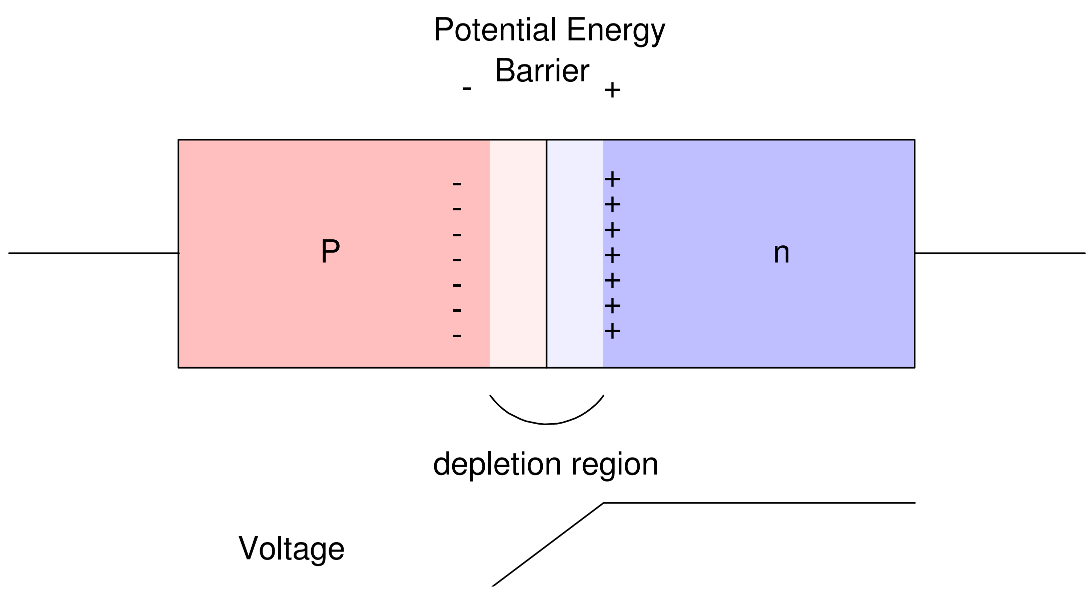
Diodes are Valves (take 3)

A potential energy barrier exists p to n

- Holes on the p-side diffuse to the n-side and are not replaced
- Electrons on the n-side diffuse to the p-side and are not replaced

This creates a voltage (about 0.7V for silicon)

- You need at least 0.7V p to n to overcome this potential energy barrier



Implications

- Diodes are inherently capacitors.
- The voltage depends upon doping

$$V_d = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right)$$

$$V_d = (0.026V)\ln\left(\frac{10^{16} \cdot 10^{16}}{(1.5 \cdot 10^{10})^2}\right) = 0.697V \approx 0.7V$$

- The voltage varies with different types of materials. These are approximately as follows:

  Silicon: 0.7V
  Germanium: 0.3V
  Red LED: 1.9V (varies)
  Blue LED: 3.3V (varies)

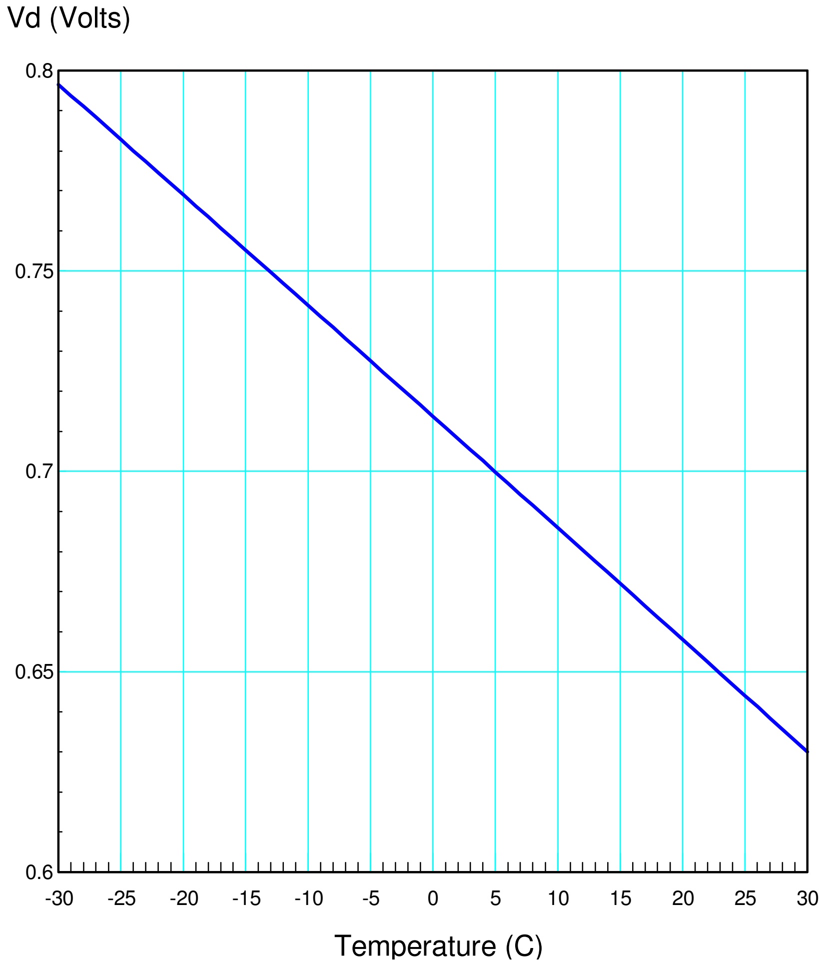
- The voltages varies with temperature

  This is one way to measure temperature

$$n_i^2 = A_o T^3 e^{-E'_G/kT}$$

$$V_T = \frac{T}{11{,}600}$$

```
C = [-30:30]';
T = C + 273;
Ao = 2.33e33;
k = 8.617e-5;
Eg = 1.4;

ni=(Ao*(T.^3).*exp(-Eg./(k*T))).^0.5;
Vt =  T / 11600;

Vd = Vt .* log(1e28 ./ (ni .^ 2) );


plot(C,Vd)
xlabel('Temperature (Celcius)');
ylabel('Vd');
```



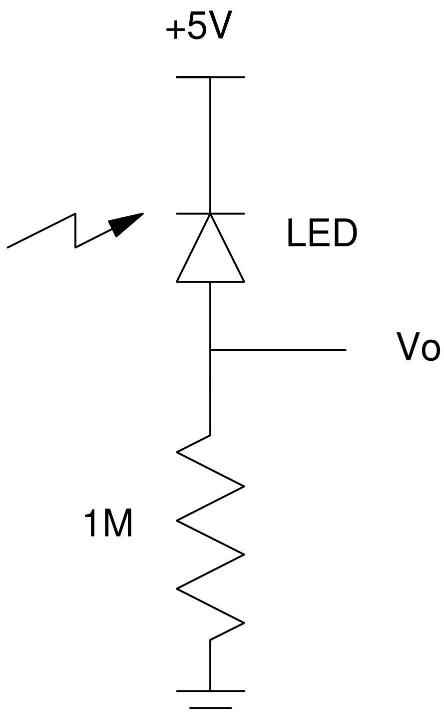
Diode Radiation Sensors

Diodes also detect radiation

- The current for a reverse biased diode is almost zero
- If you hit the pn junction with radiation, you create electron/hole pairs
- The more radiation you have, the more current flow you have

This is duality

- Current produces light (for LEDs)
- Light produces current

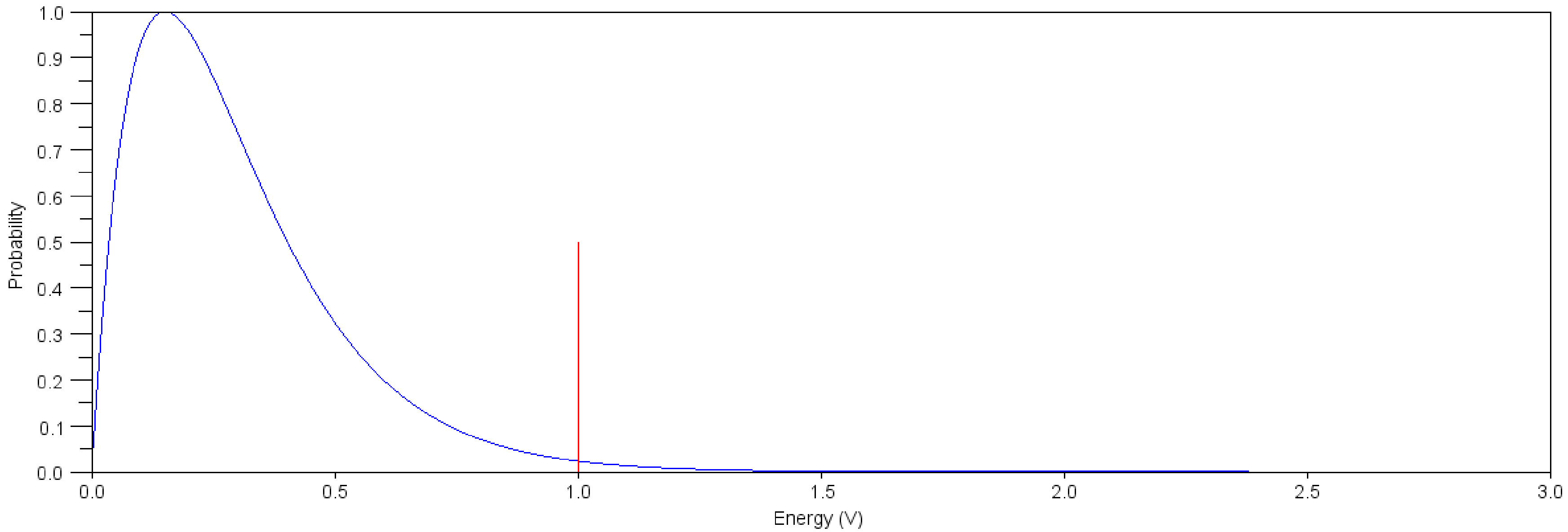


Diodes VI Characteristics

- When you have a diode, you have a potential energy barrier
- Electrons with enough energy can pass (current flows)

The pdf for the energy in a given electron follows a Gamma distribution:

$$p(V) = \frac{\beta^{\alpha}}{\Gamma(\alpha)} V^{\alpha-1} e^{-\beta V}$$



Gamma Distribution for the Energy of a Given Electron.

The current through a diode is exponential with respect to voltage:

$$I_d = I_o(e^{V_d/\eta V_T} - 1)$$

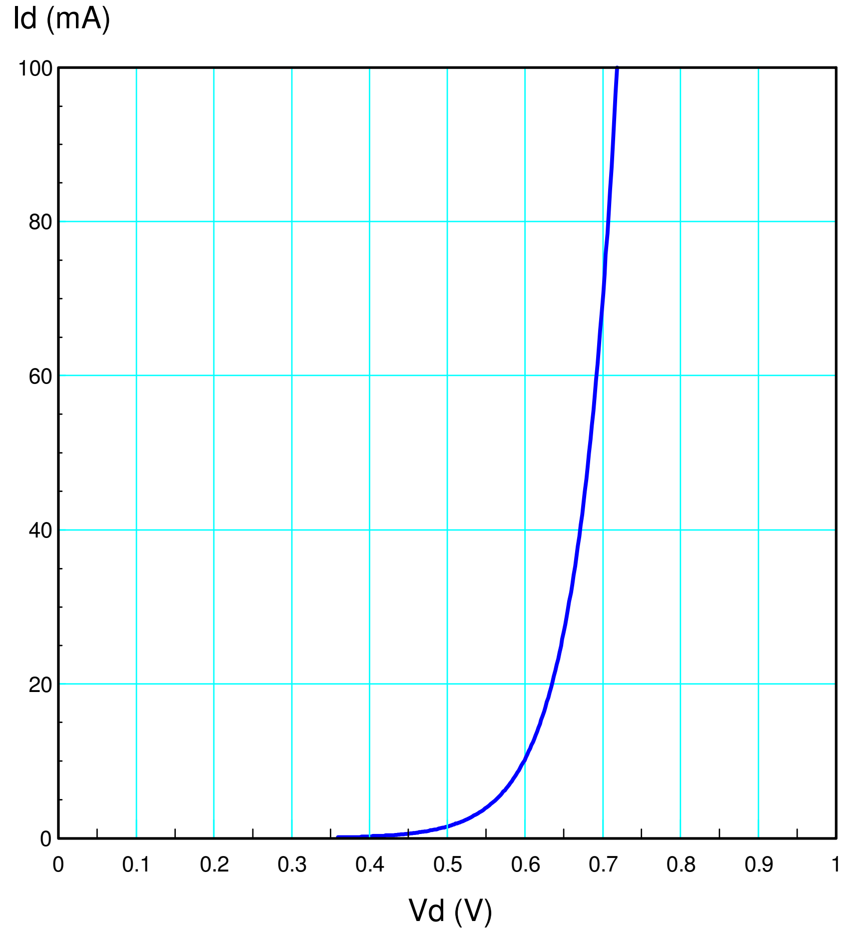
$$V_d = \eta V_T \cdot \ln(I_d/I_o + 1)$$

where

η is a constant (1.45 for silicon)

$V_t = 0.026V$ at 300K

I_o is the reverse saturation current



For silicon diodes

$$I_d = 7.69 \cdot 10^{-11}\left(\exp\left(\frac{V_d}{0.0377}\right) - 1\right)$$

$$V_d = 0.0377 \cdot \ln\left(\frac{I_d}{7.69e{-11}} + 1\right)$$

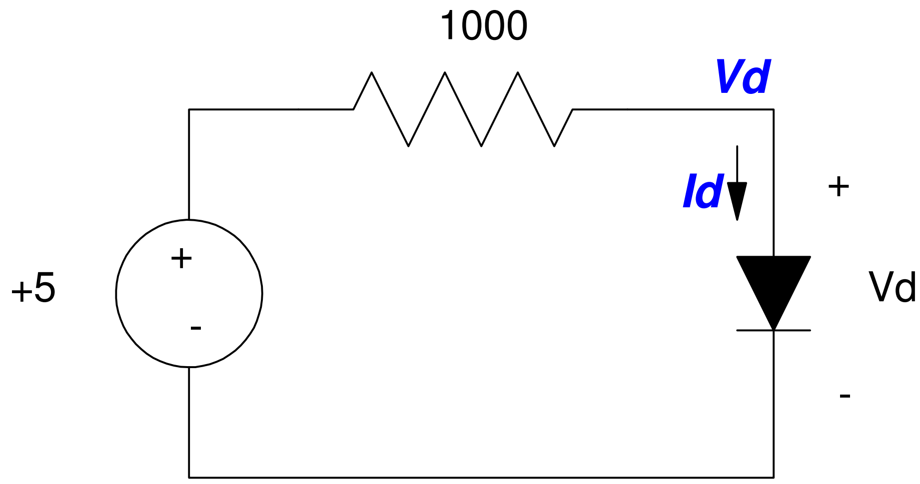
Circuit Analysis with Diodes

Write N equations to solve for N unknowns for the following circuit:

Voltage Nodes:

$$I_d = 7.69 \cdot 10^{-11} \left(\exp\left(\frac{V_d}{0.0377} \right) - 1 \right)$$

$$\left(\frac{V_d - 5}{1000} \right) + I_d = 0$$



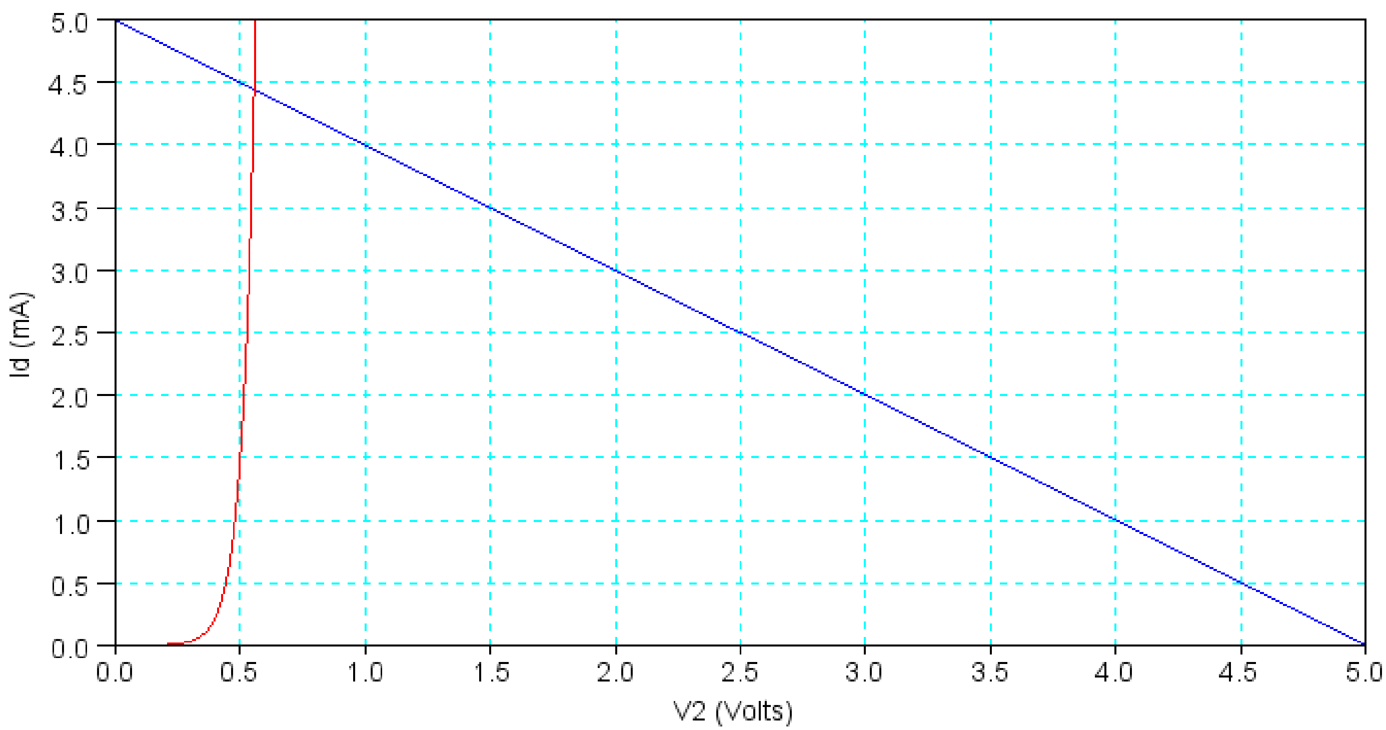
Current Loops

$$V_d = 0.0377 \cdot \ln\left(\frac{I_d}{7.69 \cdot 10^{-11}} + 1 \right)$$

$$-5 + 1000 \cdot I_d + V_d = 0$$

Solving: Graphical Solution

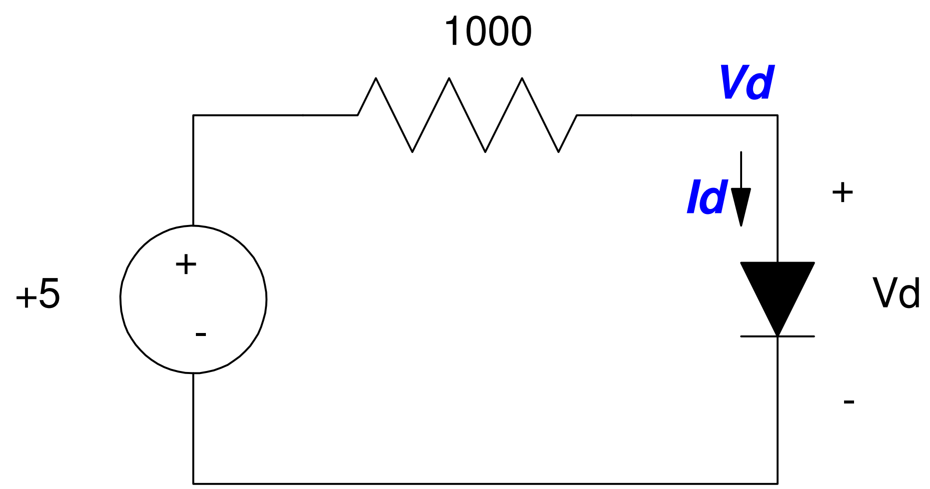
```
I = [0:0.001:1]'  * 0.005;
V1 = 0.0377*log( I / 7.69e-11 + 1);
V2 = 5 - 1000*I;

plot(V1,I*1000,V2,I*1000);
xlabel('V2 (Volts)')
ylabel('Id (mA)');
```



Solving: Numerical Solution

- Create a funciton in Matlab
- Pass your guess of Vd, returns the sum-squared error

```
function [ J ] = diode1( Vd )
   Id = 7.65e-11*(exp(Vd/0.0377)-1);
   E = 5 - 1000*Id - Vd;
   J = E ^ 2;
   end
```



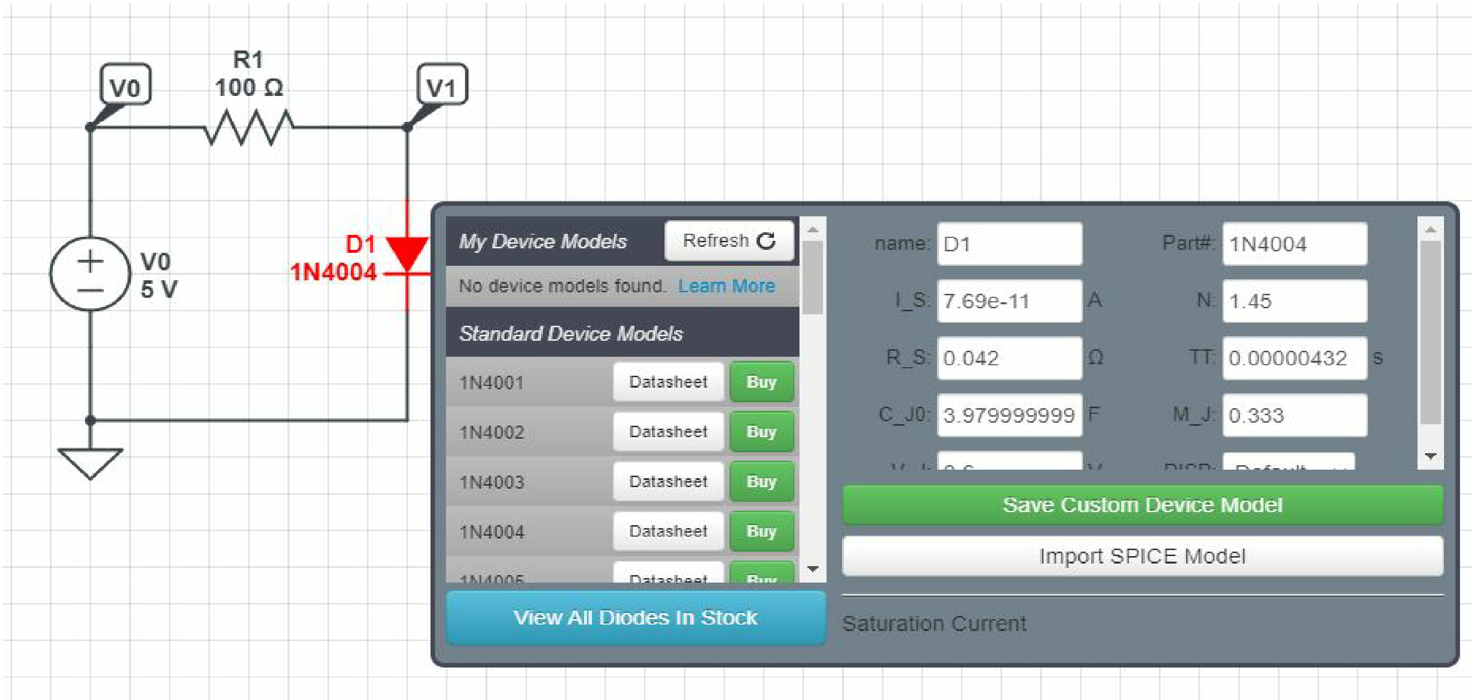
Calling from Matlab:

```
Vd = fminsearch('diode1',0.7)

Vd =    0.6730
```

The solution is (0.6730V, 4.3270mA)

CircuitLab

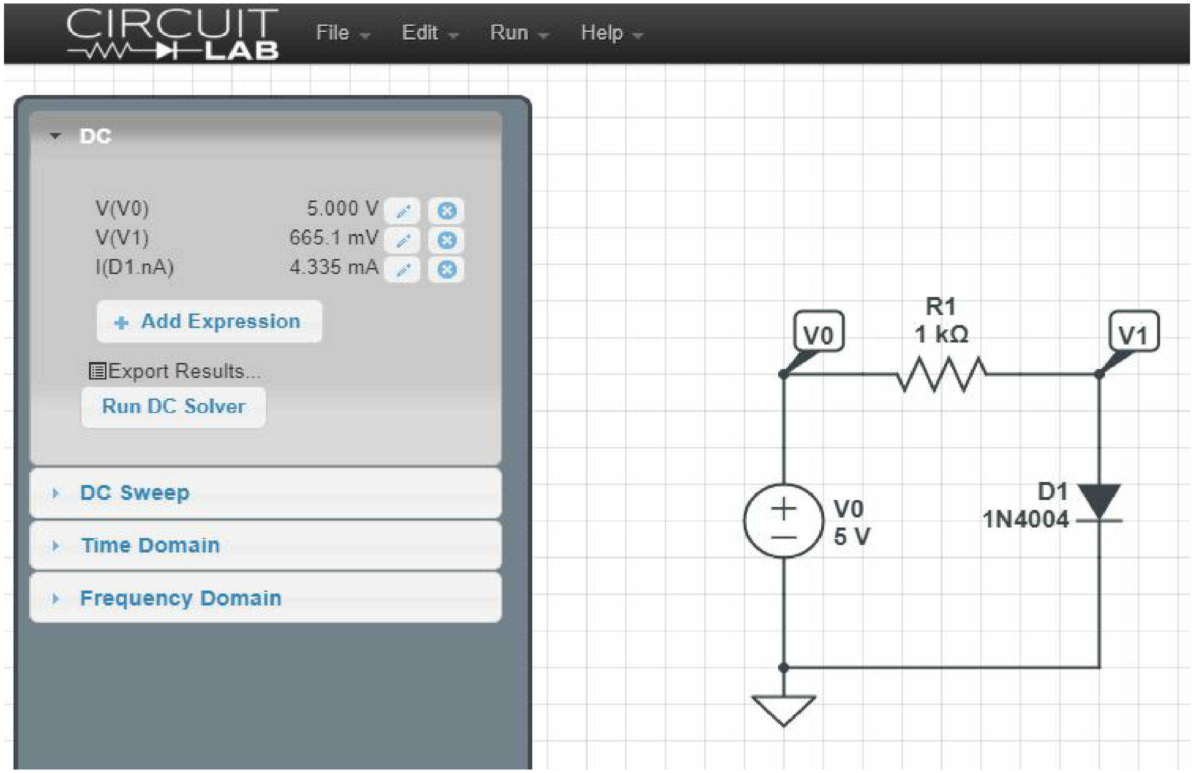
- Parameters for a 1N4004 diode
- Idss = 6.79e-11
- n = 1.45
- n Vt = 0.0377



CircuitLab

- One circuit, three solutions

	Vd	Id
Matlab	0.6730 V	4.327mA
CircuitLab	0.6651 V	4.335mA
Hardware	?	?



Example 2: Circuit with Two Diodes:

- Find V1, V2, V3

Start with the diode equations

$$I_{d1} = I_{dss}\left(\exp\left(\frac{V_2 - V_3}{nV_T}\right) - 1\right)$$

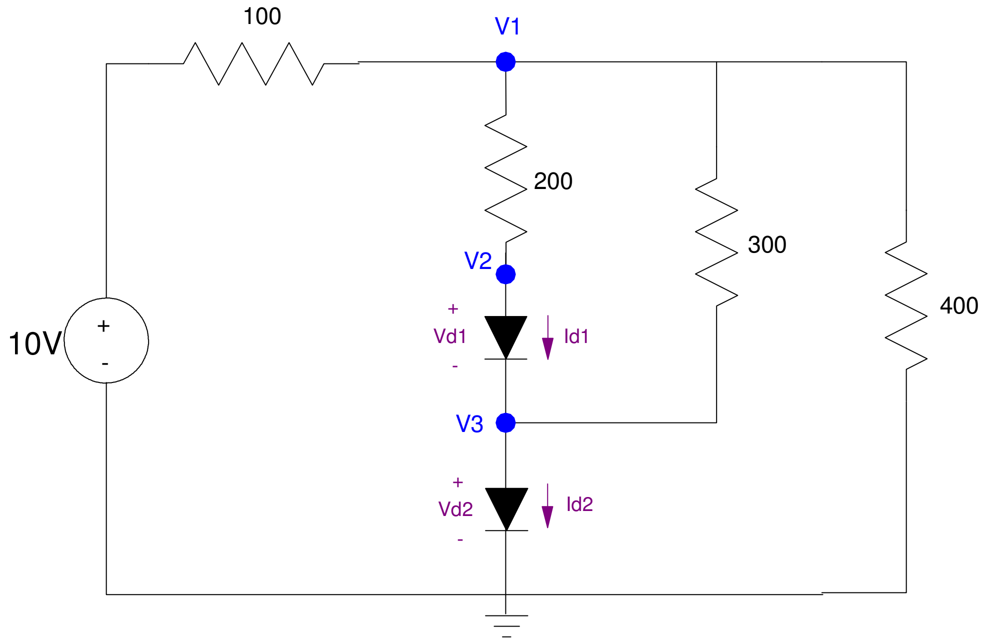
$$I_{d2} = I_{dss}\left(\exp\left(\frac{V_3 - 0}{nV_T}\right) - 1\right)$$

Write the node equations

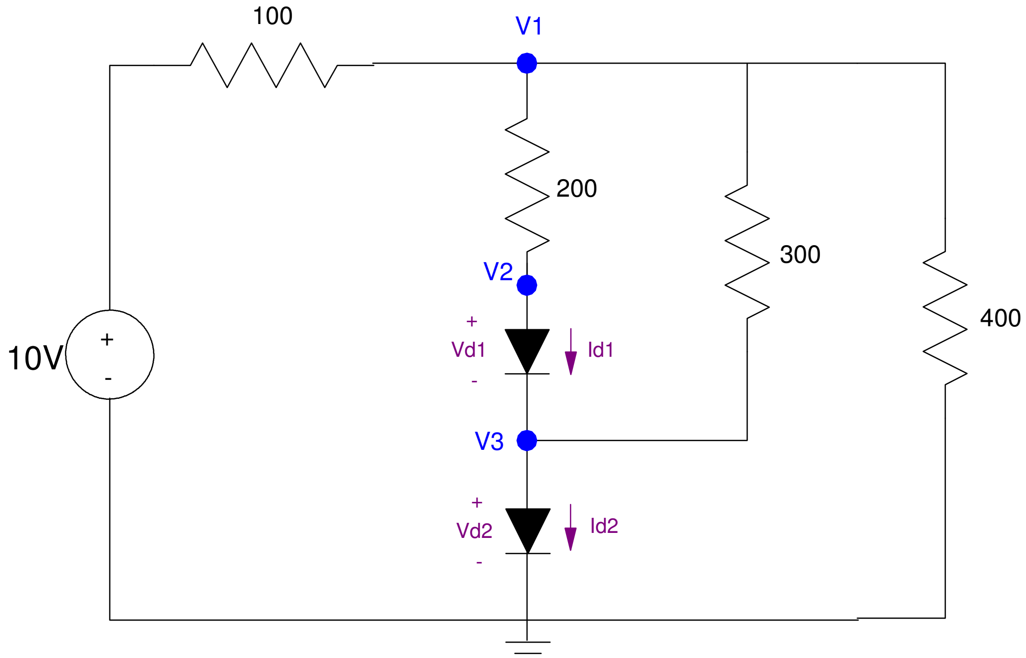
$$\left(\frac{V_1 - 10}{100}\right) + \left(\frac{V_1 - V_2}{200}\right) + \left(\frac{V_1 - V_3}{300}\right) + \left(\frac{V_1}{400}\right) = 0$$

$$\left(\frac{V_2 - V_1}{200}\right) + I_{d2} = 0$$

$$-I_{d1} + I_{d2} + \left(\frac{V_3 - V_1}{300}\right) = 0$$

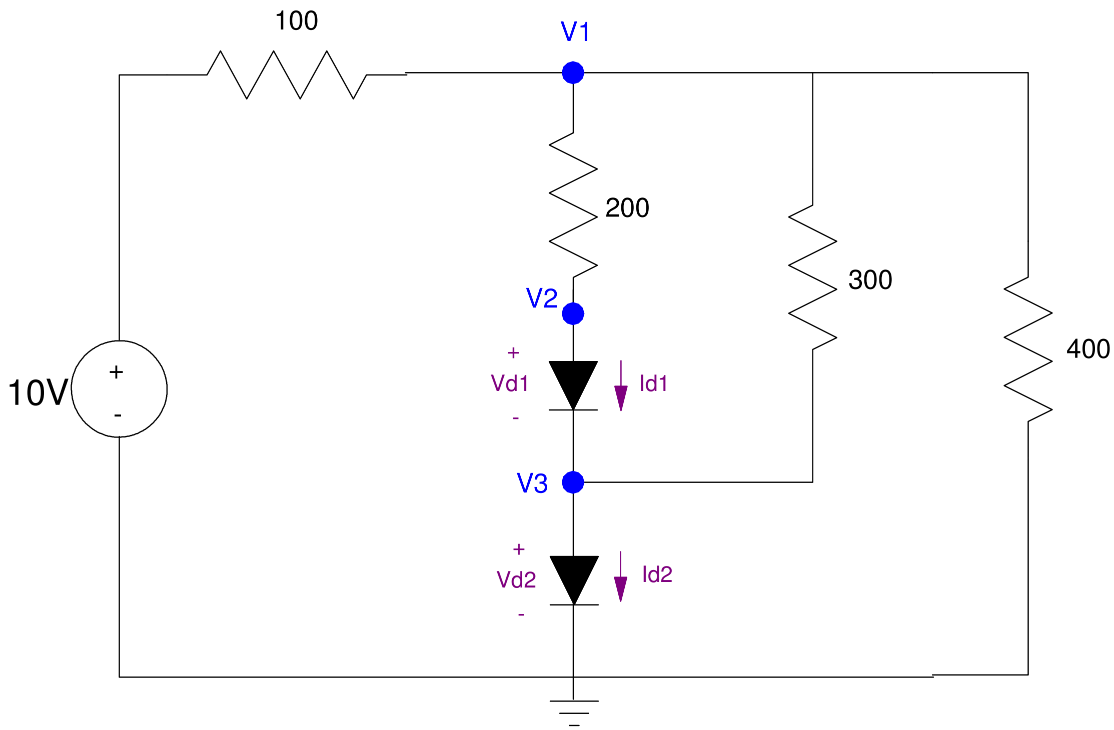


```
function [ J ] = diode2( X )
   V1 = X(1);
   V2 = X(2);
   V3 = X(3);

   Idss = 7.69e-11;
   nVt = 0.0377;

   Id1 = Idss * ( exp( (V2 - V3) /nVt ) - 1);
   Id2 = Idss * ( exp( (V3 - 0) / nVt ) - 1);

   E1 = (V1 - 10)/100 + (V1 - V2)/200 + (V1 - V3)/300 + V1/400;
   E2 = (V2 - V1)/200 + Id2;
   E3 = -Id1 + Id2 + (V3 - V1)/300;

   J = E1^2 + E2^2 + E3^2;

end
```



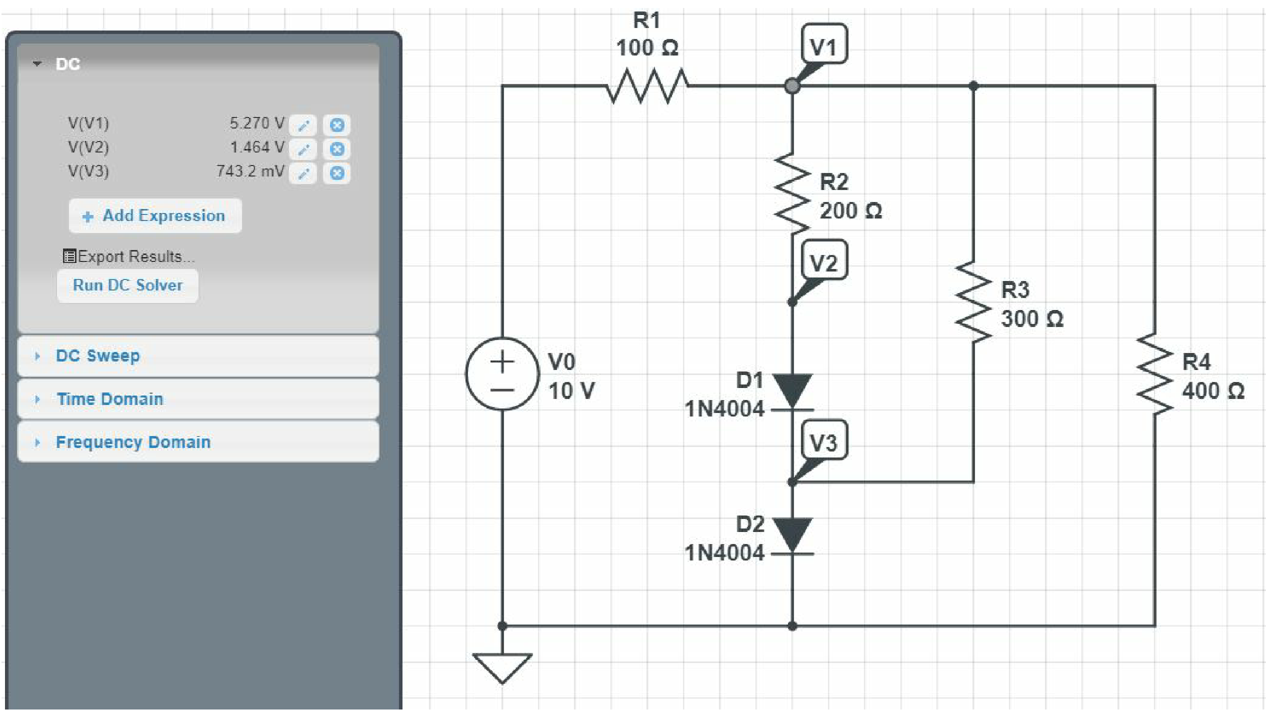
Solving using fminsearch()

```
[V, e] = fminsearch('diode2',[0.7,1.4,2.1])
          V1          V2          V4
V =    5.2528    1.4006    0.7291

e =  2.4581e-012
```



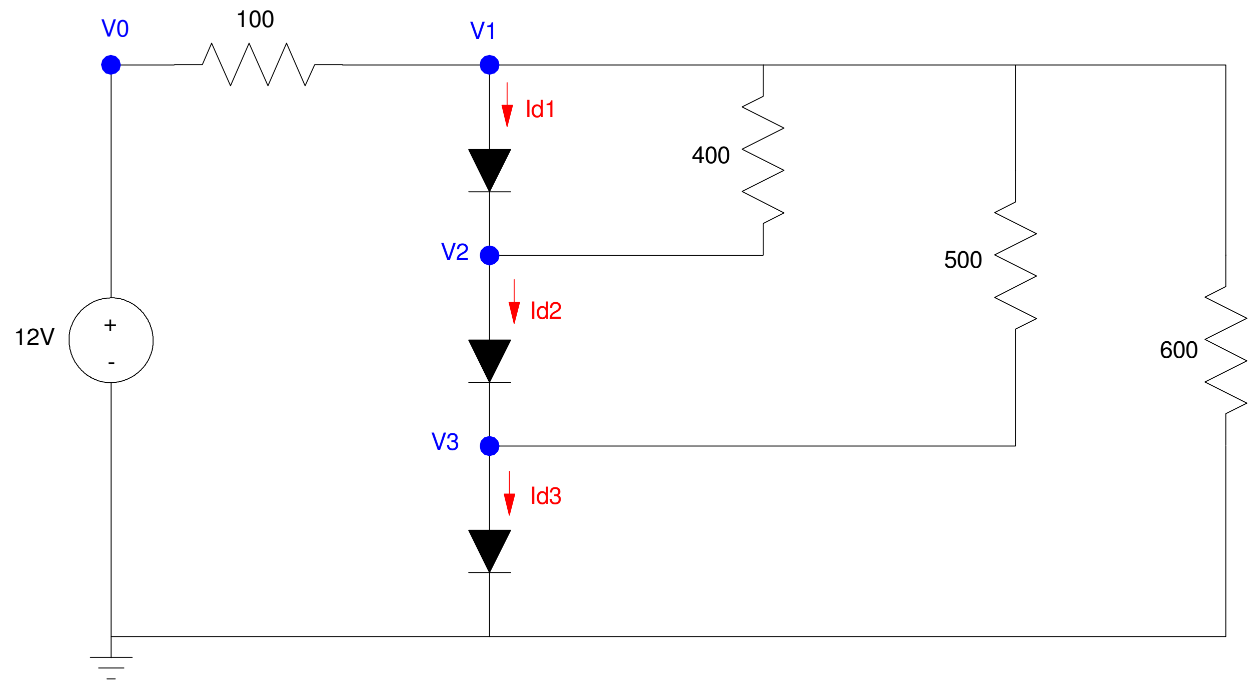
Solving using CircuitLab

	V1	V2	V3
Matlab	5.2528 V	1.4006 V	0.7291 V
CircuitLab	5.270 V	1.464 V	0.7432 V
Hardware	?	?	?



Handout

Write N equations for N unknowns for the following diode circuit



Summary

A pn junction forms a diode

- Current can only flow p to n (anode to cathode)

It takes about 0.7V for a silicon diode to turn on

- Varies with temperature
- Varies with material and doping

The VI characteristics are highly nonlinear

- $I_d = I_{dss} \cdot \left(\exp\left(\frac{V_d}{nV_T}\right) - 1 \right)$

You can still write N voltage node / current loop equations for diode circuits

- Much harder to solve since they're nonlinear
- fminsearch or CircuitLab can solve these equations
- We need a better tool...