TÉCNICO LISBOA

Circuit Theory and Electronics Fundamentals

Lecture 11: Semiconductor Components: Resistors and Diodes

- Semiconductors and their classification
- Intrinsic semiconductor and carrier concentration
- Extrinsic semiconductor and carrier concentration
- Semiconductor resistors
- PN junctions at rest and with forward and reverse biased
- The Diode: carrier concentration variations and I-V plot
- Example diode circuit

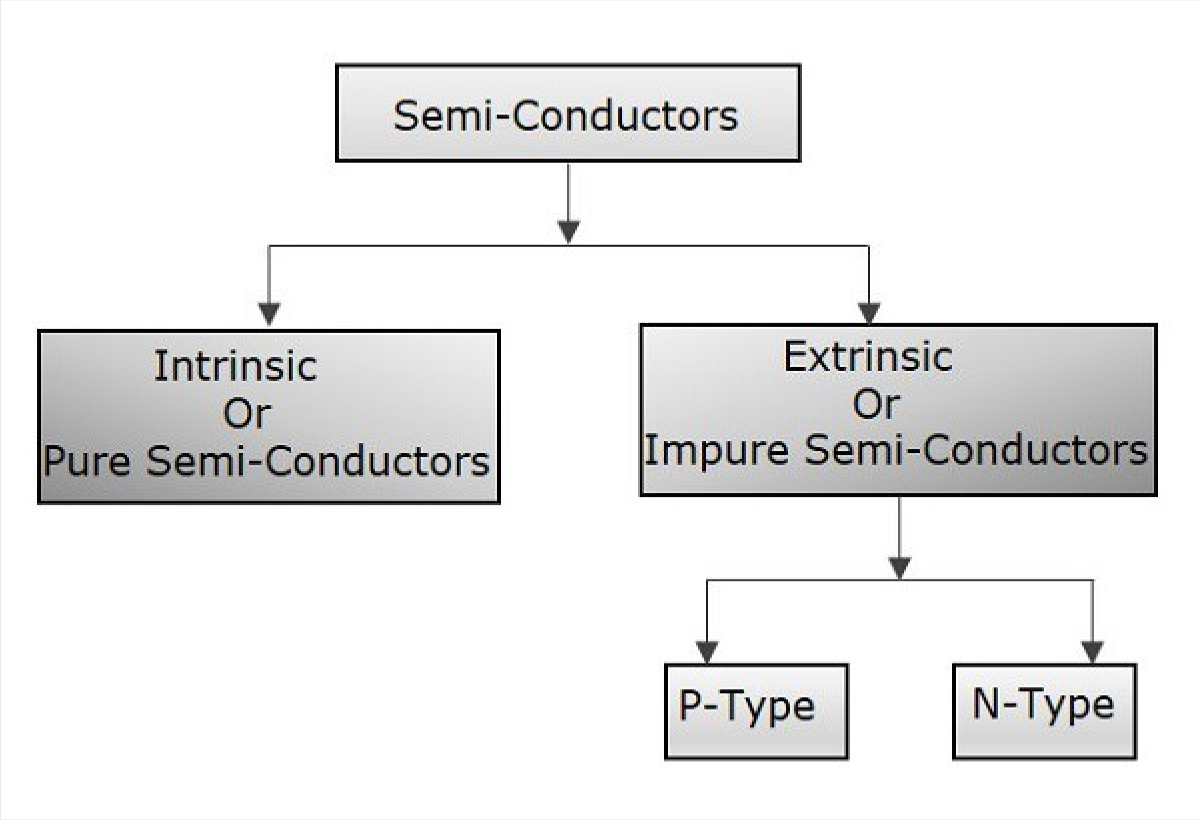
The semiconductor revolution

- The use of semiconductors can be traced back to 1874 when an AC/DC converter was built using this material
- Semiconductors began their rise to supremacy in the middle of the 20th century with the invention of the transistor by a Bell Labs team
- Semiconductors led the development of non-linear components which are key to modern electronic chips
- The ***non-linear curves*** that describe their behaviour makes it possible to use the same device in distinct operation modes over time!
- ***Digital circuits***, for example, switch between ON/OFF states coded as True/False logic values!
- The execution of ***propositional logic*** programs on electronic devices became a reality!

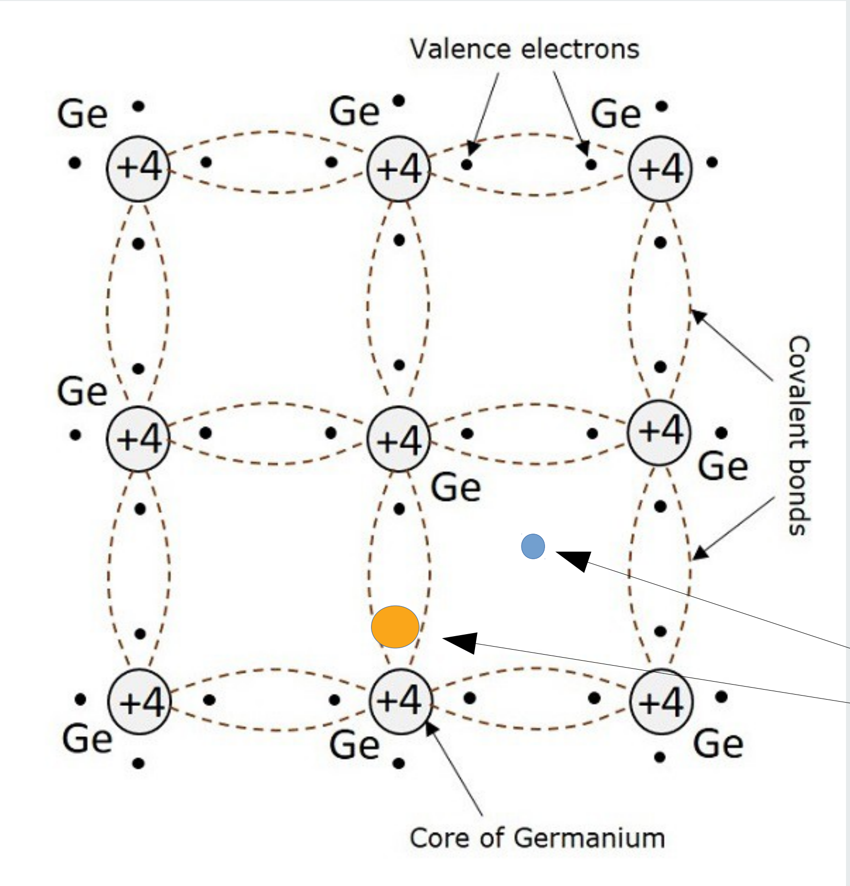
What is a semiconductor

- A semiconductor is a substance whose resistance is midway between conductors and insulators
- The resistance decreases with the temperature and vice-versa
- Semiconductors can be used to make resistors
- Adding impurities to a semiconductor (***doping***) changes its properties – this is essential to making electronic devices
- Putting semiconductors with different doping densities in contact creates devices with notable properties:
  - The diode
  - The transistor

Classification of semiconductors

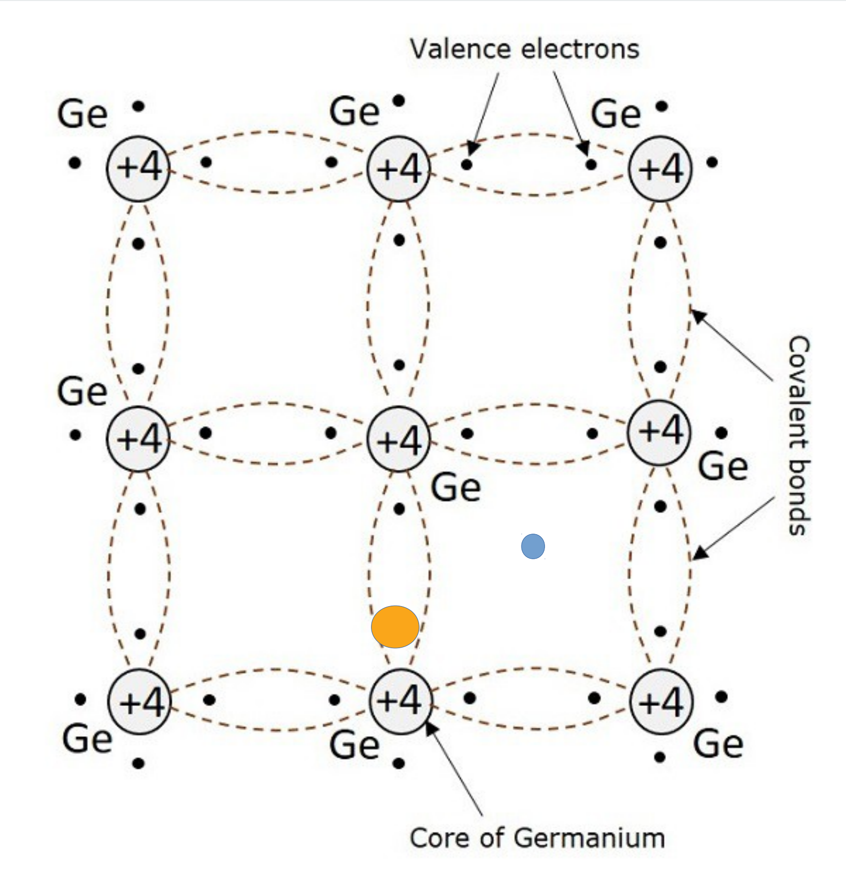


Intrinsic semiconductor: Germanium (Ge)



- 32 electrons, 4 in the last orbital – **valence band**
- Valence electrons form covalent bonds with neighbour atoms
- A diamond crystal structure is thus formed
- Applying energy may break some covalent bonds – electrons pass to **conduction band**
- Energy can be applied by raising the temperature or applying an electric field
- Each broken covalent bond creates
  - a free electron
  - a **hole**
- Current in semiconductors:
  - Electrons jump from hole to hole
  - Holes “move” in the oposite direction of electrons
  - Electrons and holes are called charge ***carriers***

Intrinsic semiconductor: carrier concentration



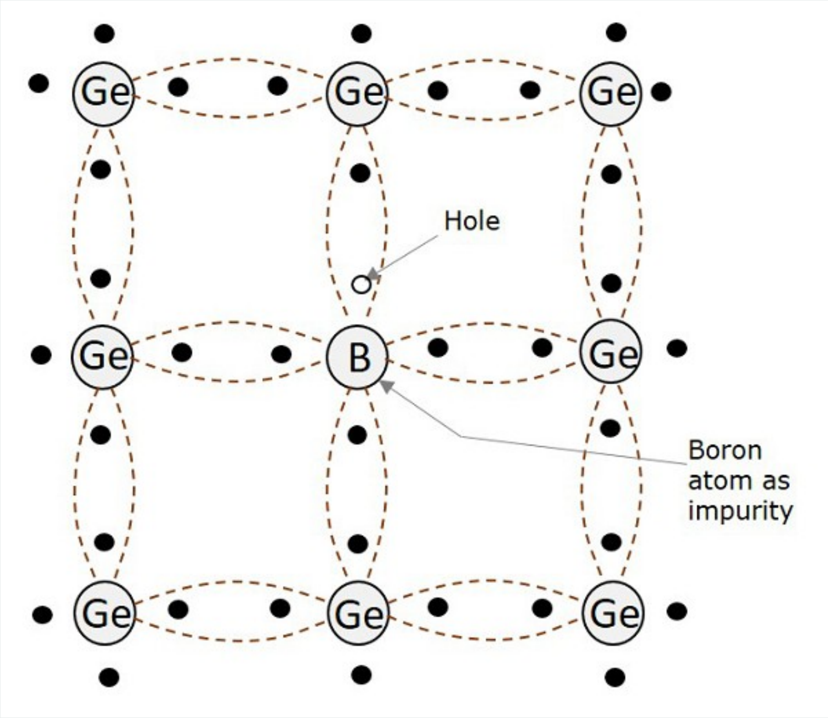
- At temperature T=0K there are no carriers
- The number of carriers increases with temperature
- ***p***: hole density
- ***n***: electron density
- n_i: intrinsic carrier concentration

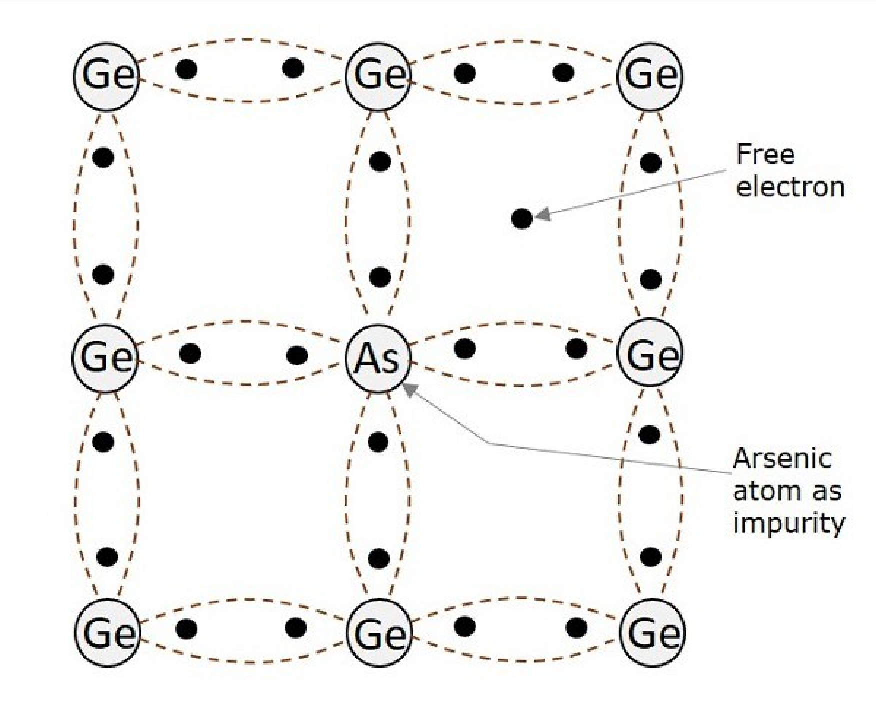
$$p = n = n_i$$

$$n_i = C\,T^{\frac{3}{2}}\,e^{\frac{-E_g}{2kT}}\,[m^{-3}]$$

- $C = 1.66 \times 10^9$ is a constant
- $E_g = 0.66\ eV$: energy required to free one electron in germanium
- ***k***: Boltzmann constant

Extrinsic semiconductor: Germanium + impurities





Boron atom creates hole

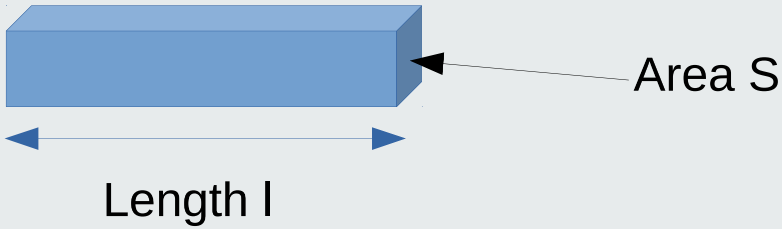
P-Type semiconductor

$$p\,n = n_i^2$$

Arsenic atom creates free electron

N-Type semiconductor

Semiconductor resistor



$$R = \frac{l}{S\,\sigma}$$

$$\sigma = q\left(n\mu_n + p\mu_p\right)$$

σ: conductivity [Sm^{-1}]

Semiconductors have much lower conductivity than metals

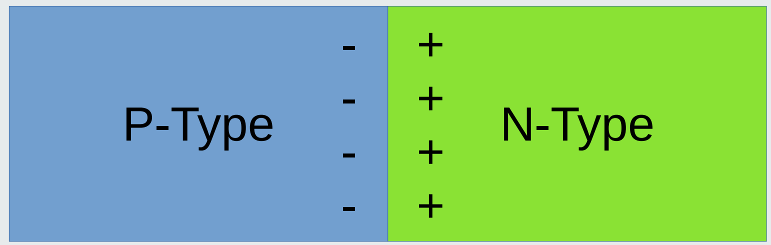
q: electron charge

μ_n : electron mobility (material constant)

μ_p : hole mobility (material constant)

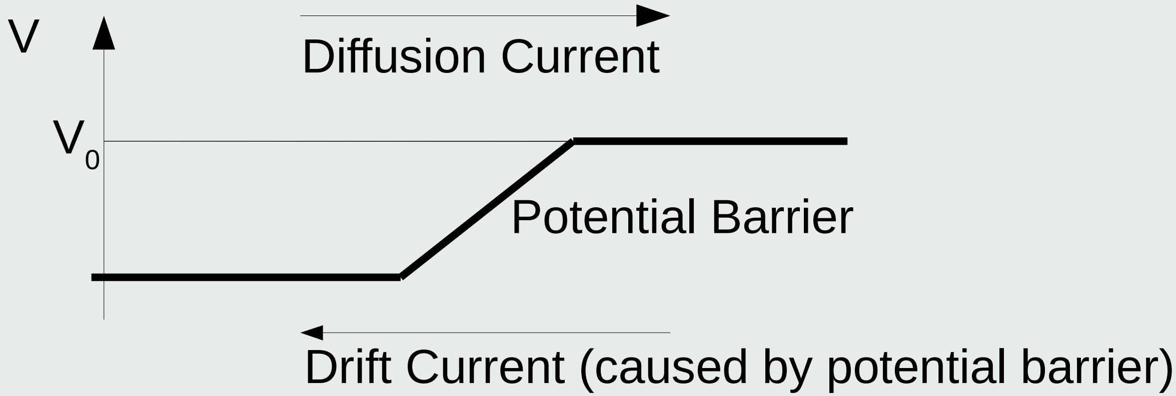
If concentrations **n** and **p** increase due to **doping** or **temperature rise** then the conductivity increases

PN-Junction



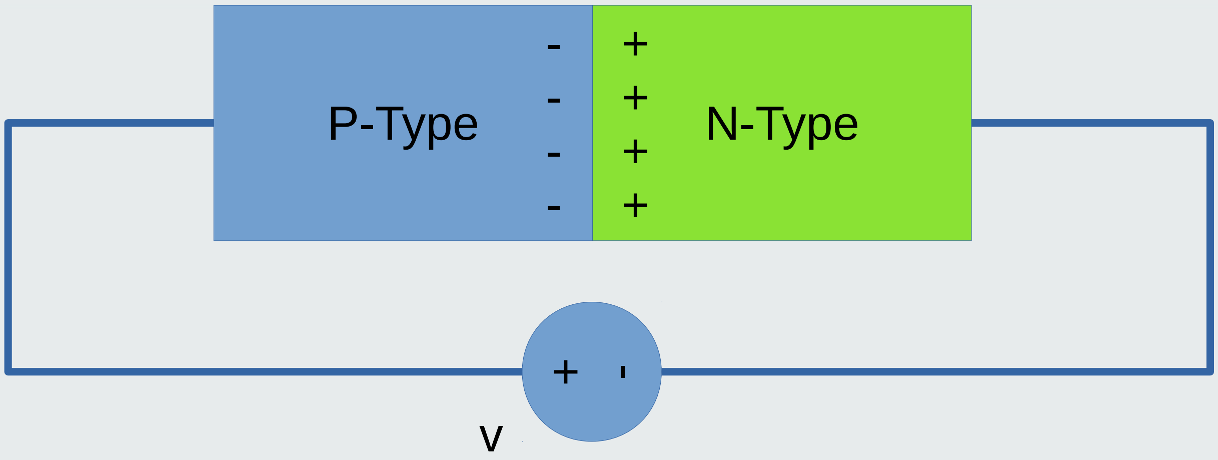
Some electrons move to P-Side by **diffusion** and combine with holes

Some holes move to N-Side by **diffusion** and combine with electrons



Drift Current = **Diffusion Current** (equilibrium)

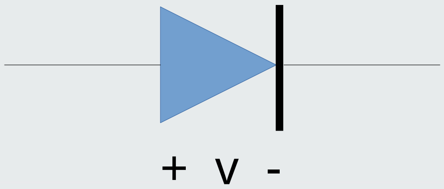
The Diode



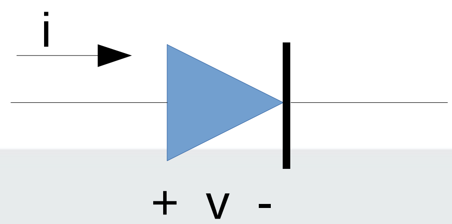
Forward Bias (P-N direction): *v>0* lowers the potential barrier

Reverse Bias (N-P direction): *v<0* reinforces the potential barrier

A biased PN-Junction forms a notable device called a ***DIODE***



Diode Current-Voltage Relationship



$$i = i_p + i_n$$

Total current is ***hole current*** plus ***electron current***

$$i_p \propto \Delta p_n$$

Hole current proportional to hole density change in N-region

$$i_n \propto \Delta n_p$$

Electron current proportional to electron density change in P-region

$$p_n = p_p e^{-\frac{v_B}{\eta V_T}}$$

$$n_p = n_n e^{-\frac{v_B}{\eta V_T}}$$

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

The ***Boltzmann relationship*** gives us p_n *and* n_p

- $\boldsymbol{v_B}$ is the ***potential barrier voltage***
- $\boldsymbol{V_T}$ is the ***thermal voltage***
- ***η*** is the ***material constant***. For germanium η=1, and for silicon η=2. Assume η=1 for the time being.

- ***T*** is the temperature in Kelvin
- ***k*** is the Boltzmann constant
- ***q*** is the electron charge

V_T=25 mV at room temperature (25ºC)

Computing electron and hole density variations

$$v=0 \Rightarrow p_n(0)=p_p e^{-\frac{V_0}{V_T}}$$

If the applied voltage *v* is null, the hole density in the N-region is given only by the open-circuit potential barrier voltage V_0

$$v \neq 0 \Rightarrow p_n(v)=p_p e^{-\frac{V_0}{V_T}} e^{\frac{v}{V_T}}$$

If a voltage *v* is applied, the hole density in the N-region increases!

$$v_B=V_0-v$$

$$\Delta p_n=p_n(v)-p_n(0)=p_p e^{-\frac{V_0}{V_T}}\left(e^{\frac{v}{V_T}}-1\right) \propto e^{\frac{v}{V_T}}-1$$

$$\Delta n_p=n_p(v)-n_p(0)=n_n e^{-\frac{V_0}{V_T}}\left(e^{\frac{v}{V_T}}-1\right) \propto e^{\frac{v}{V_T}}-1$$

(by symmetry)

Diode I-V Characteristic

$$i = i_p + i_n$$

Total current is ***hole current*** plus ***electron current***

$$i_p \propto \Delta p_n$$

Hole current is proportional to electron density change in N-region

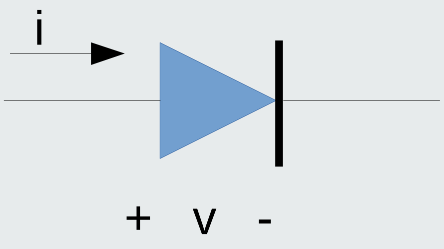
$$i_n \propto \Delta n_p$$

Electron current is proportional to electron density change in P-region

$$i_p \propto e^{\frac{v}{V_T}} - 1$$

$$i_n \propto e^{\frac{v}{V_T}} - 1$$

From previous slide



$$i = I_S \left(e^{\frac{v}{\eta V_T}} - 1 \right)$$

I_S is the proportionality constant called the **Reverse Saturation Current**

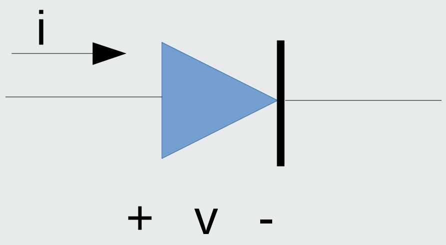
Material constant η restored

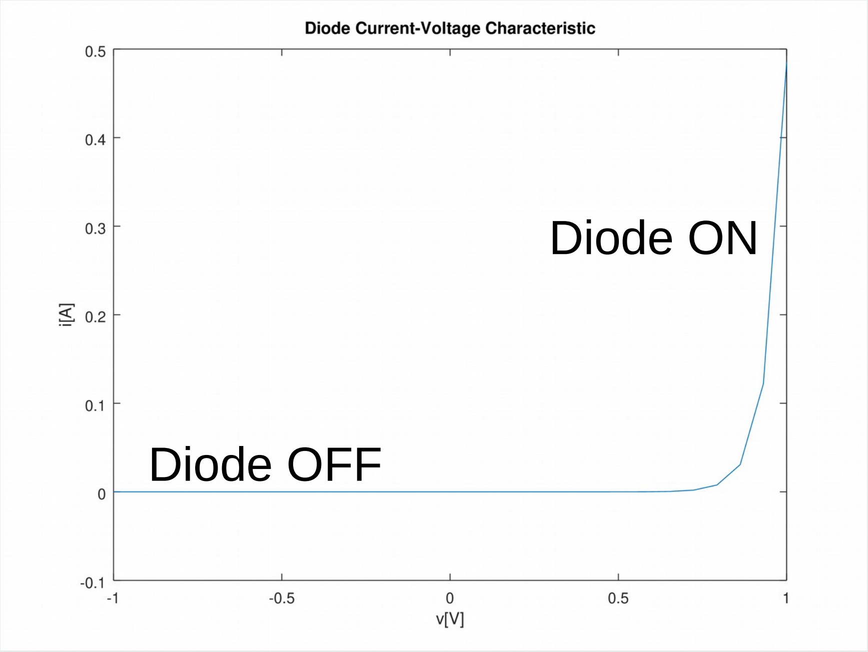
Diode I-V Plots

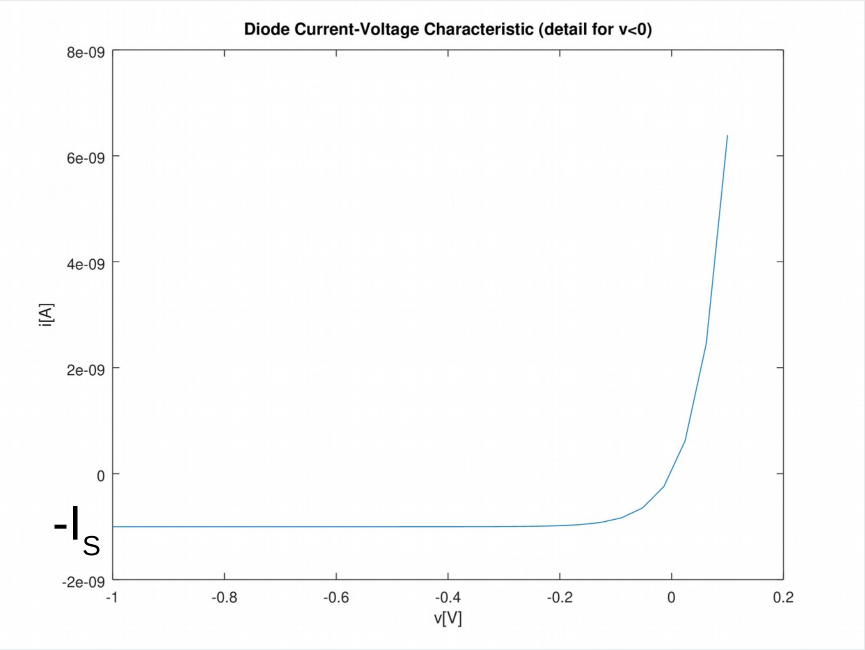
$$i = I_S\left(e^{\frac{v}{\eta V_T}} - 1\right)$$

$$I_S = 1\,nA$$

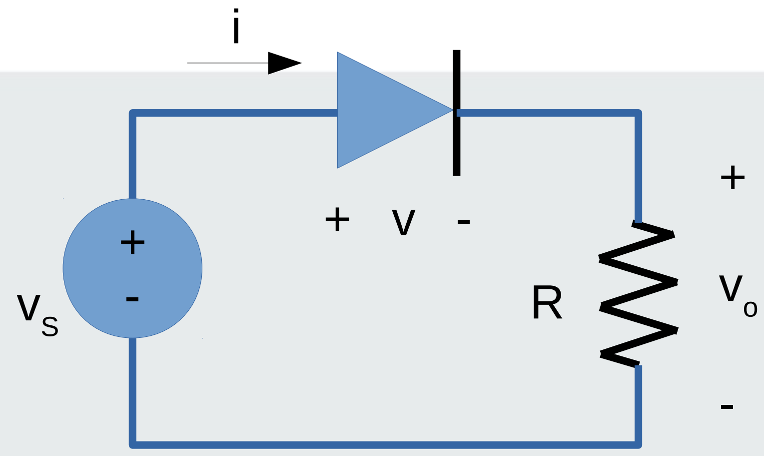
$\eta = 2$ (Silicon)







Example diode circuit



$$v + Ri - v_s = 0$$ KVL

$$v + R I_S \left(e^{\frac{v}{\eta V_T}} - 1 \right) - v_s = 0$$

Non-Linear Equation!

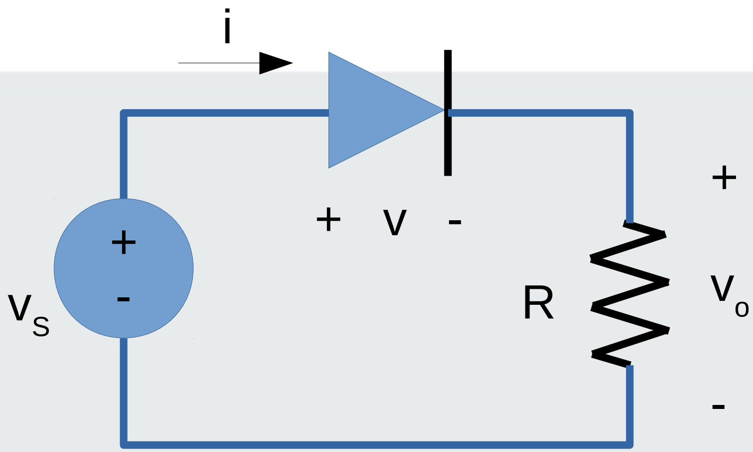
$$f(v) = v + R I_S \left(e^{\frac{v}{\eta V_T}} - 1 \right) - v_s$$ Define error function

$$f(v) = 0$$ Solve non-linear equation for v

$$x_{n+1} = x_n - \frac{f(x_n)}{f'(x_n)}$$ Use **Newton Raphson's iterative method**

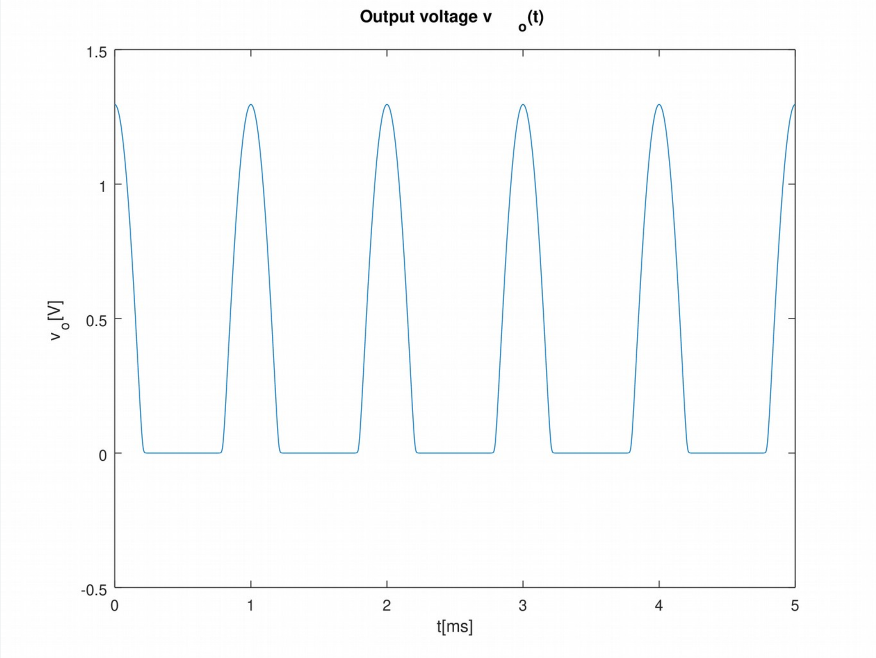
$$|x_{n+1} - x_n| < \delta$$ Stop condition: δ is the desired error

Example diode circuit solution



$$v_s(t)=2\cos(2\pi f\,t)$$
$$I_S=1\,nA$$
$$R=1\,k\Omega$$
$$f=1\,kHz$$
$$v_o=v_s-v\,;v_o=0$$
$$i=\frac{v_o}{R}\,;i=0$$

(ON; OFF)



Octave script l11.m solves 1 non-linear equation for v, for each time instant t

HALF WAVE RECTIFIER CIRCUIT

Conclusion

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- Example diode circuit