Lecture3: Diode

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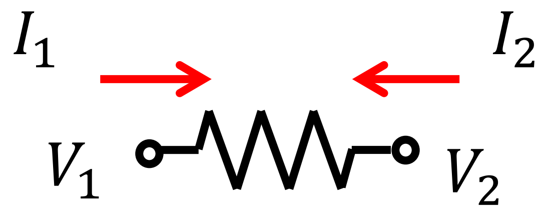
Two-terminal element



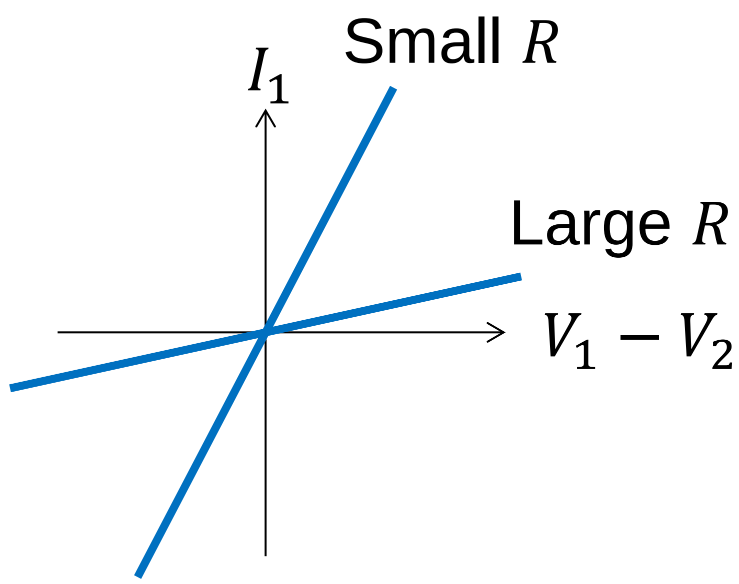
- Terminal quantities
  - Two terminal voltages
  - Two terminal currents

- Number of independent quantities
  - Note that $I_1 + I_2 = 0$.
  - Note that a common change in V_1 and V_2 does not make a difference.
  - Therefore, I_1 and $V_1 - V_2$ can be regarded as independent variables.

- Each two-terminal elements has its own relation between I_1 and $V_1 - V_2$.

Current vs. voltage

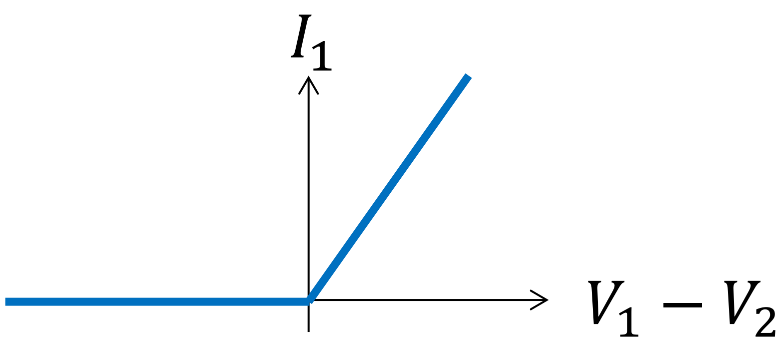
- Sources
  - Voltage source: $V_1 - V_2 = \boldsymbol{V_{source}}$
  - Current source: $I_1 = -I_2 = \boldsymbol{I_{source}}$



- R, L, C
  - Resistor: $I_1 = \frac{V_1 - V_2}{\boldsymbol{R}}$
  - Capacitor: $I_1 = \boldsymbol{C}\frac{d(V_1 - V_2)}{dt}$
  - Inductor: $V_1 - V_2 = \boldsymbol{L}\frac{dI_1}{dt}$
  - They are linear. (When you scale the voltage, the current is scaled with the same factor.)

Nonlinearity?

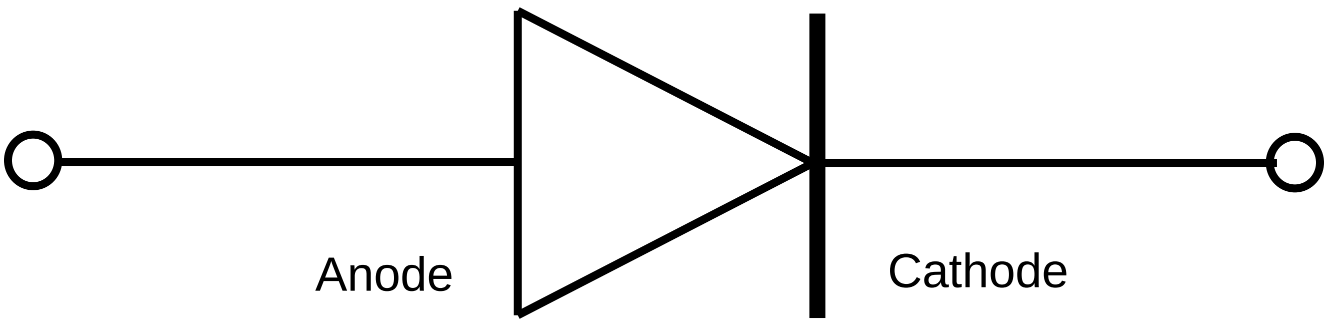
- Consider a toggle light switch.
- Assume a circuit element.



  - For a negative voltage, it's electrically open.
  - For a positive voltage, it's resistive.
  - Is there such a circuit element? Yes!

Diode

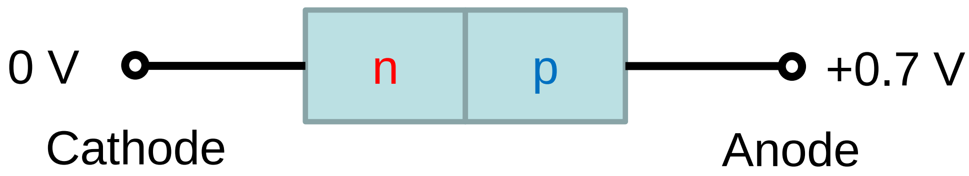
- In 1919, the term *diode* was coined from the Greek roots *di* (from *δί*), meaning 'two', and *ode* (from *ὁδός*), meaning 'path'. (Taken from Wikipedia)
  - Its symbol



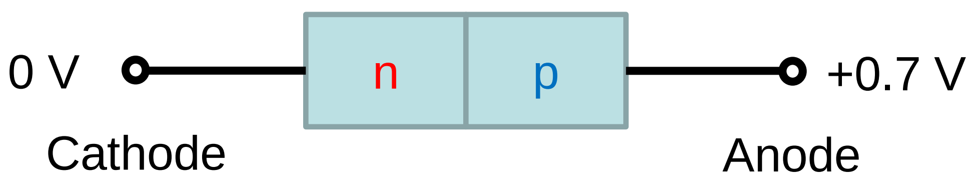
  - Current ➔ : Allowed
  - Current 🡐 : Not allowed

Forward/reverse

- Forward bias
  - The voltage at the cathode is higher than the adode voltage.

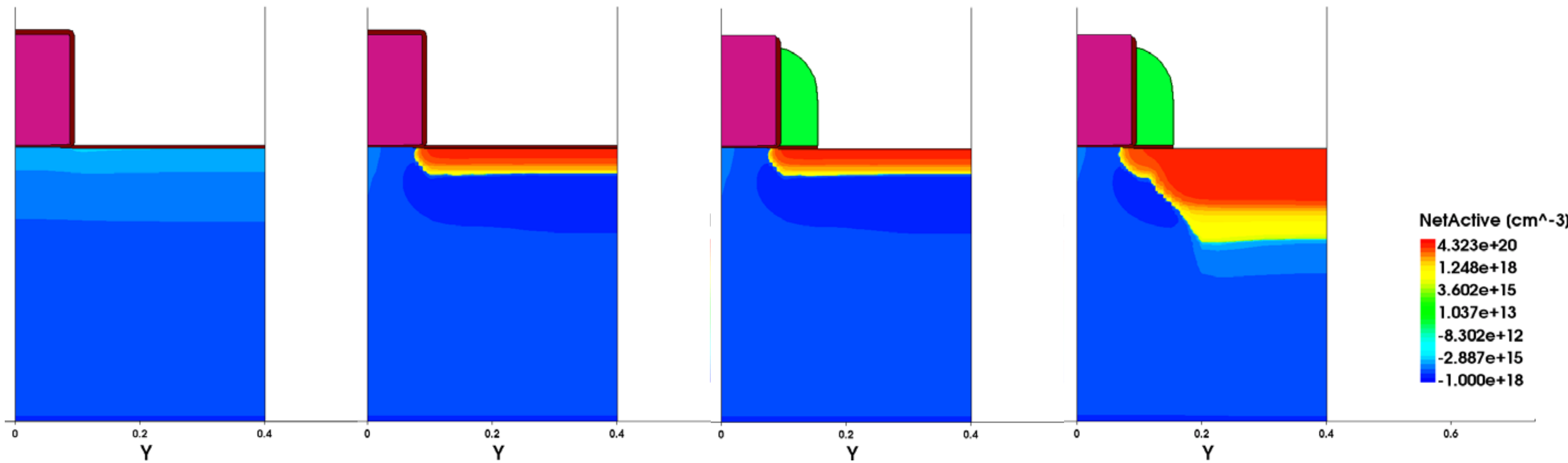


- Reverse bias
  - The voltage at the anode is lower than the cathode voltage.



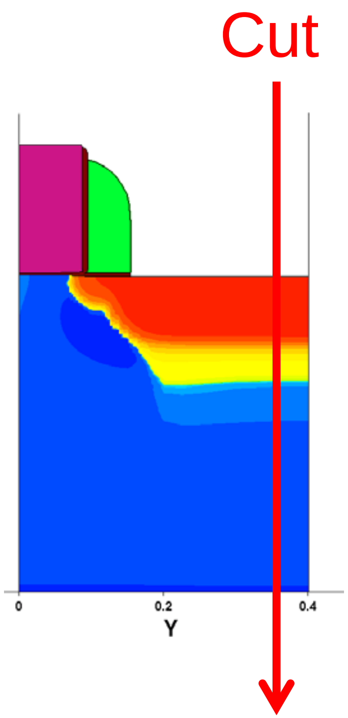
Fabrication

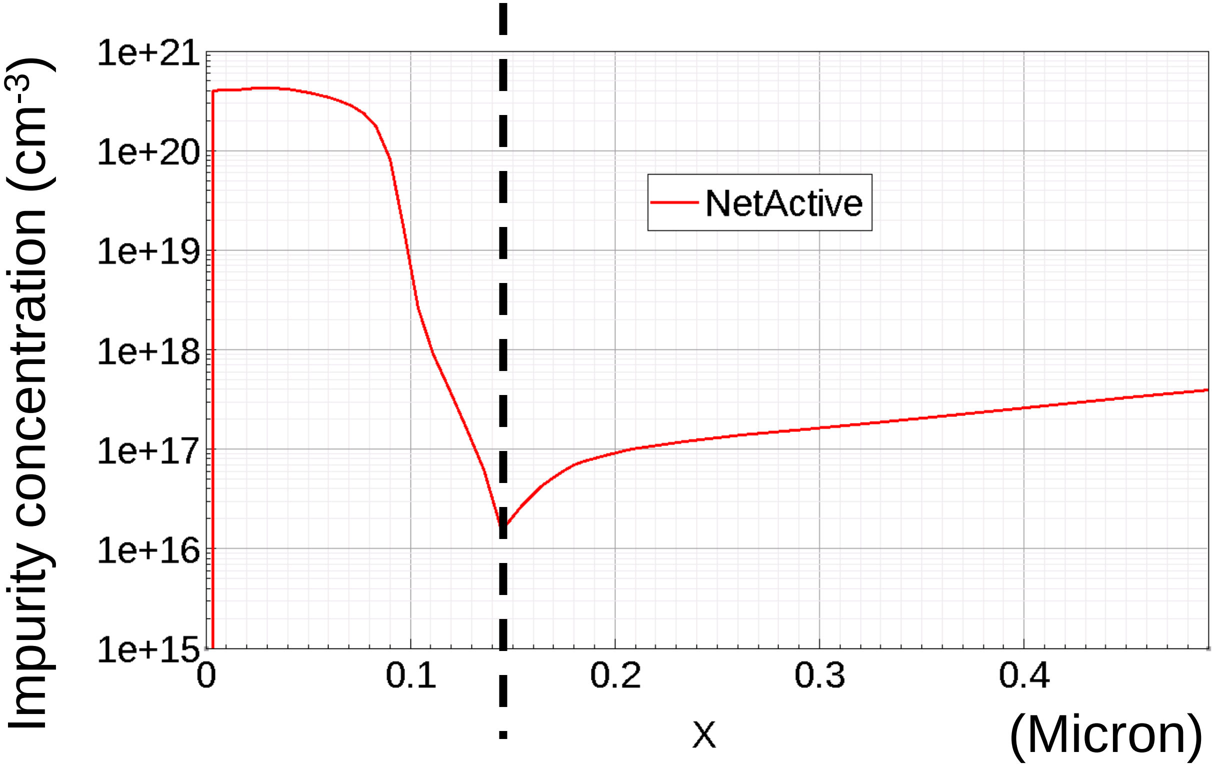
- PN junction
  - Results of the process simulation are shown.
  - Red: Silicon region with Arsenic ions
  - Blue: Silicon region with Boron ions



Vertical doping profile

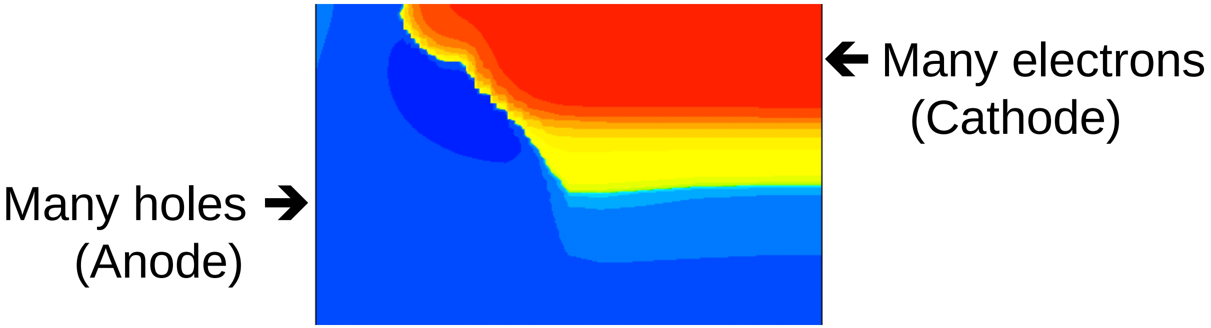
- Active dopant





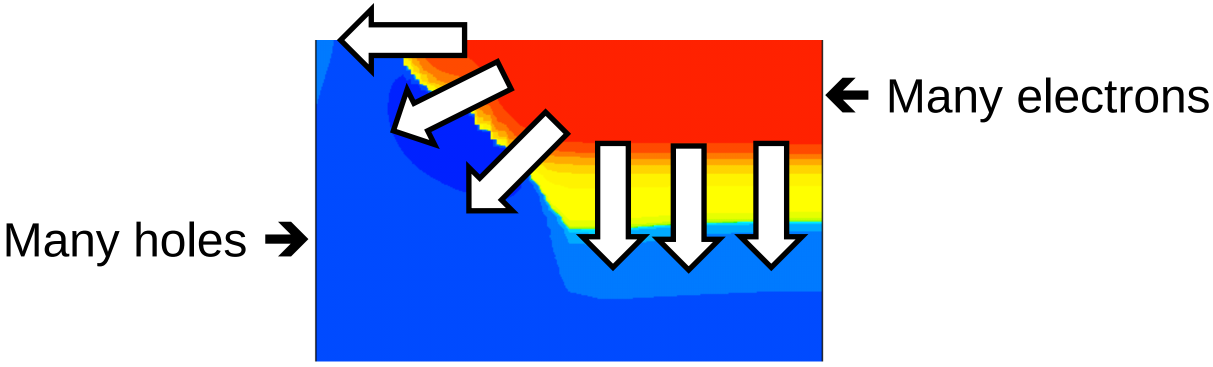
Equilibrium (1)

- When the applied voltage is zero, no current occurs.
  - Many electrons in the "red" region. (Doped with Arsenic ions. "n-type")
  - Many holes in the "blue" region. (Doped with Boron ions. "p-type")
  - Due to the diffusion mechanism, they tend to spread over.
  - Then, we will have the net current! (It's not possible.)



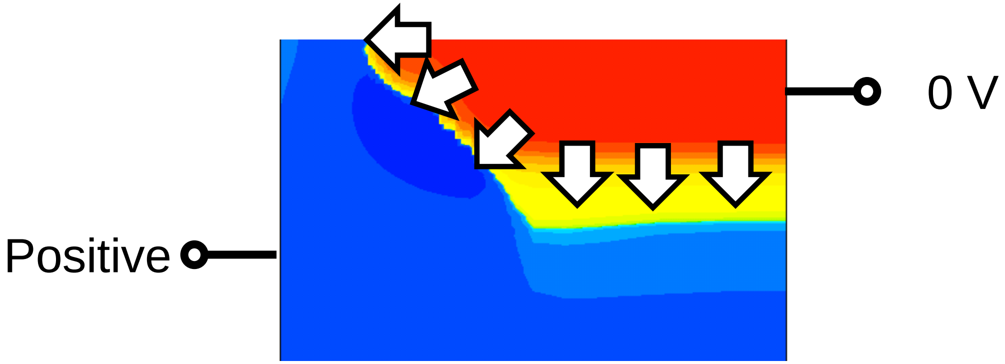
Equilibrium (2)

- An electric field is built. (Built-in field)
  - It pushes the electrons back to the n-type region.
  - It pushes the holes back to the p-type region.
  - Direction of the electric field?
  - At equilibrium, drift (due to the electric field) and diffusion (due to the density difference) are exactly matched.



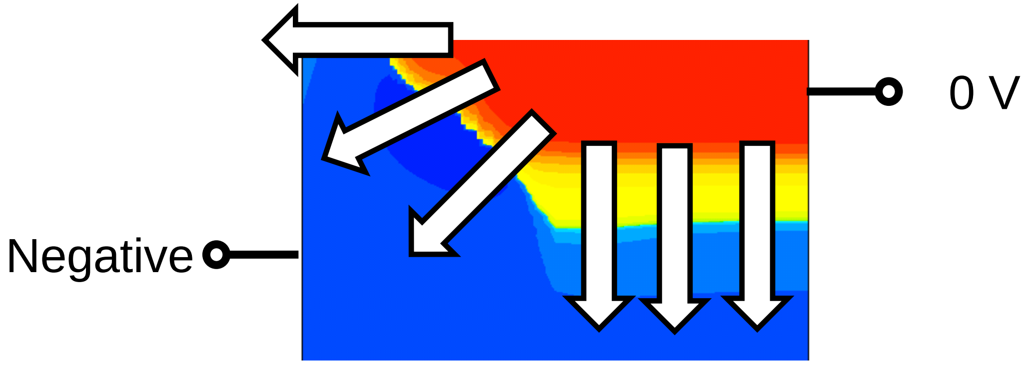
Forward bias

- We have a positive voltage at the anode.
  - Additional electric field from positive to 0 V
  - The external voltage opposes the built-in potential.
  - No sufficiently strong electric field to prevent the diffusion
  - It raises the diffusion currents substantially.



Reverse bias

- We have a negative voltage at the anode.
  - Additional electric field from 0 V to negative
  - The applied voltage enhances the field.
  - Even stronger electric field to prevent the diffusion
  - It prohibits the current flow.
- Highly nonlinear operation!



IV characteristics (1)

- Review
  - The diode current, I_D, is depedent on the diode voltage, V_D.
  - Then, what is $I_D(V_D)$?
- Compare $V_D = 0.3$ V, 0.4 V, and 0.5 V.
  - We know that the electric field for 0.5 V is weakest.
  - Of course, for 0.3 V, it is strongest.
  - Anyway, they are different by a constant voltage, 0.1 V.
  - Then, what about $I_D(0.3)$, $I_D(0.4)$, and $I_D(0.5)$?
  - Do you expect a linear dependence?

IV characteristics (2)

- Exponential dependence on V_D
  - V_D is normalized by the thermal voltage, $V_T = \frac{k_B T}{q}$.
  - At 300 K, $V_T \approx 0.002585\ \mathrm{V} = 25.85\ \mathrm{mV}$.
  - Then, the diode current can be written as

$$I_D = I_S \left(\exp \frac{V_D}{V_T} - 1 \right)$$

  - Here, the “reverse saturation current” (I_S) is a given constant. It’s a small current.

IV characteristics (3)

- Some limiting cases:

$$I_D = I_S\left(\exp\frac{V_D}{V_T} - 1\right)$$

  - When V_D is close to zero, $\exp\frac{V_D}{V_T} \approx 1 + \frac{V_D}{V_T}$

$$I_D = I_S\frac{V_D}{V_T}$$

  - When V_D is negative and $V_D \ll -V_T$, $\exp\frac{V_D}{V_T} \approx 0$

$$I_D = -I_S$$

  - When V_D is positive and $V_D \gg V_T$, $I_D = I_S \exp\frac{V_D}{V_T}$