Lecture3: Diode

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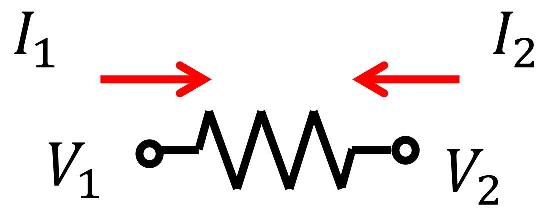
Two-terminal element

- Terminal quantities
  - Two terminal voltages
  - Two terminal currents

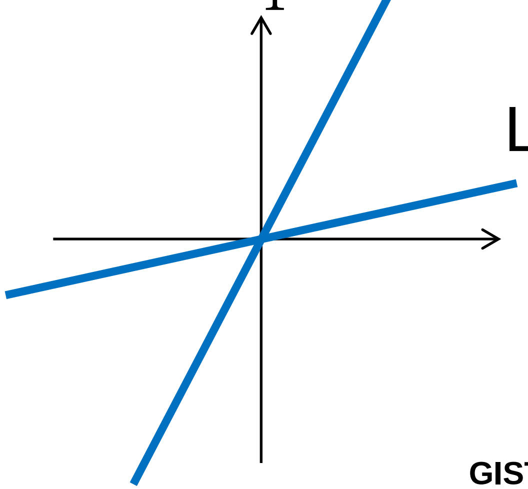


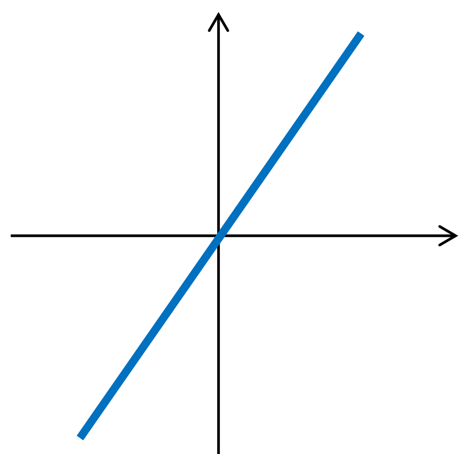
- Number of independent quantities
  - Note that $I_1 + I_2 = 0$.
  - Note that a common change in V_1 and V_2 does not make a difference.
  - Therefore, I_1 and $V_1 - V_2$ can be regarded as independent variables.

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

I-V curve

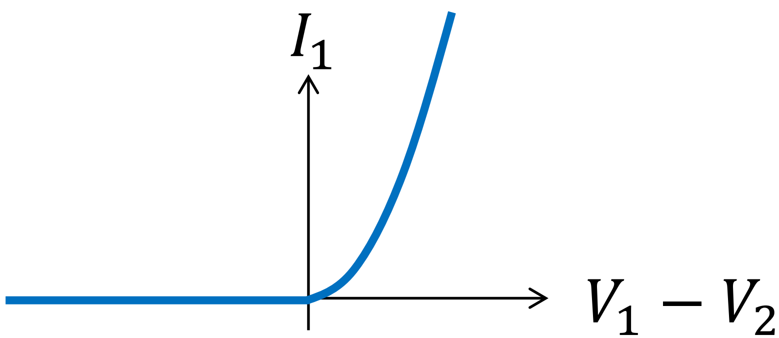
- R, L, C
  - Resistor: $I_1 = \frac{V_1 - V_2}{\boldsymbol{R}}$
  - Capacitor: $I_1 = \boldsymbol{C}\frac{d(V_1 - V_2)}{dt}$
  - Inductor: $V_1 - V_2 = \boldsymbol{L}\frac{dI_1}{dt}$
  - They are linear. (When you scale the voltage, the current is scaled with the same factor.)





Nonlinear element

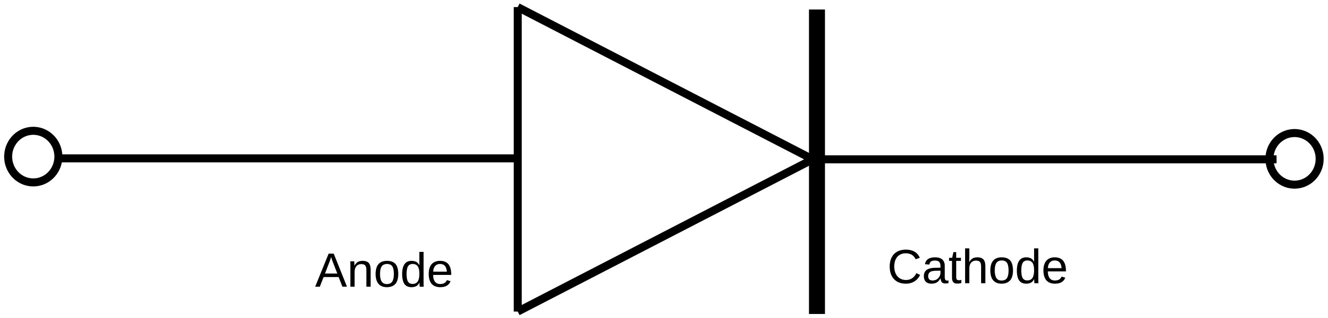
- Assume a circuit element.



  - For a negative voltage, it's electrically open.
  - For a positive voltage, it conducts.
  - It is a nonlinear element.

Diode

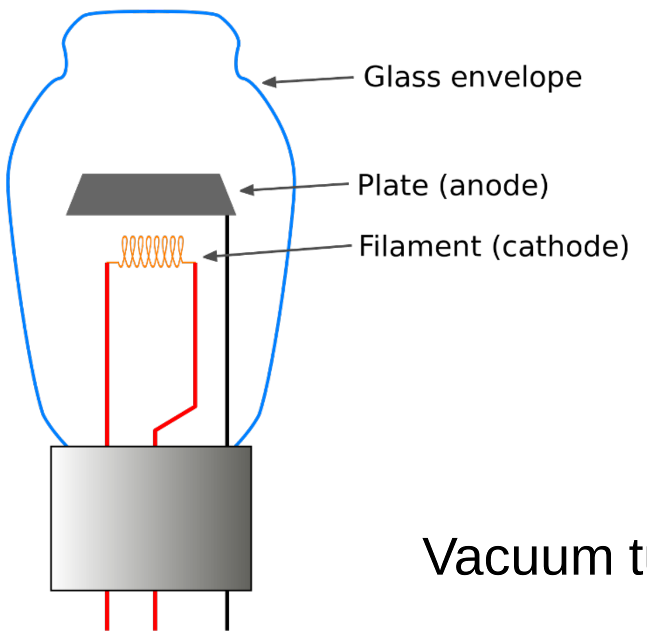
- In 1919, the term *diode* was coined from the Greek roots *di* (from *δί*), meaning 'two', and *ode* (from *ὁδός*), meaning 'path'. (Taken from Wikipedia)
  - Its symbol



  - Current ➔ : Allowed
  - Current 🡐 : Not allowed

Vacuum tube

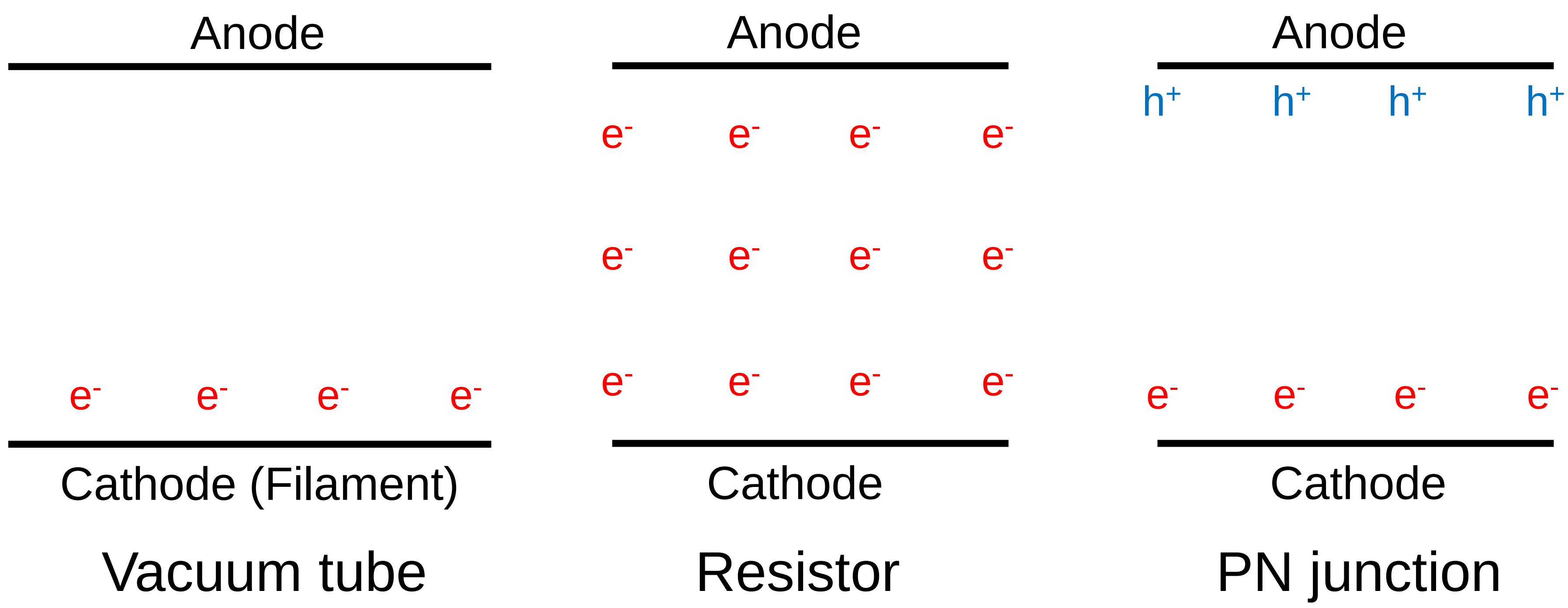
- Original implementation of a diode
  - The heated filament emits electrons.
  - When the anode voltage is larger than the cathode voltage, those electrons move toward the anode.
  - Asymmetry between two terminals is the key factor!



Vacuum tube (Wiktionary)

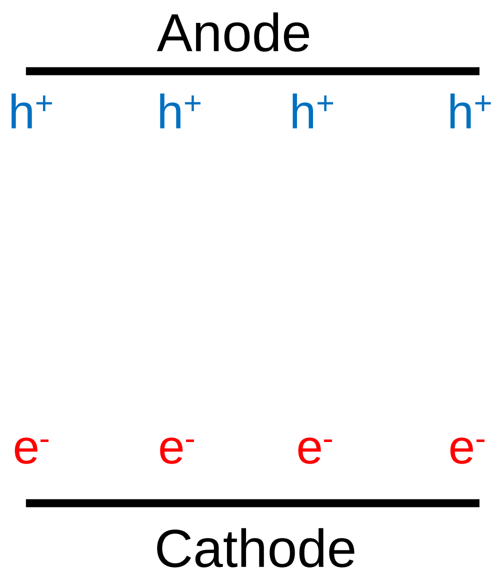
Concept

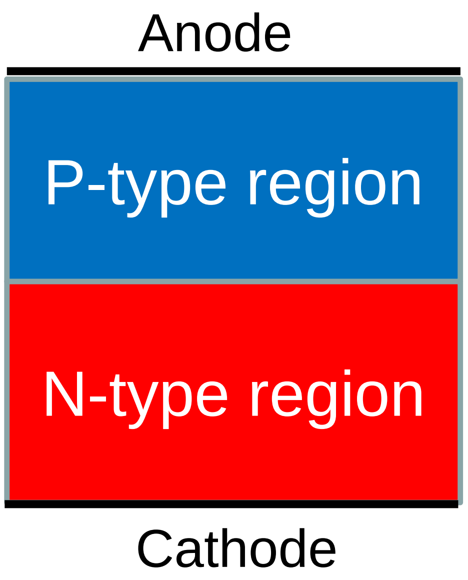
- (Spatial) asymmetry is the key to realize the nonlinearity.
  - Homogeneously distributed electrons?
  - Electrons near the cathode, holes near the anode?



PN junction

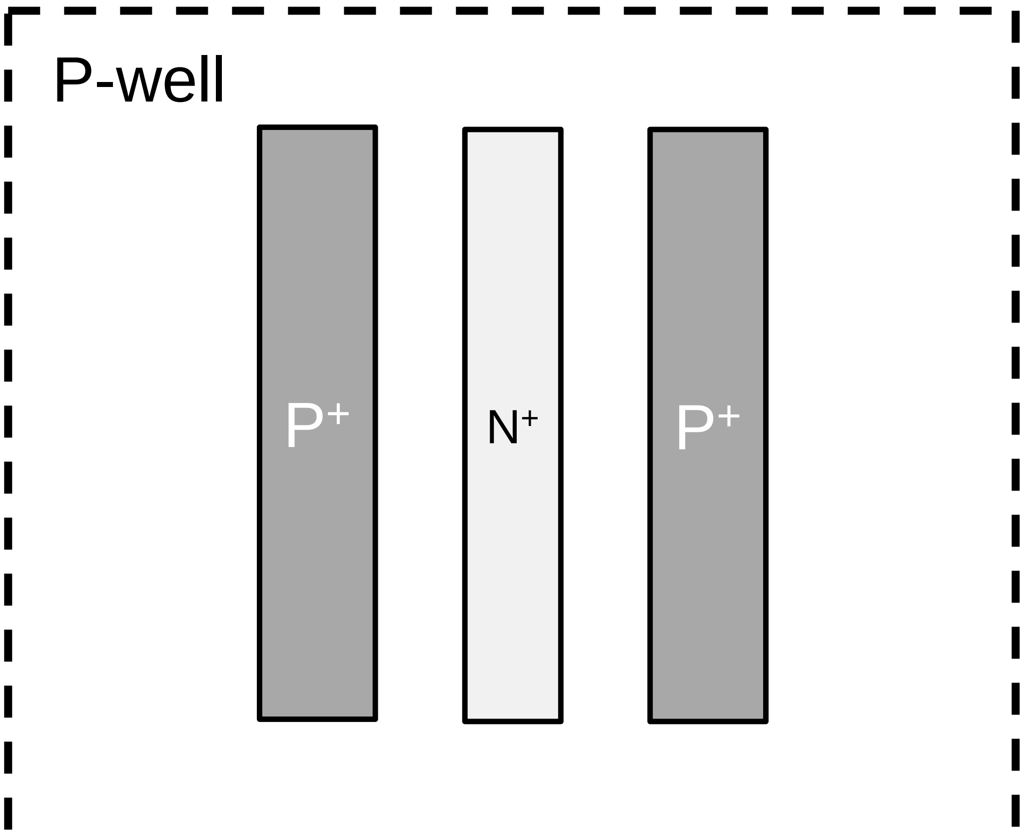
- Dope the substrate twice with different polarities.
  - Junction between a P-type region and an N-type region
  - A fabrication method which is friendly to the integrated circuit?





Layout

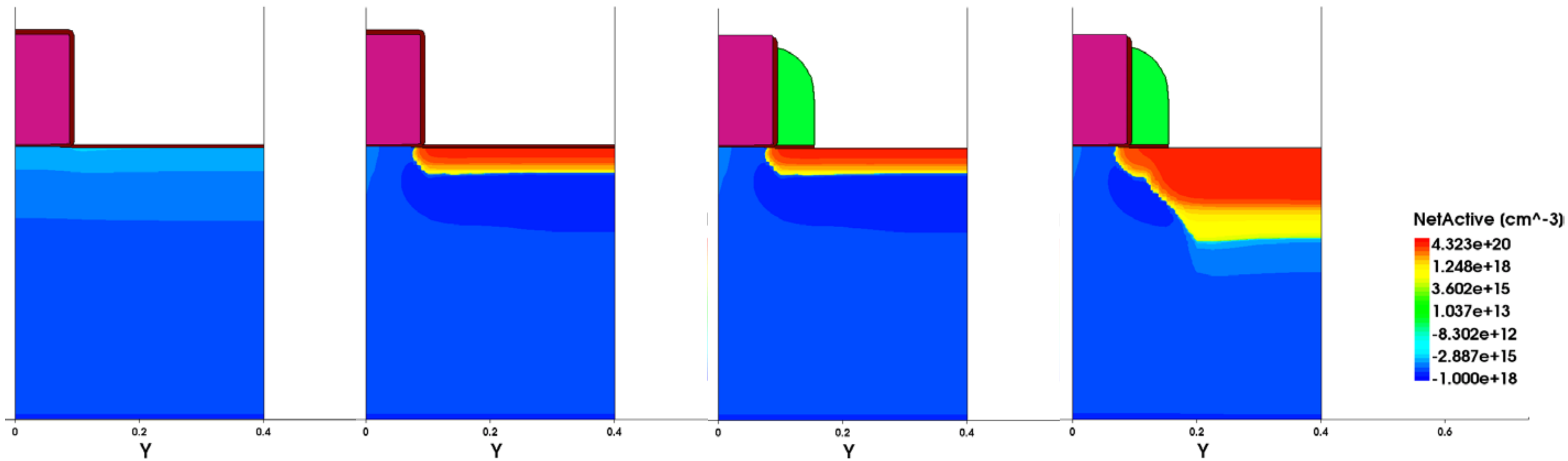
- At a single side, both terminals are made.
  - The N^+ and P^+ regions are connected to metal lines.



Layout of a PN diode used in the ESD protection

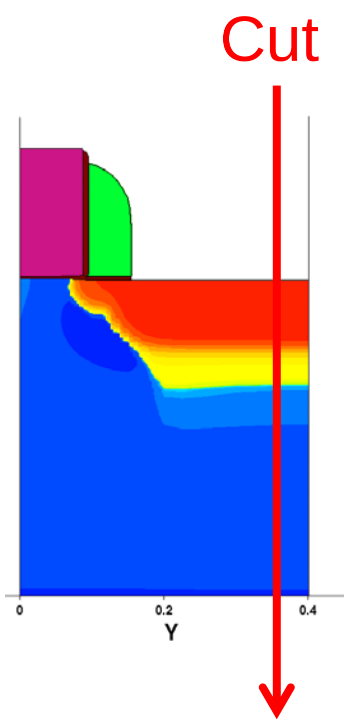
PN junction inside transistors

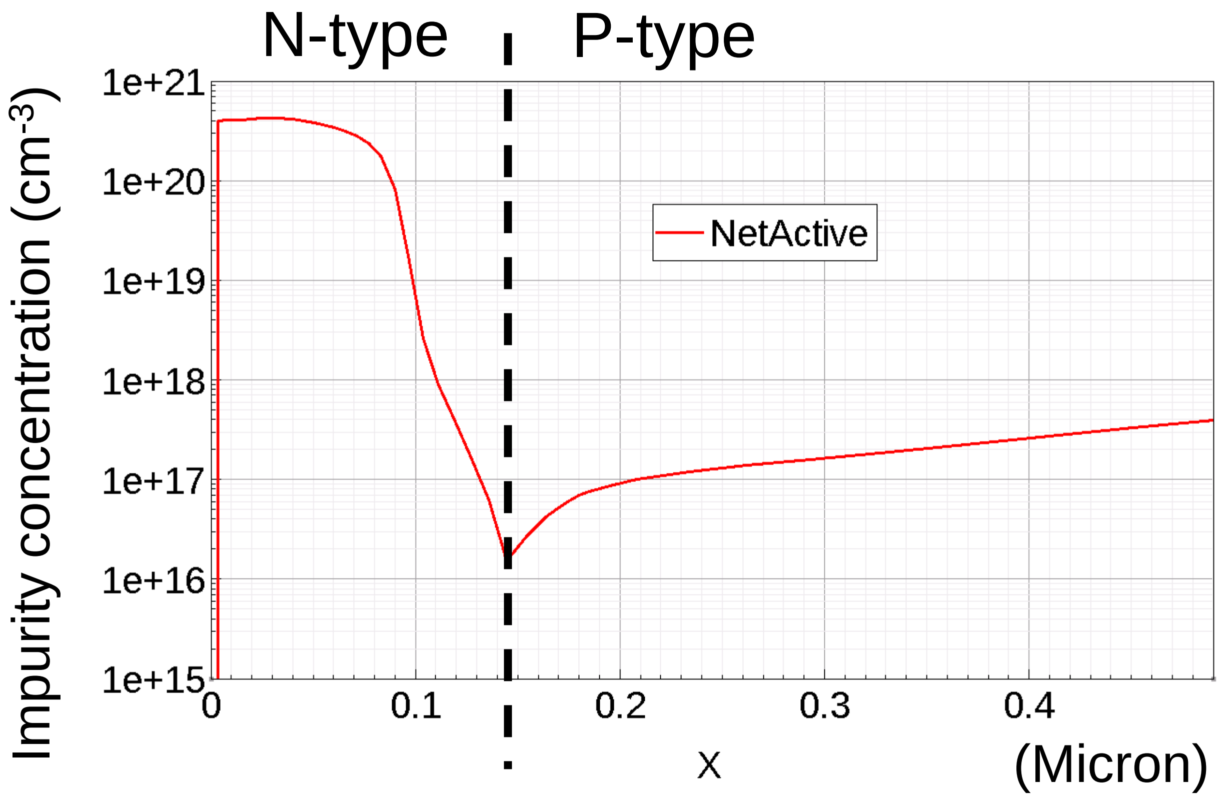
- A building block of transistors
  - Results of the process simulation are shown.
  - Red: Silicon region with Arsenic ions
  - Blue: Silicon region with Boron ions



Vertical doping profile

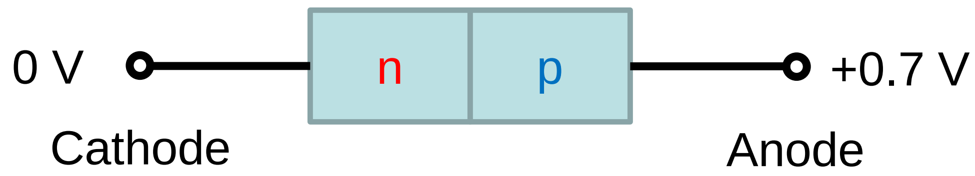
- Active dopant



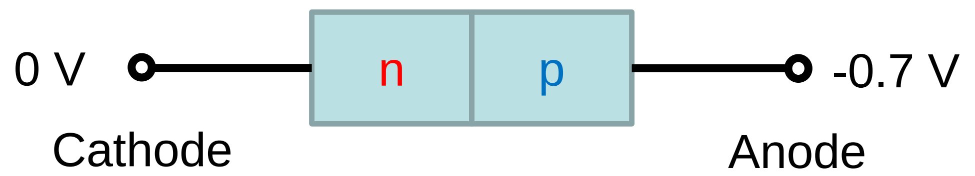


Forward/reverse

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



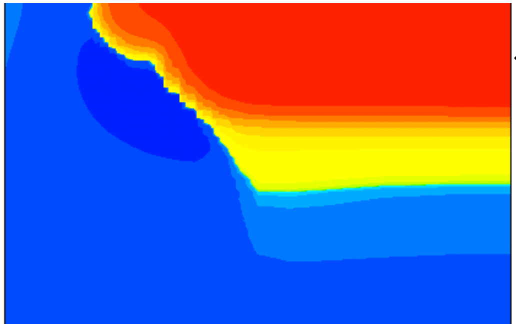
- Reverse bias
  – The voltage at the anode is lower than the cathode voltage.



- Equilibrium? (Anode voltage) = (Cathode voltage)

Equilibrium

- Bottom line: No current is allowed.
  - Many electrons in the N-type region
  - Many holes in the P-type region
  - Question) Assume $N_D = 10^{20}\ \mathrm{cm}^{-3}$ and $N_A = 10^{17}\ \mathrm{cm}^{-3}$. Calculate the electron densities in both regions.
  - Strong gradient in the electron (or hole) density, ∇n (or ∇p)



Many holes (Anode) →

← Many electrons (Cathode)

Diffusion current

- Diffusion current density

$$\mathbf{J}_n^{diff} = qD_n \nabla n$$
$$\mathbf{J}_p^{diff} = -qD_p \nabla p$$

  - In the 1D structure (along the x direction),

$$J_{n,x}^{diff} = qD_n \frac{dn}{dx}$$
$$J_{p,x}^{diff} = -qD_p \frac{dp}{dx}$$

  - Large diffusion current
- However, we must have $J_{n,x} = J_{p,x} = 0$ everywhere…

Drift current

- Drift current density

$$\mathbf{J}_n^{drift} = q\mu_n n\, \mathbf{E}$$
$$\mathbf{J}_p^{drift} = q\mu_p p\, \mathbf{E}$$

  – In the 1D structure (along the x direction),

$$J_{n,x}^{drift} = q\mu_n n\, E_x$$
$$J_{p,x}^{drift} = q\mu_p n\, E_x$$

- Possible mechanism to counterbalance the diffusion current

Qualitative analysis

- An electric field from the N-type region to the P-type region
  - It pushes the electrons back to the N-type region.
  - It pushes the holes back to the P-type region.
- Electric field needs the net charge.
  - Where can we find the net charge to support the electric field?
  - “Depletion”