# Lecture5: Diode
# Part1: Asymmetry in I-V

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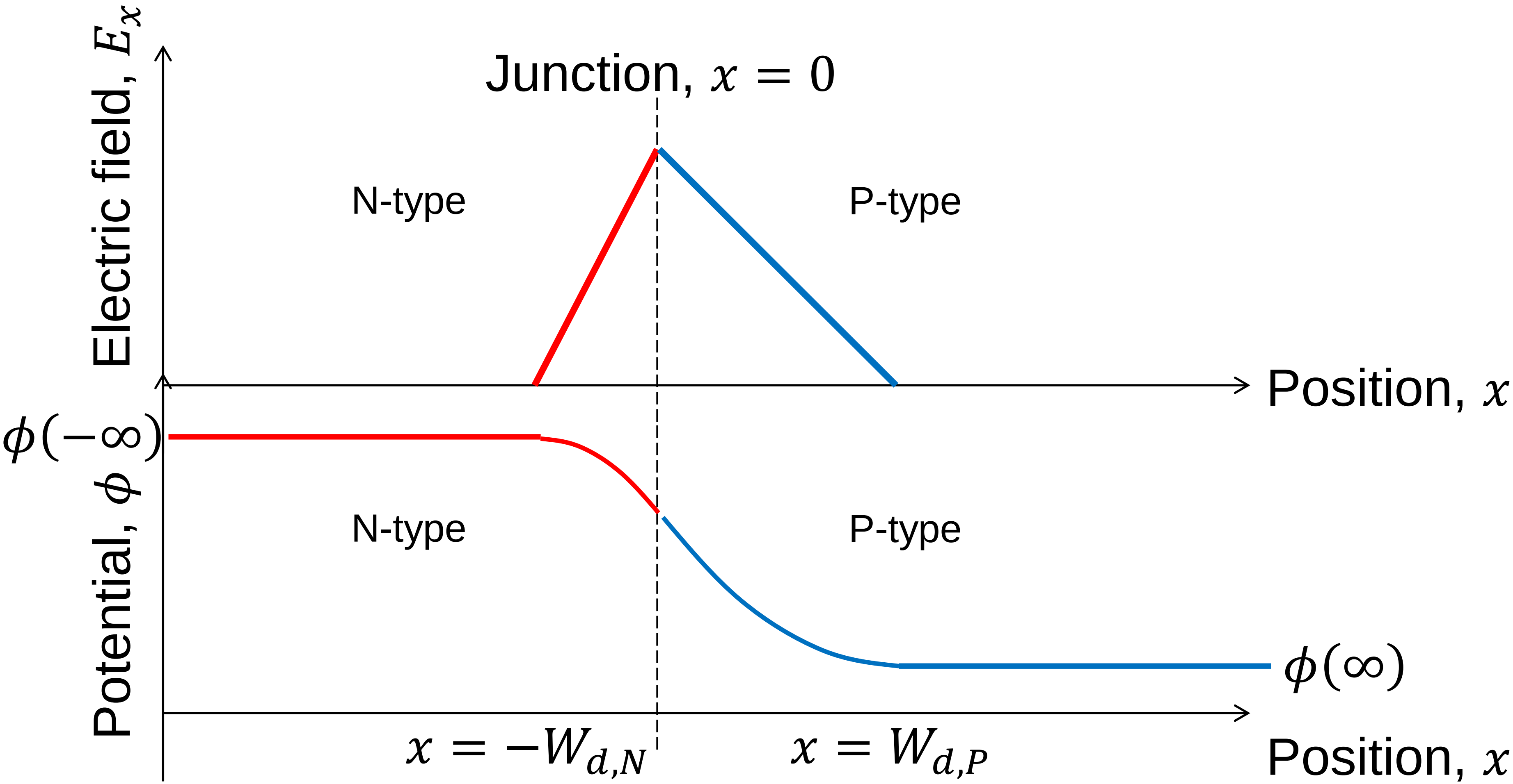
**GIST On-Line Lecture on March 30, 2020 (Internal use only)**

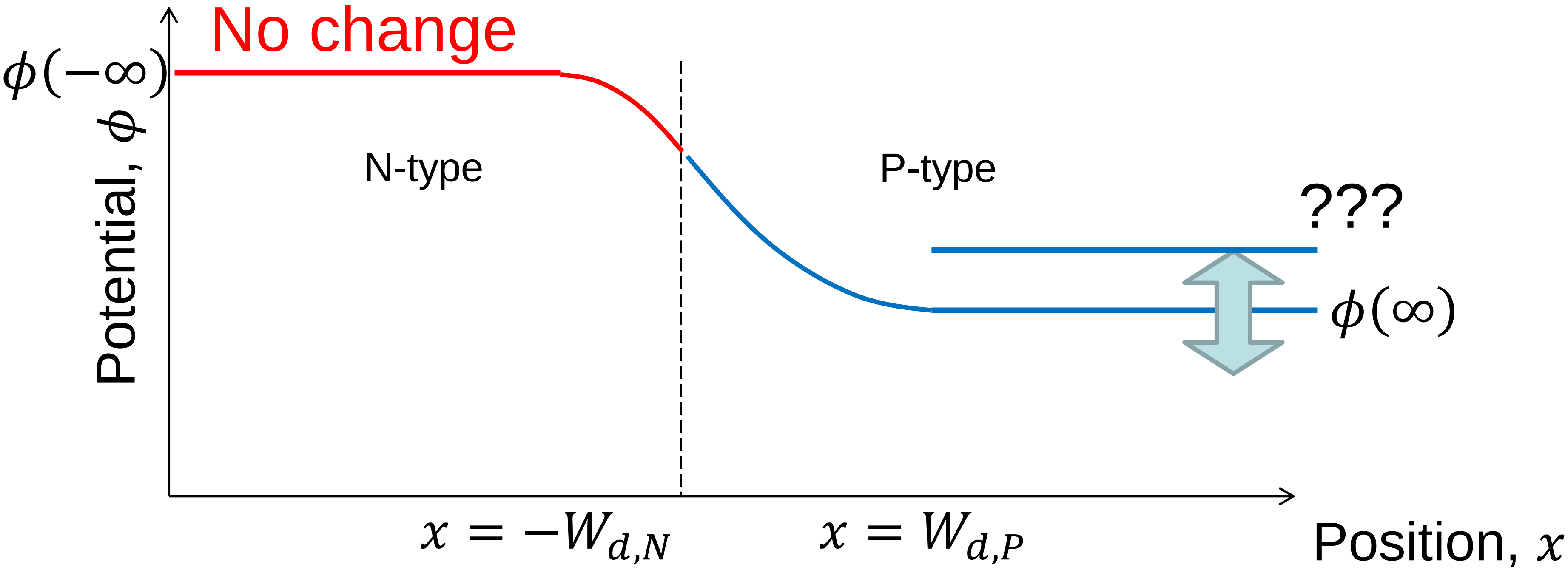
# Equilibrium state

- Perfect balance



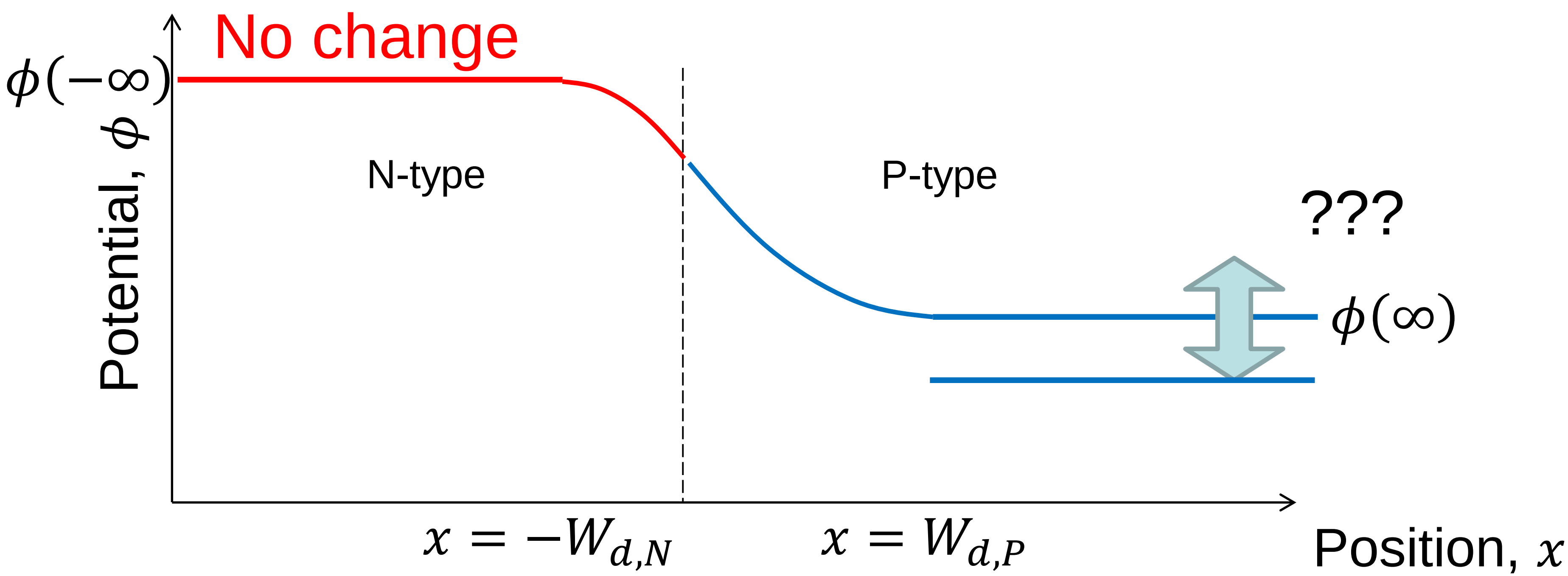
# Forward bias

- Assume that $V_{cathode} = 0\ \mathrm{V}$ and $V_{anode} > 0\ \mathrm{V}$ .
  - What will happen to $\phi(-\infty)$ and $\phi(\infty)$?
  - Is $\mathbf{E}$ stronger or weaker? Weaker.
  - No sufficiently strong electric field to prevent the diffusion
  - It raises the diffusion currents substantially.



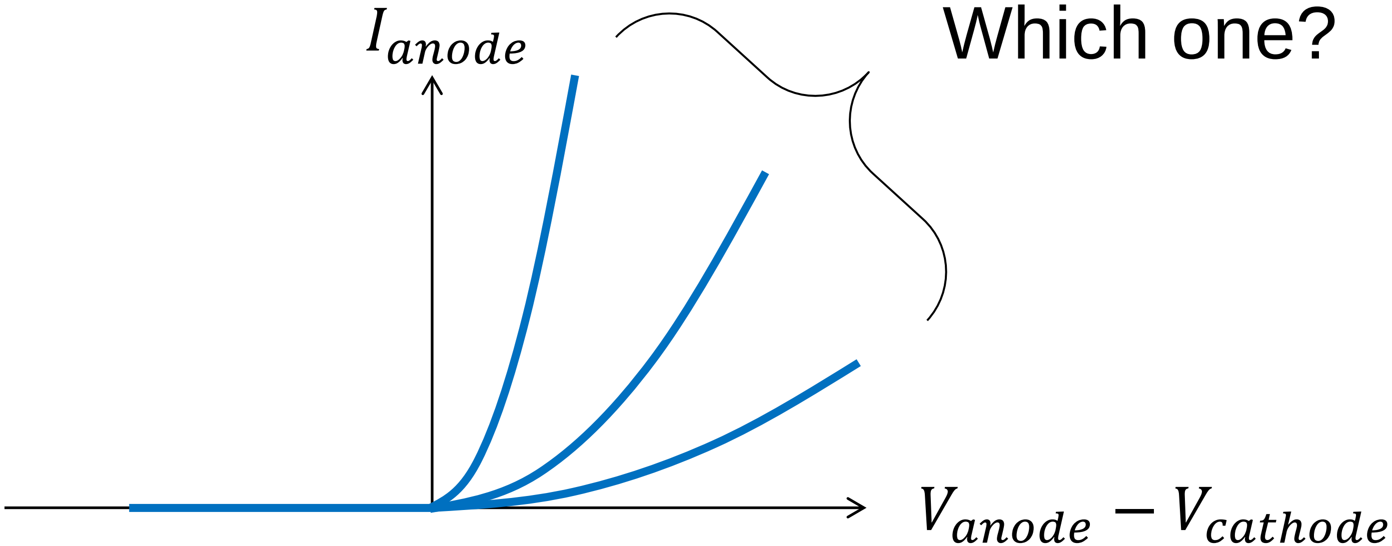
# Reverse bias

- Assume that $V_{cathode} = 0\ \mathrm{V}$ and $V_{anode} < 0\ \mathrm{V}$ .
  - What will happen to $\phi(-\infty)$ and $\phi(\infty)$?
  - Is $\mathbf{E}$ stronger or weaker? Stronger.
  - Even stronger electric field to prevent the diffusion
  - It prohibits the current flow.



# Qualitatively,

- We can expect the following I-V curve.
  - For a reverse bias, almost no current flows.
  - For a forward bias, the diode conducts.
  - What is the analytic expression of the diode current?



# $n$ and $p$ across junction

- At equilibrium,
  - We have the following relation:

$$n = n_i \exp\left(\frac{\phi}{V_T}\right), \qquad p = n_i \exp\left(-\frac{\phi}{V_T}\right)$$

  - At two points across the junction, $x = -W_{d,n}$ and $x = W_{d,p}$.

$$n(-W_{d,n}) = n_i \exp\left(\frac{\phi(-W_{d,n})}{V_T}\right)$$

$$n(W_{d,p}) = n_i \exp\left(\frac{\phi(W_{d,p})}{V_T}\right)$$

$$= n_i \exp\left(\frac{\phi(-W_{d,n})}{V_T}\right) \exp\left(\frac{\phi(W_{d,p}) - \phi(-W_{d,n})}{V_T}\right)$$

$$= n(-W_{d,n}) \exp\left(\frac{\phi(W_{d,p}) - \phi(-W_{d,n})}{V_T}\right)$$

# The law of the junction

- Even at non-equilibrium,
  - The previous relation holds:

$$n(W_{d,p}) = n(-W_{d,n})\exp\left(\frac{\phi(W_{d,p}) - \phi(-W_{d,n})}{V_T}\right)$$

- Potential difference, $\phi(W_{d,p}) - \phi(-W_{d,n})$
  - When the cathode voltage is zero,

$$\phi(W_{d,p}) - \phi(-W_{d,n}) = -V_{bi} + V_{anode}$$

- The minority carrier density
  - It is simply given by

$$n(W_{d,p}) = n_0(W_{d,p})\exp\left(\frac{V_{anode}}{V_T}\right)$$

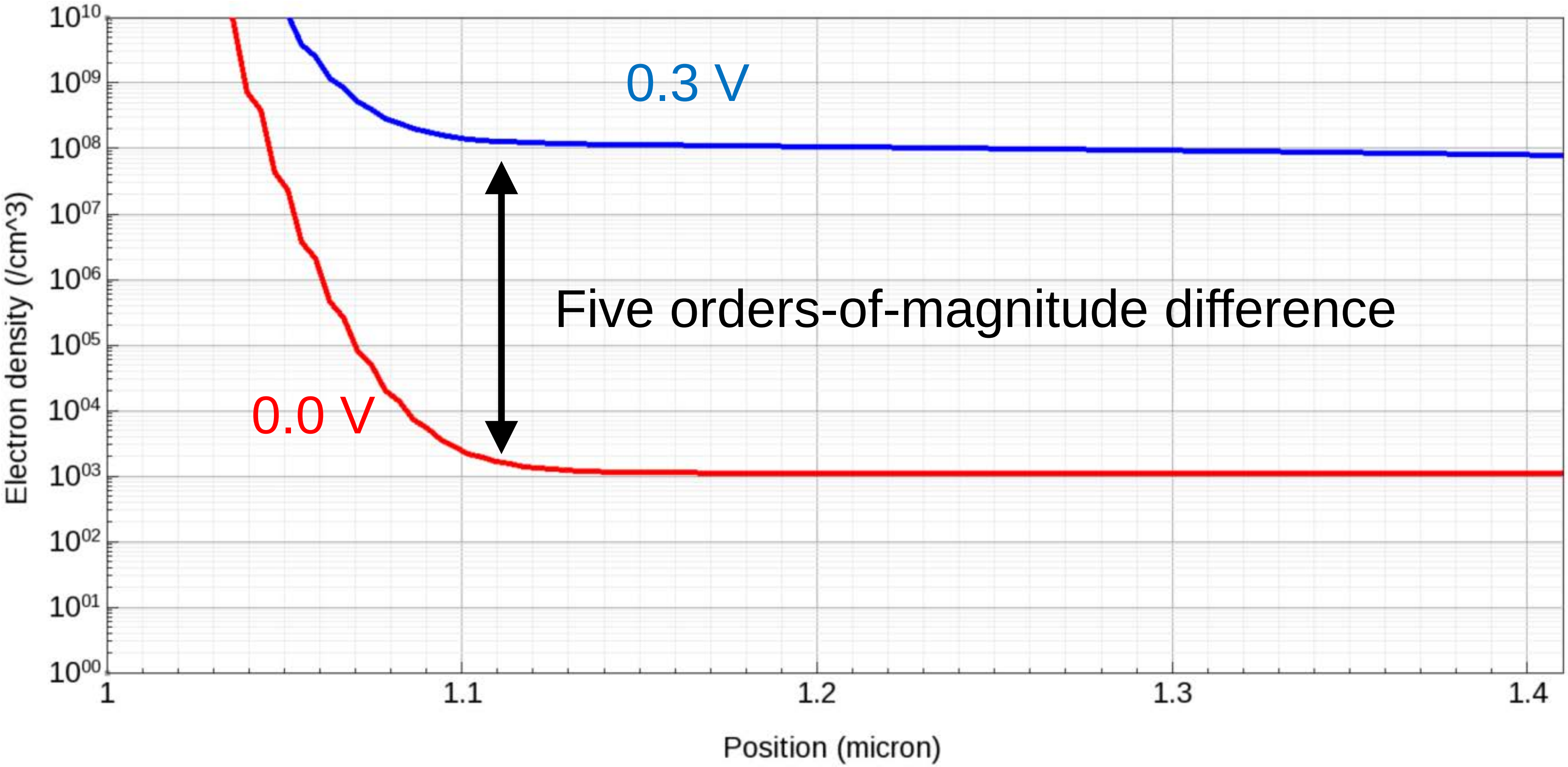
Equilibrium density

# What does it mean?

- Assume that $N_D = 10^{20}\ \mathrm{cm}^{-3}$ and $N_A = 10^{17}\ \mathrm{cm}^{-3}$.
  - At equilibrium, the minority electron density in the P-type region is $10^{3}\ \mathrm{cm}^{-3}$.
  - When a forward bias voltage of 0.3 V is applied, the minority electron density at the edge of the depletion region is $10^{8}\ \mathrm{cm}^{-3}$.
  - When a reverse bias voltage of 0.3 V is applied ($V_{anode} = -0.3\ \mathrm{V}$), the minority electron density at the edge of the depletion region becomes very small. (It is not $10^{-2}\ \mathrm{cm}^{-3}$, but small anyway.)

# Numerical example

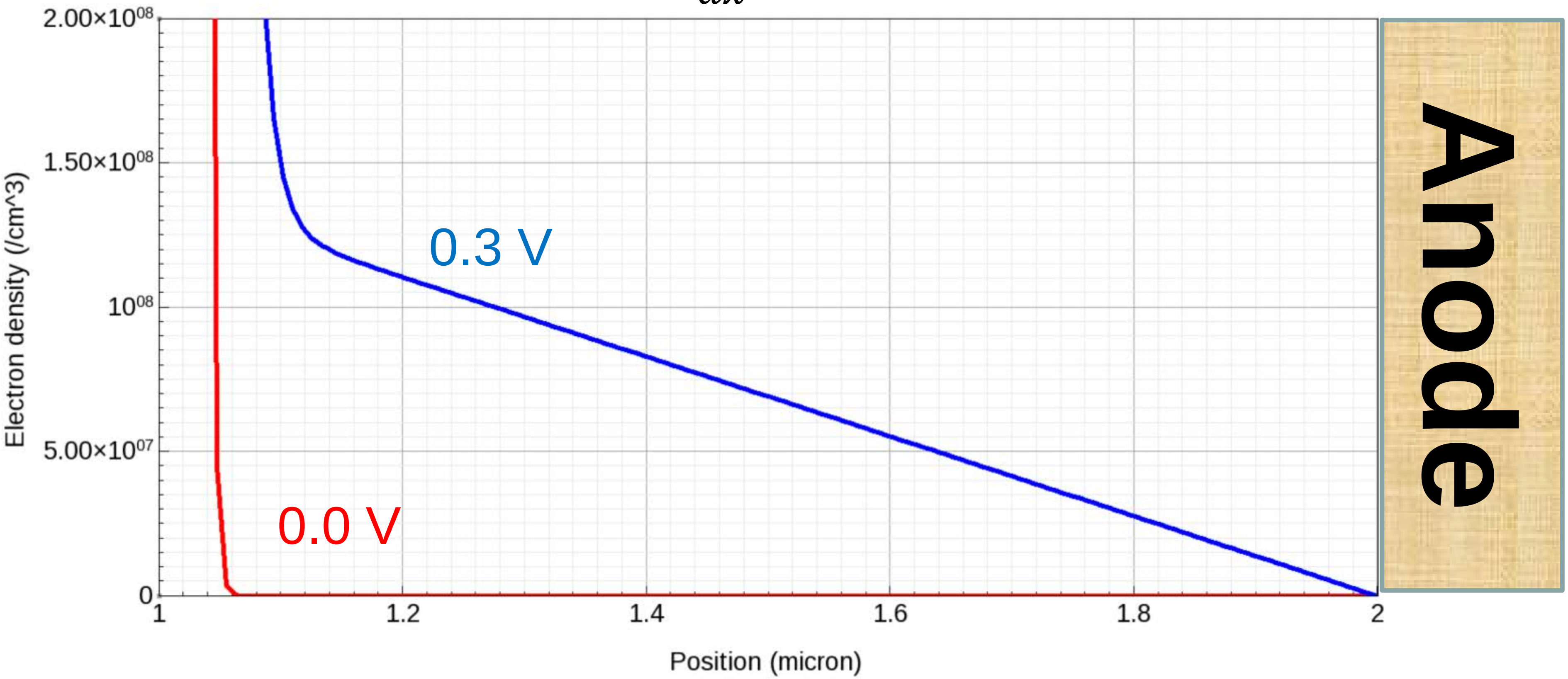
- Three bias voltages, +0.3 V and 0.0 V



# $n$ in linear scale

- In the neutral P-type region, the electric field is quite small.
  - Only the diffusion mechanism is important.

$$J_{n,x}^{diff} = qD_n \frac{dn}{dx} = \text{a constant}$$



# Diffusion equation

- Its solution, $n(x)$, is a linear function.
  - Try this:

$$n(x) = ax + b$$

  - We need two boundary conditions.
  - Law of the junction

$$n(x = W_{d,p}) = n_0 \exp\left(\frac{V_{anode}}{V_T}\right)$$

  - Anode contact

$$n(x = L_p) = n_0$$

- The current density becomes

$$J_{n,x}^{diff} = qD_n \frac{dn}{dx} = -qD_n \frac{n_0}{L_p - W_{d,p}} \left( \exp\left(\frac{V_{anode}}{V_T}\right) - 1 \right)$$

# I-V characteristics

- Exponential dependence on $V_{anode}$
  - $V_{anode}$ is normalized by the thermal voltage, $V_T = \frac{k_B T}{q}$.
  - At 300 K, $V_T \approx 0.02585\ \mathrm{V} = 25.85\ \mathrm{mV}$.
  - Then, the diode current can be written as

$$I_{anode} = I_S \left( \exp \frac{V_{anode}}{V_T} - 1 \right)$$

  - Here, the "reverse saturation current" ($I_S$) is a given constant. It's a small current.

$$I_s = Aqn_i^2 \left( \frac{D_n}{N_A L_n} + \frac{D_p}{N_D L_p} \right)$$

# Some limiting cases

- Useful relations:

$$I_{anode} = I_S \left( \exp \frac{V_{anode}}{V_T} - 1 \right)$$

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

$$I_{anode} = I_S \frac{V_{anode}}{V_T}$$

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

$$I_{anode} = -I_S$$

  - When $V_{anode}$ is positive and $V_{anode} \gg V_T$, $I_{anode} = I_S \exp \frac{V_{anode}}{V_T}$