HW#2

- Razavi, 2nd edition (International edition)
  - P2.10
  - P2.11
  - P2.12

- Due: March 23, 2016 (next Wednesday)
  - Submit your HW to Mr. Junsung Park (“quasarp at gist.ac.kr”, SIC Building, C-411)
  - No delayed submission is accepted.

Lecture5: Basic physics of semiconductor (4)

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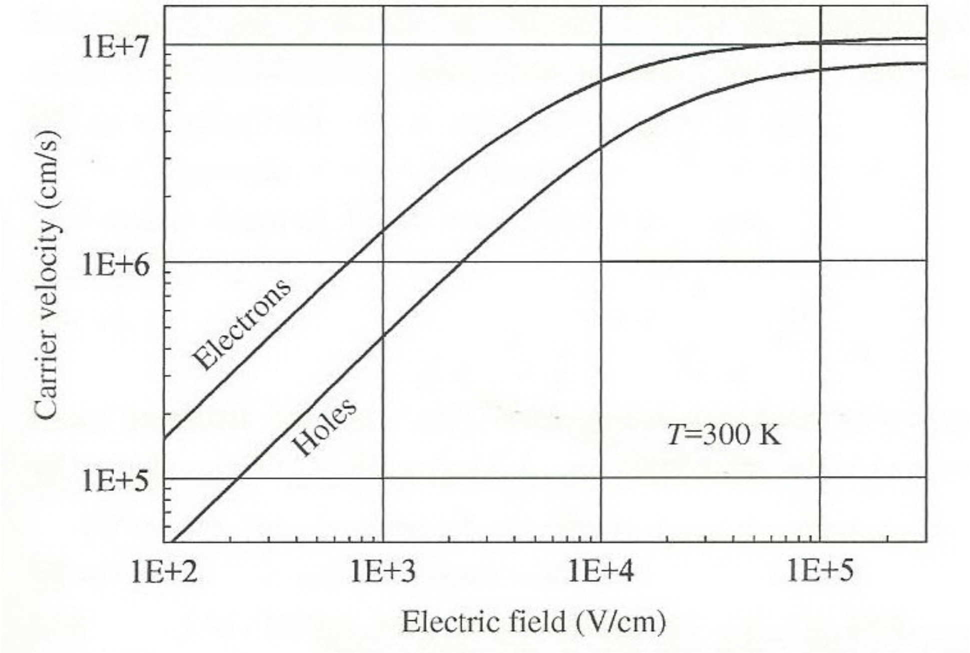
Velocity vs. electric field

- Directly affects the DC current
  - At low electric fields, the linear relationship is valid.
  - At high electric fields, the velocity saturation starts to occur. The saturation velocity of Si is about 10^7 [cm/sec].



Velocity-field relationship in Si at 300K
(Y. Taur and T. H. Ning, Fundamentals of modern VLSI devices)

Velocity saturation

- A simple expression
  - A field-dependent mobility

$$\mu = \frac{\mu_0}{1 + bE}$$

- Real expression used
  - An additional parameter

$$\mu = \frac{\mu_0}{(1 + (bE)^{\beta})^{1/\beta}}$$

Diffusion

- Another mechanism
  - "A drop of ink falls into a glass of water."
  - The density gradient, ∇n, will be relaxed by the diffusion.

$$\mathbf{J}_n \propto \nabla n$$

  - Diffusion constant as the proportional coefficient (actually, qD_n)

- Drift and diffusion

$$\mathbf{J}_n = qn\mu_n\mathbf{E} + qD_n\nabla n$$

  - *Consider the temperature dependence of μ_n and D_n.*

Einstein relation

- Valid at equilibrium
  - Mobility and diffusion constant

$$D = \frac{k_B T}{q} \mu$$

  - (Useful number: $\frac{k_B T}{q} \approx 25.85\ mV$ at 300K)

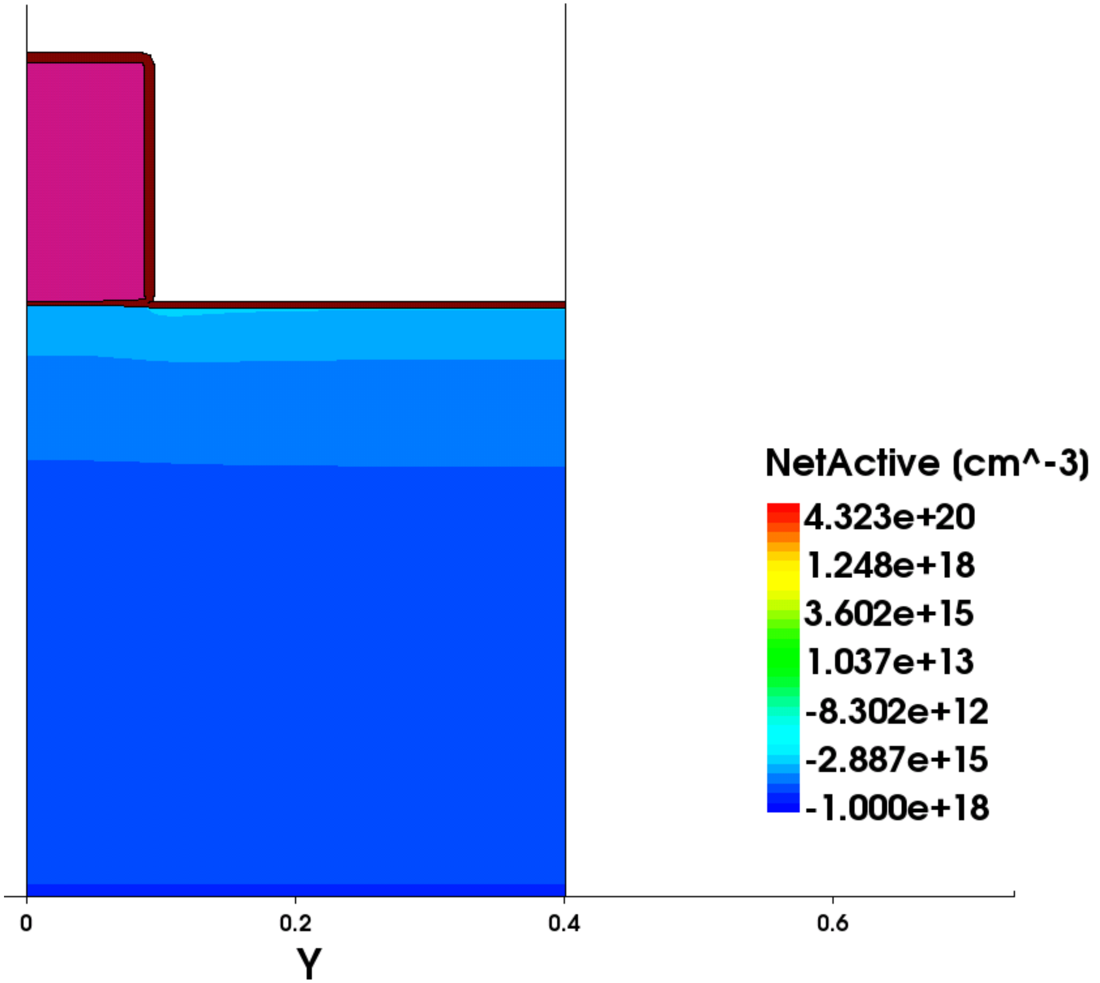
- Why do we have relations valid at equilibrium only?

PN junction

- What is it?
  - Junction of two different extrinsic regions
- Why do we study it?
  - It is a basic building block of electron devices.
- Today, only the equilibrium case will be discussed.
  - Nonequilibrium? Next lecture!

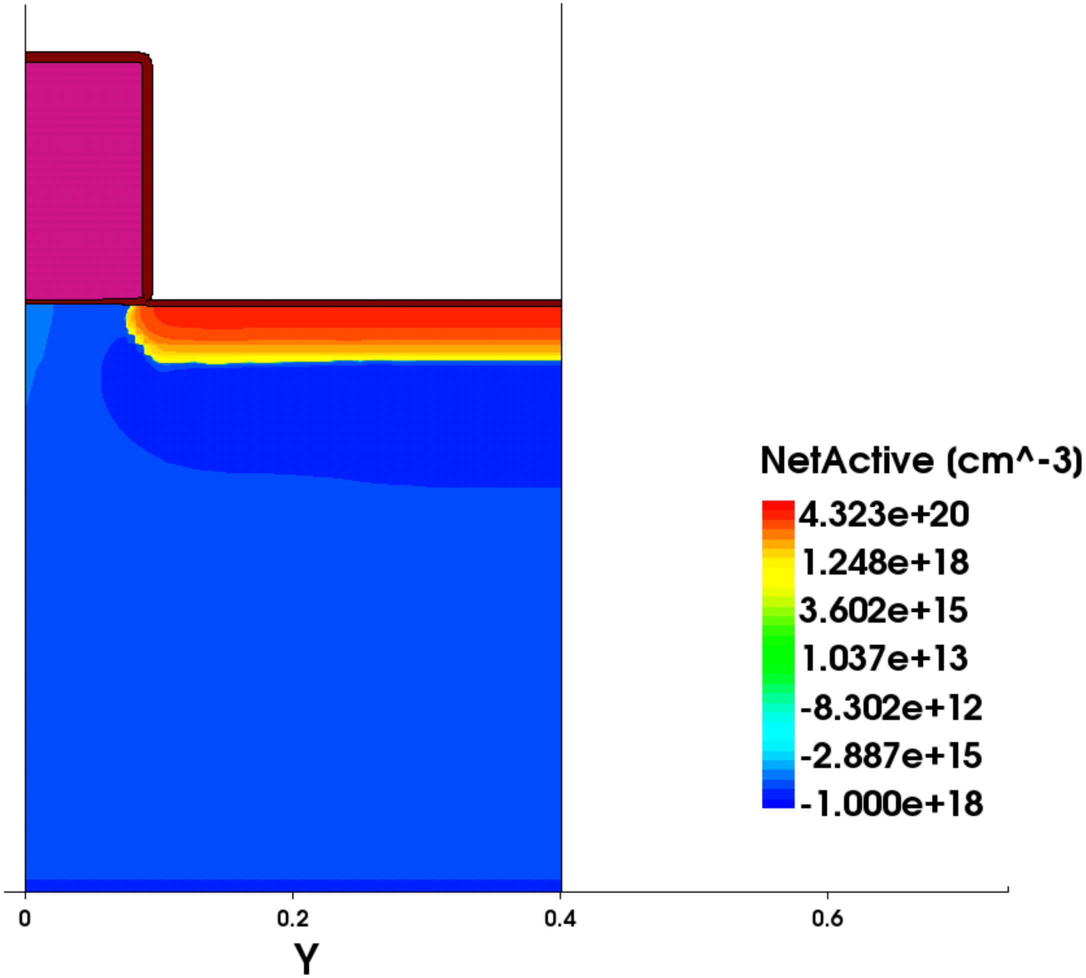
Fabrication (1/4)

- How to fabricate a pn junction
  - p-well and gate patterning



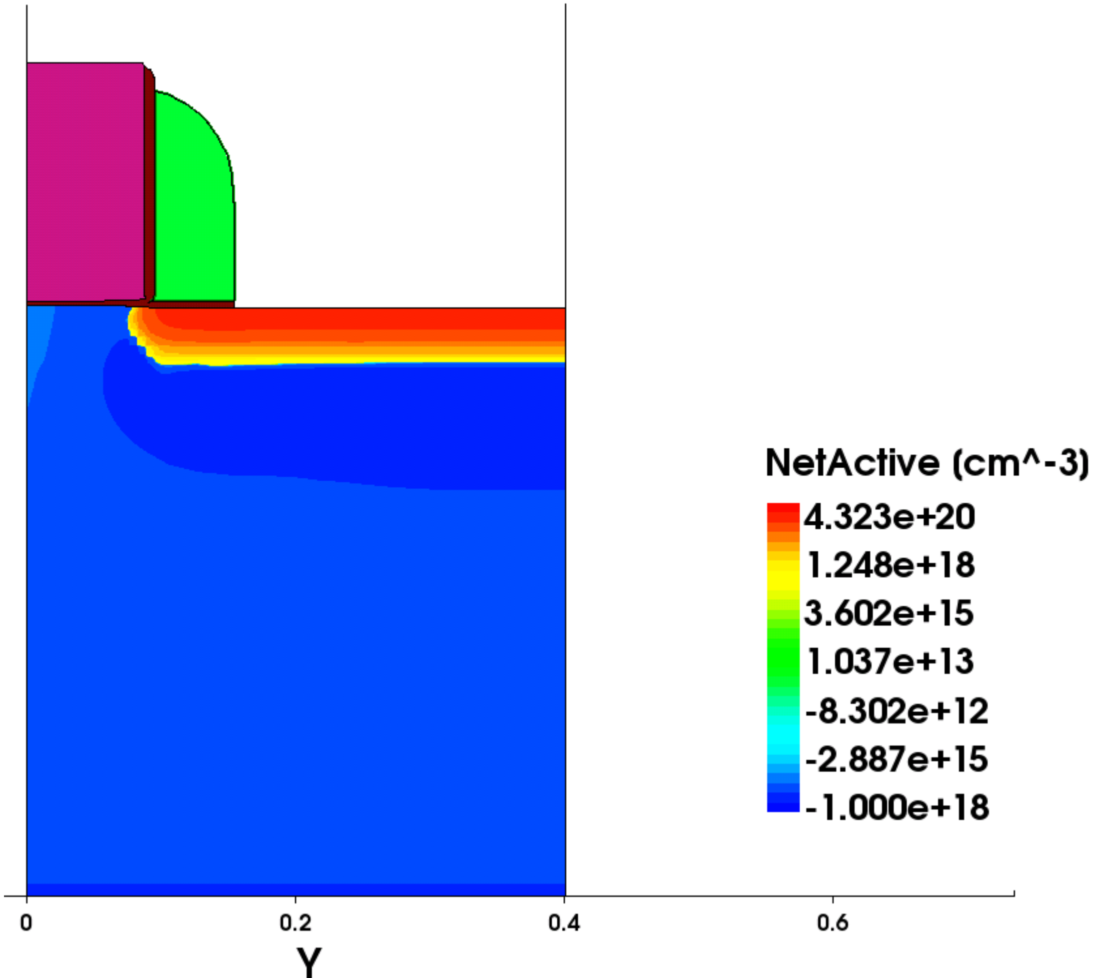
Fabrication (2/4)

- Ion implantation for LDD formation
  - Arsenic, dose = 4e12<cm-2>, energy=10<keV>



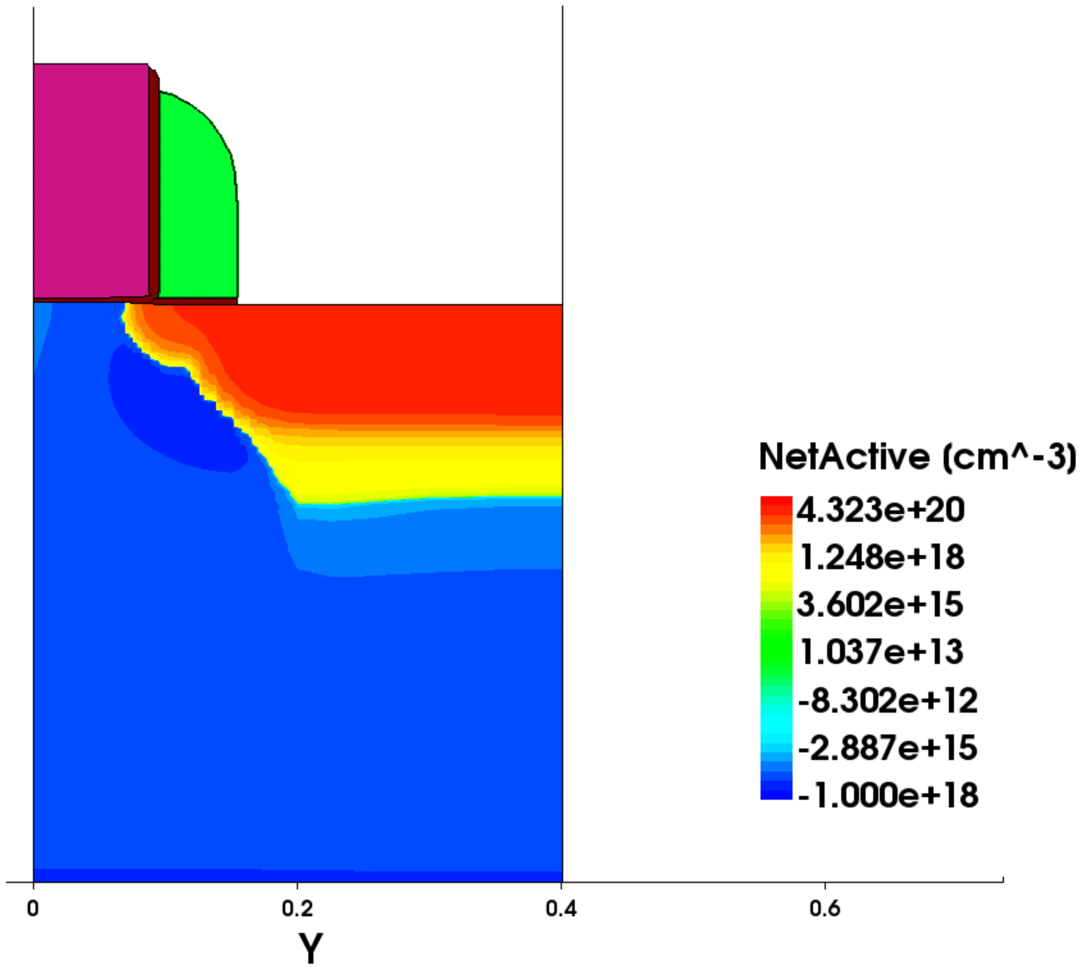
Fabrication (3/4)

- Spacer patterning
  - Silicon nitride spacer for the source/drain doping



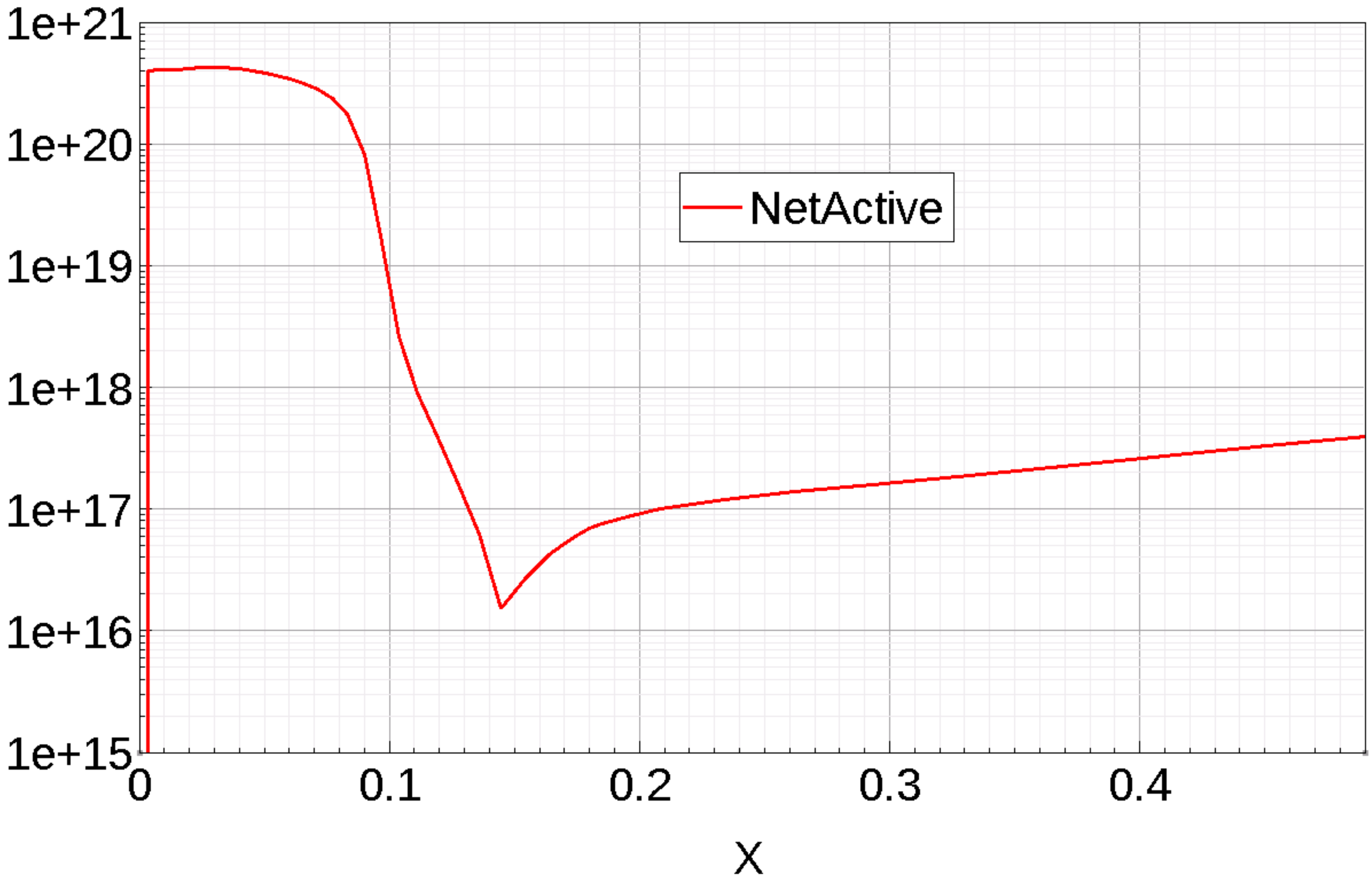
Fabrication (4/4)

- Ion implantation for source/drain formation
  - Arsenic, dose=5e15<cm-2>, energy=<40keV>



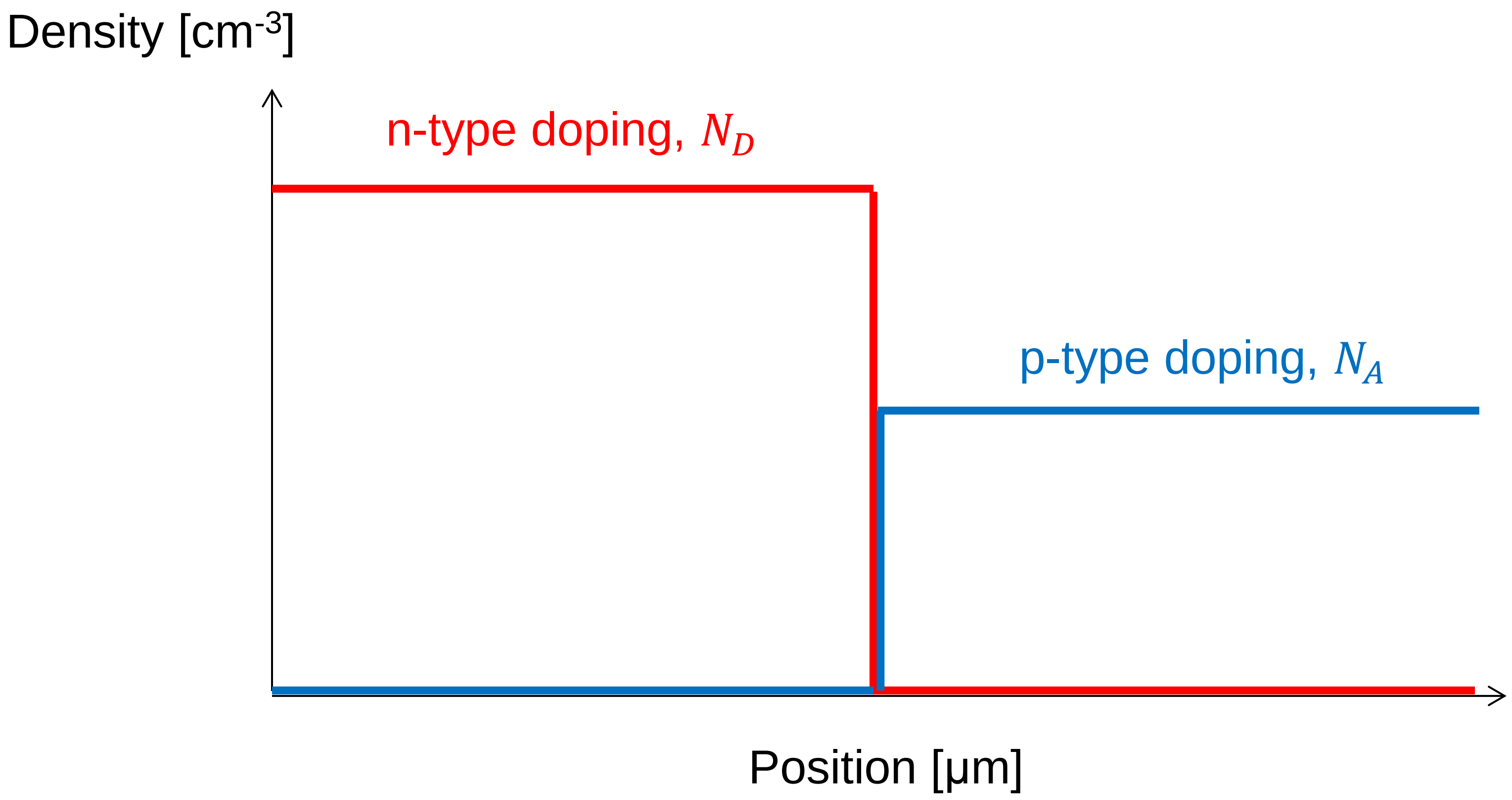
Vertical doping profile

- Ion implantation for source/drain formation
  - Arsenic, dose=5e15<cm-2>, energy=<40keV>



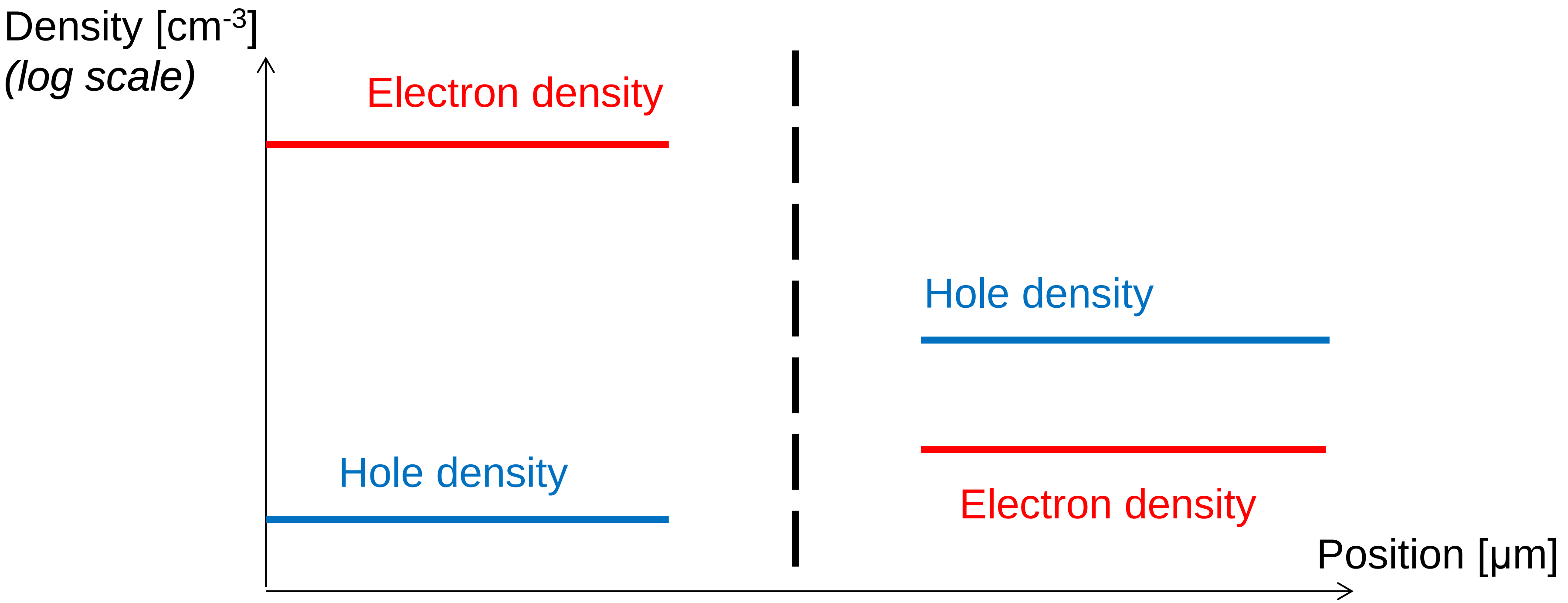
Simplified 1D structure

- For simplicity
  - An abrupt 1D junction is usually considered.



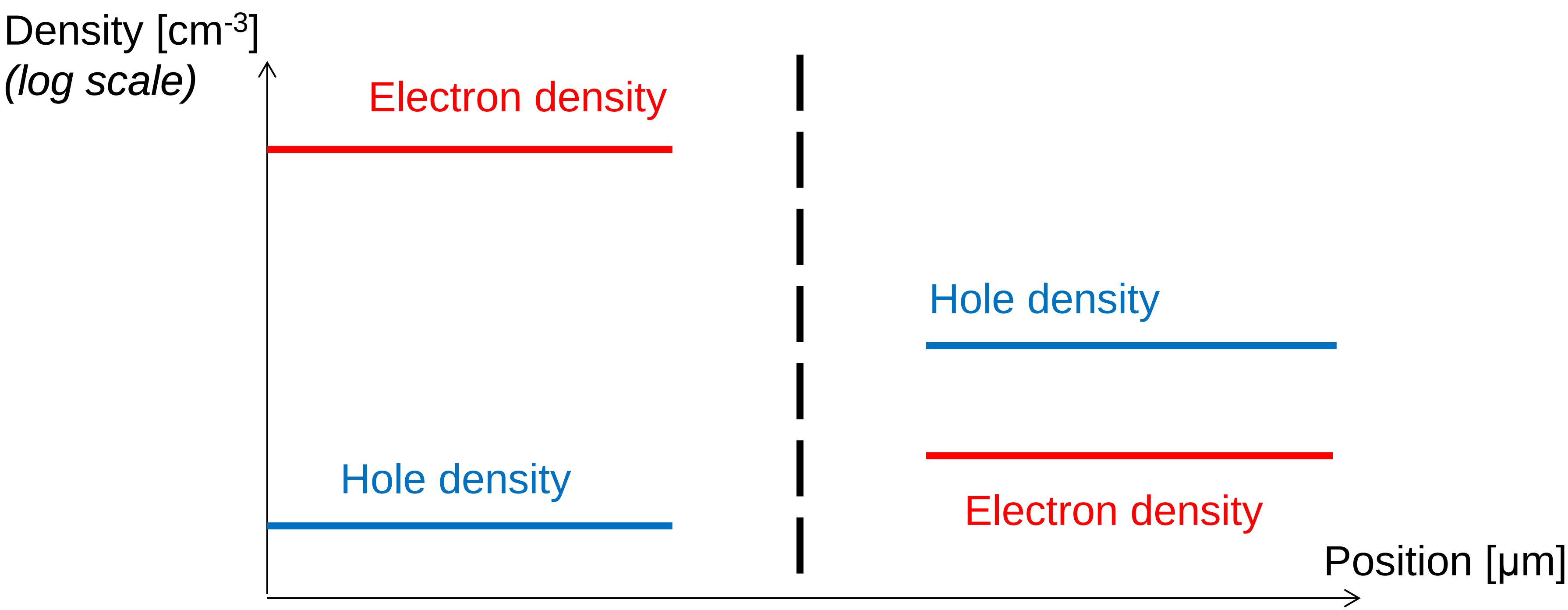
Away from the junction…

- No effect of junction!
  - In the n-type region, $n \approx N_D$ and $p \approx \frac{n_i^2}{N_D}$
  - In the p-type region, $p \approx N_A$ and $n \approx \frac{n_i^2}{N_A}$



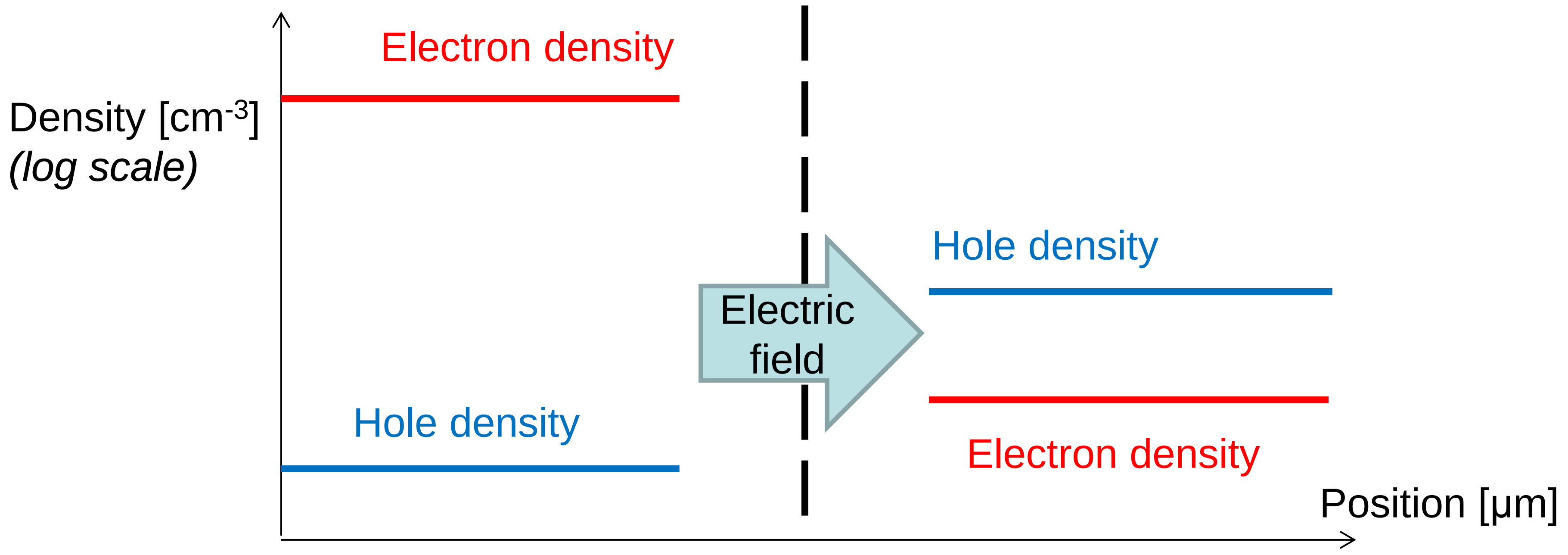
Example

- $N_D = 10^{16}$ cm^{-3} and $N_A = 5 \times 10^{15}$cm^{-3}



Across the junction…

- Large diffusion currents:
  - Electrons flow from the n side to the p side
  - Holes flow from the p side to the n side
- However, the net flux of electrons and holes is not allowed.
  - Equilibrium! Compensated by the drift current!

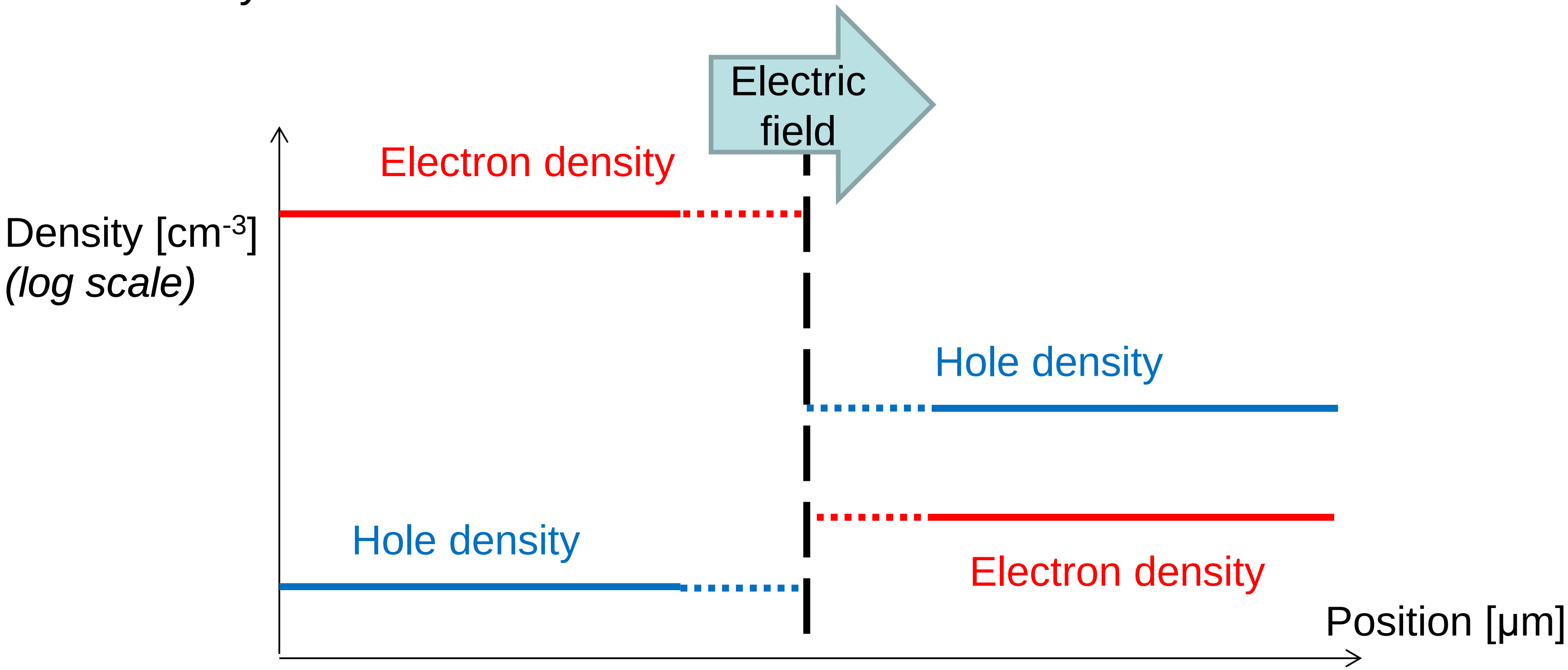


How can we have $\mathbf{E}$?

- Poisson's equation

$$\nabla \cdot \mathbf{D} = \rho$$

  – When the net charge density does not vanish, the electric field can vary.

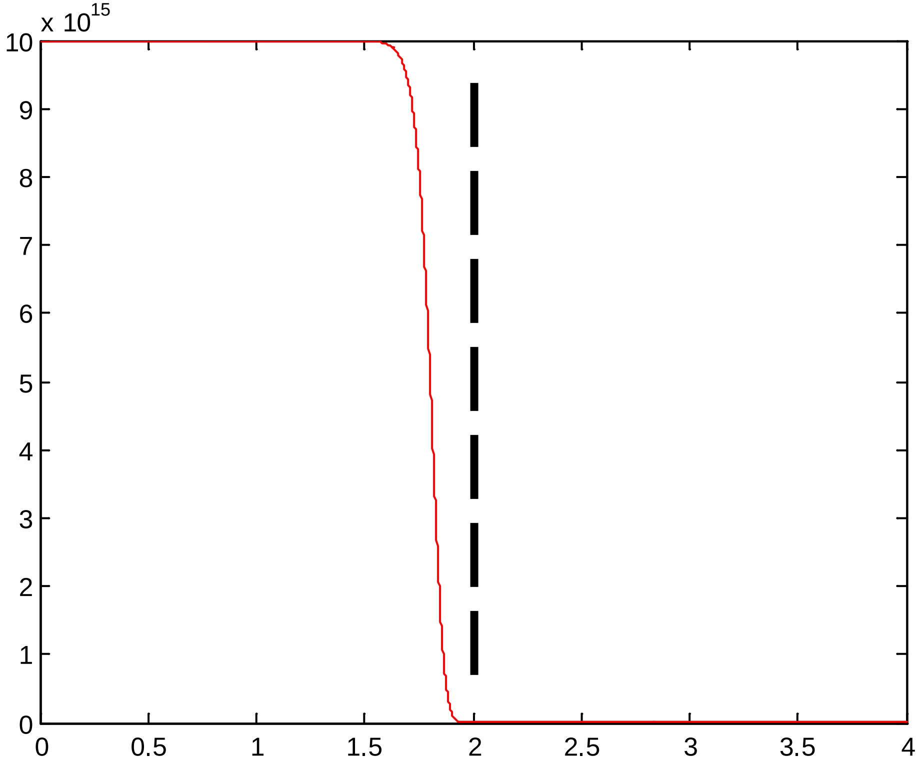


Depletion region


(Google image)

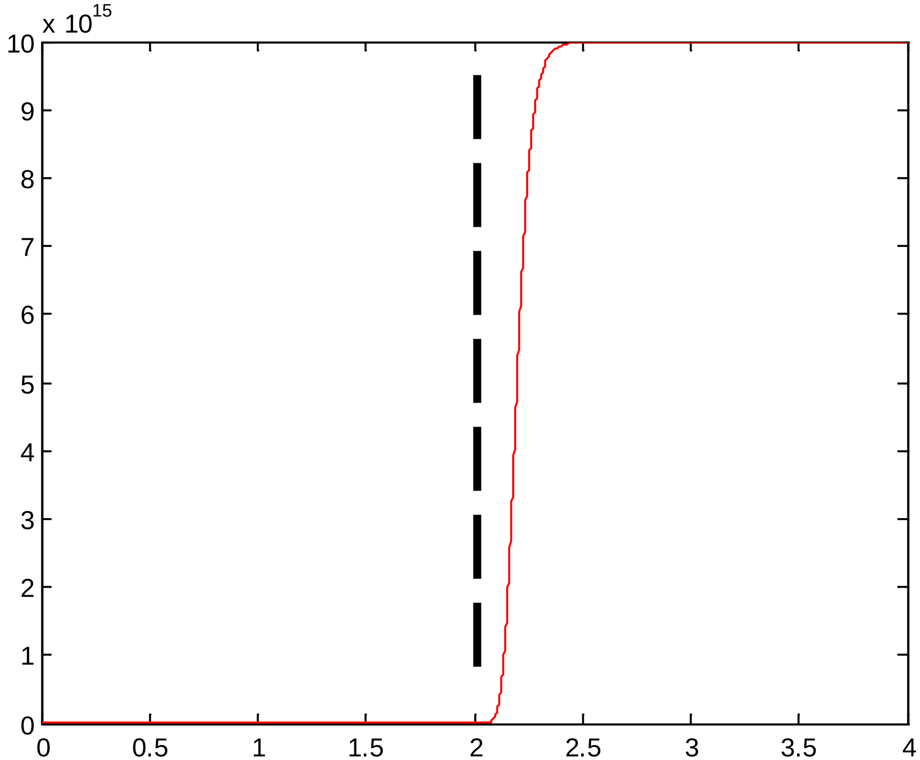
- Depletion region causes $\mathbf{E}$.
  - A symmetric pn junction with 10^{16} cm^{-3} doping density.

Electron density [cm^{-3}]



Position [μm]

Hole density [cm^{-3}]

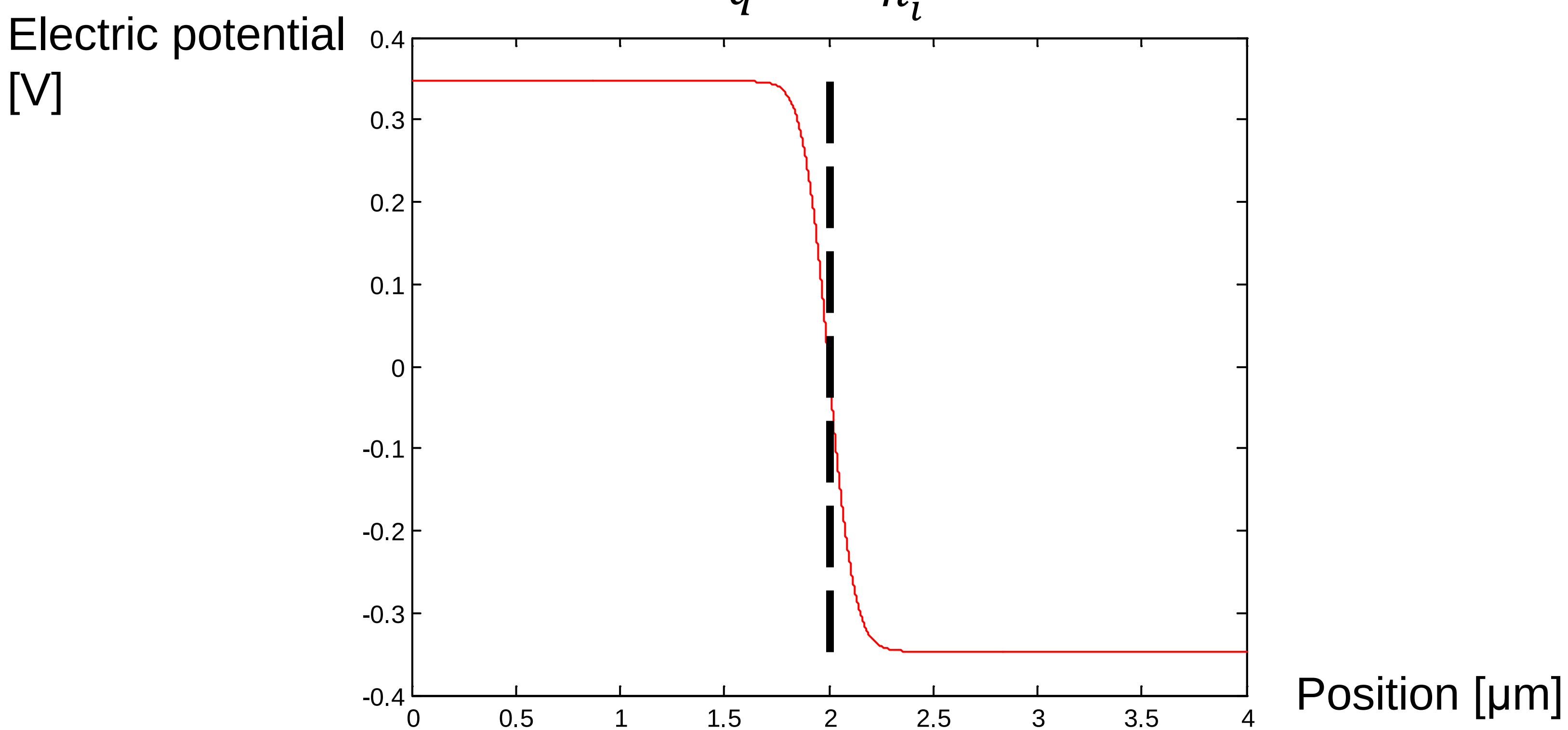


Position [μm]

Built-in potential

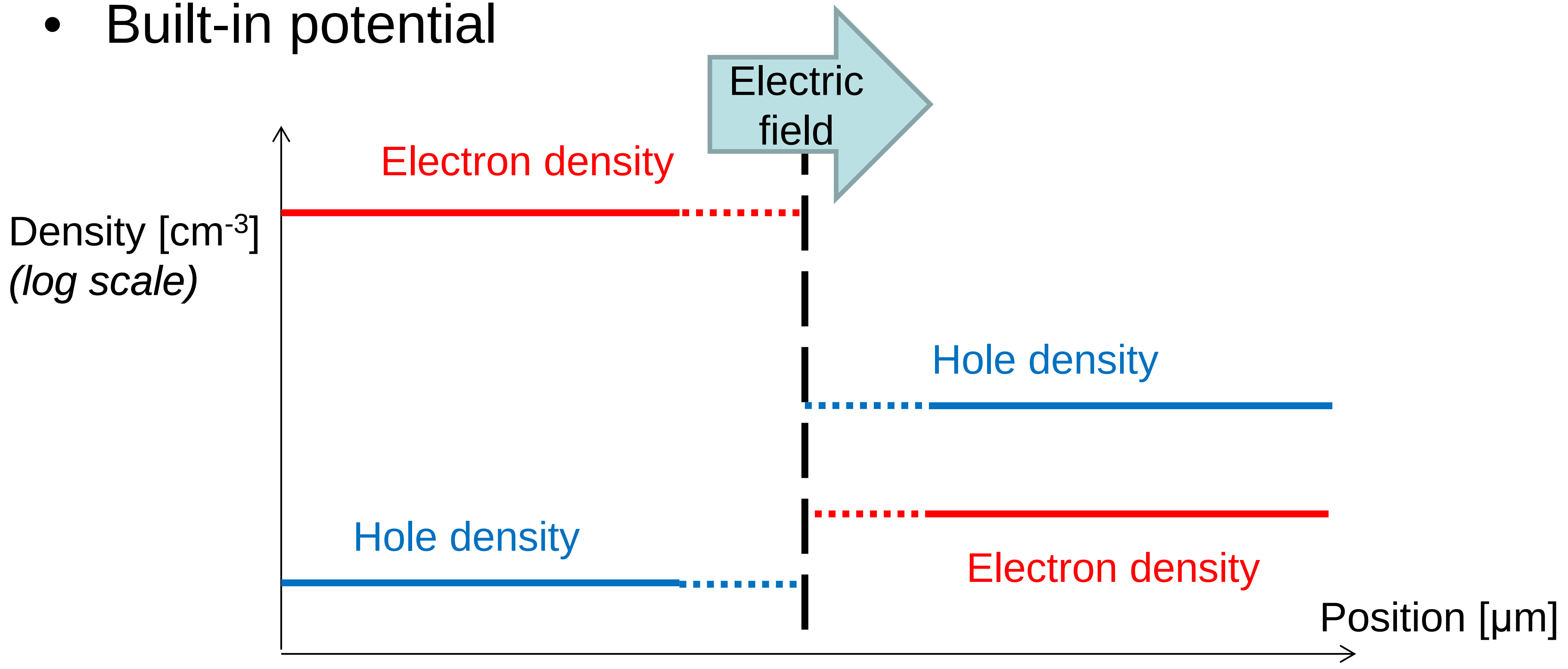
- The potential difference across the junction
  - A simple expression is available.

$$V_0 = \frac{k_B T}{q} \ln \frac{N_A N_D}{n_i^2}$$



PN junction @ equilibrium

- No current
  - Because it is at equilibrium. ☺
- Depletion region
- Built-in potential



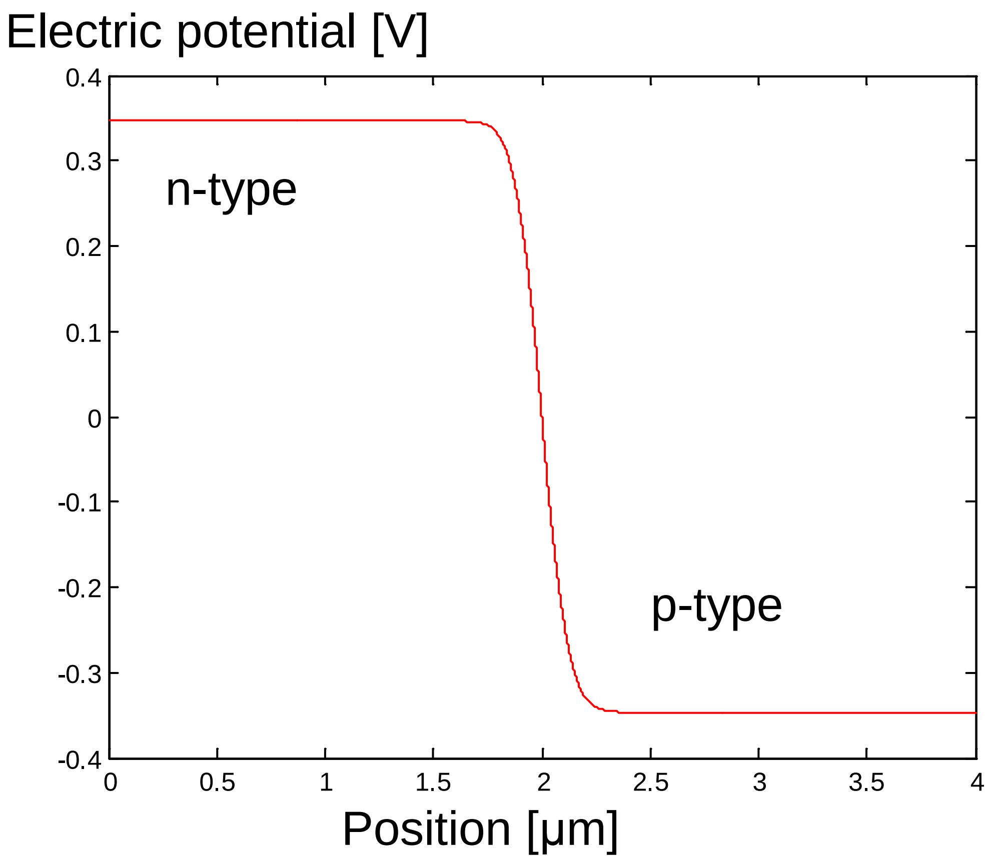
Forward/reverse

- A diode shows a strong polarity.
  - Does a resistor have a polarity?
  - In diodes, the following two cases are completely different.
- Forward bias
  - The voltage at the n-type side is higher than the p-type one.

- Reserve bias
  - The voltage at the p-type side is lower than the n-type one.

Reverse bias

- Electric field
  - Now, the magnitude of the electric becomes larger.



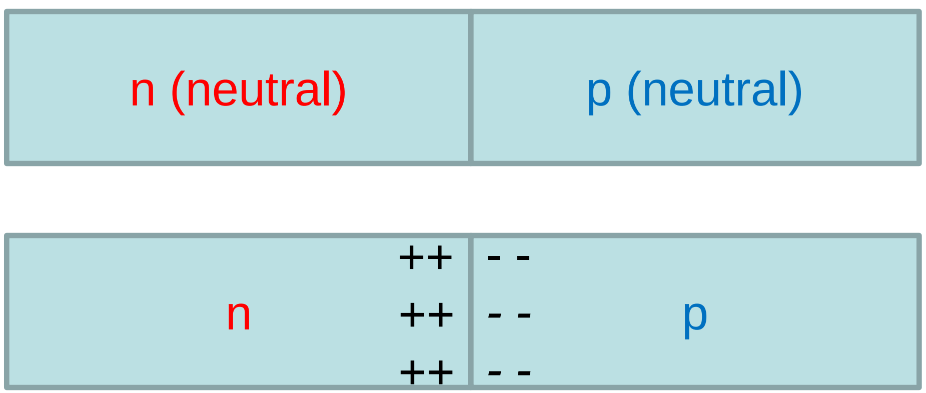
🡐 This is the equilibrium solution. What happens when the n-type region is positively biased?

Higher electric field?

- How can the pn junction generate the higher electric field?
  – At equilibrium, how did it generate the built-in electric field?

$$\nabla \cdot \mathbf{D} = \rho$$

  – Higher electric field means more space charges!



← Which one can provide nonzero electric field?

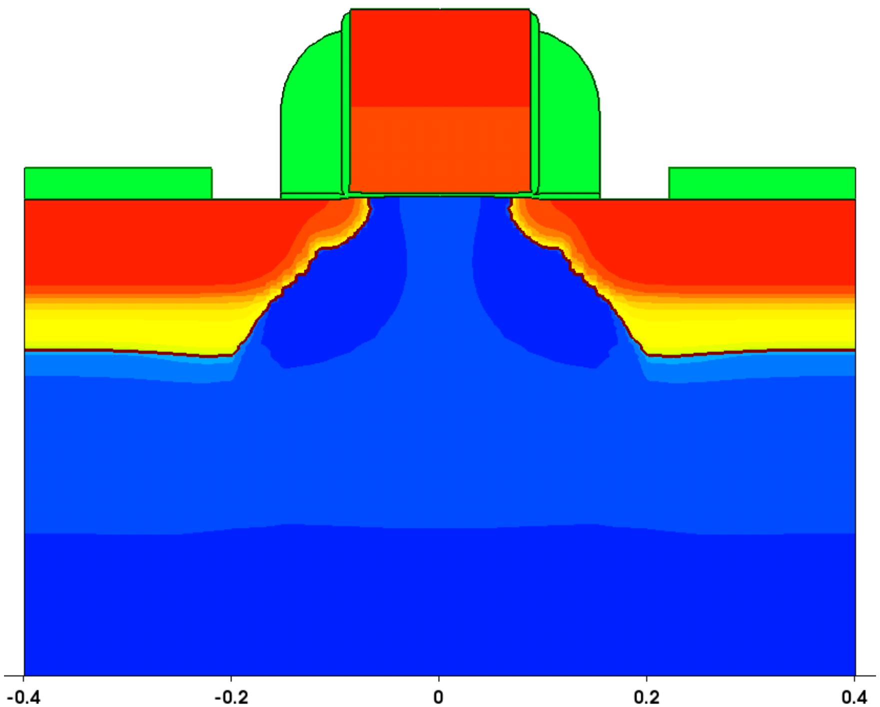
- Therefore, the depletion region becomes wider.
  – Even higher potential barrier!

Variable capacitance

- Capacitor? Why do we care about it?

$$Q = CV \text{ and } I = C\frac{dV}{dt}$$

  - Where can you find capacitance in the following structure?
  - Why is it important?



Doping profile of a typical planar MOSFET

Charge

- Charge stored in a pn junction

$$Q = A\sqrt{2\epsilon_s q \frac{N_A N_D}{N_A + N_D}(V_0 + V_R)}$$

  – Then, what is the capacitance at a given value of the reverse bias, V_R?

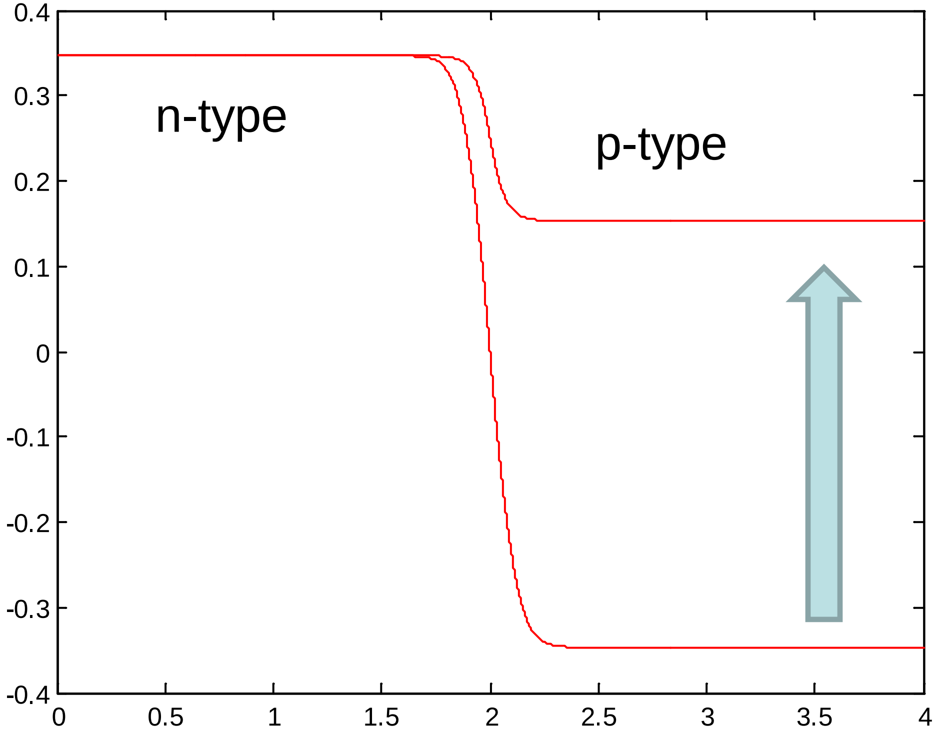
Summary of reverse bias

- Reverse bias
  - Larger electric field
  - Wider depletion region
  - (Almost) no current flow
  - Variable capacitance

Forward bias

- Forward bias
  - We can easily guess that the depletion width will be reduced.
  - Potential barrier is lowered. (Equilibrium and 0.5 V)

Electric potential [V]

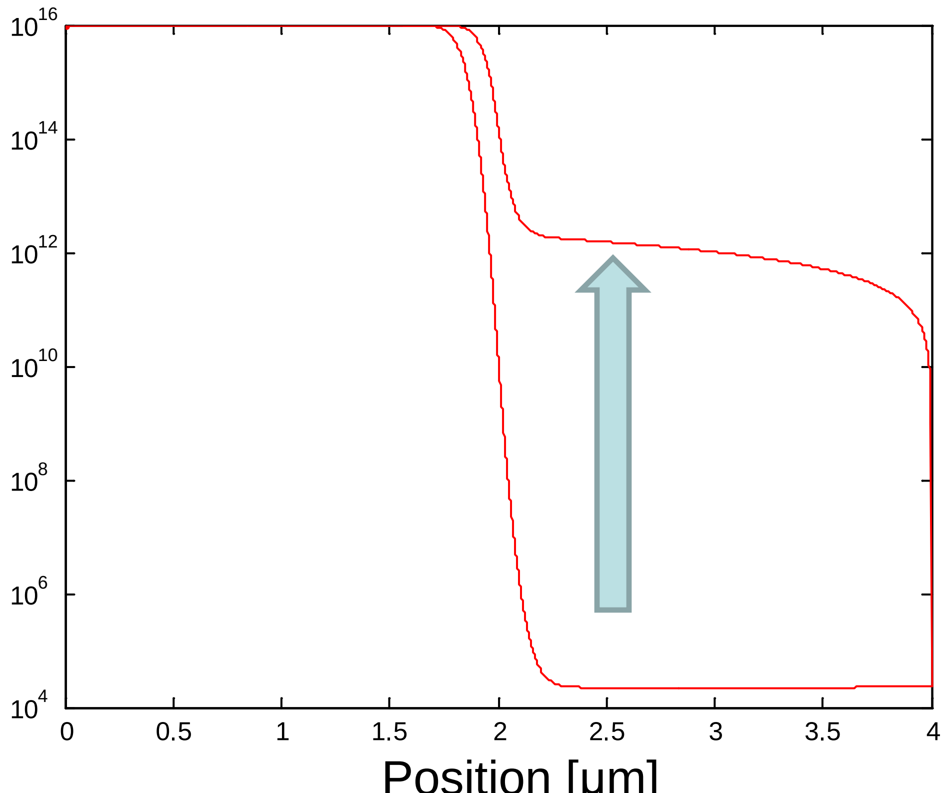


Position [μm]

Density @ forward bias

- Electron concentration (similar for hole concentration)
  - Equilibrium and 0.5 V
  - Exponential increase of electron density!

Electric density [cm^{-3}]



IV characteristics

- In forward bias,
  - The external voltage opposes the built-in potential, raising the diffusion currents substantially.
- In reverse bias,
  - The applied voltage enhances the field, prohibiting current flow.

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

  - Here, the “reverse saturation current” is given by

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

  - L_n and L_p are electron and hole “diffusion lengths,” respectively.

An example

- Determine I_S.
  - The cross section of 100 μm^2
  - L_n and L_p are 20 μm and 30 μm, respectively.
  - L_n and L_p are 20 μm and 30 μm, respectively.

- When $I_S = 1.77 \times 10^{-17}$ A,
  - Determine the forward bias current.
  - For $V_D = 300$ mV, $I_s\left(\exp\frac{V_D}{V_T} - 1\right)$ = 3.63 pA
  - For $V_D = 800$ mV, 820 μA