Lecture4: Diode

Sung-Min Hong (smhong@gist.ac.kr)

Semiconductor Device Simulation Lab.
School of Electrical Engineering and Computer Science
Gwangju Institute of Science and Technology

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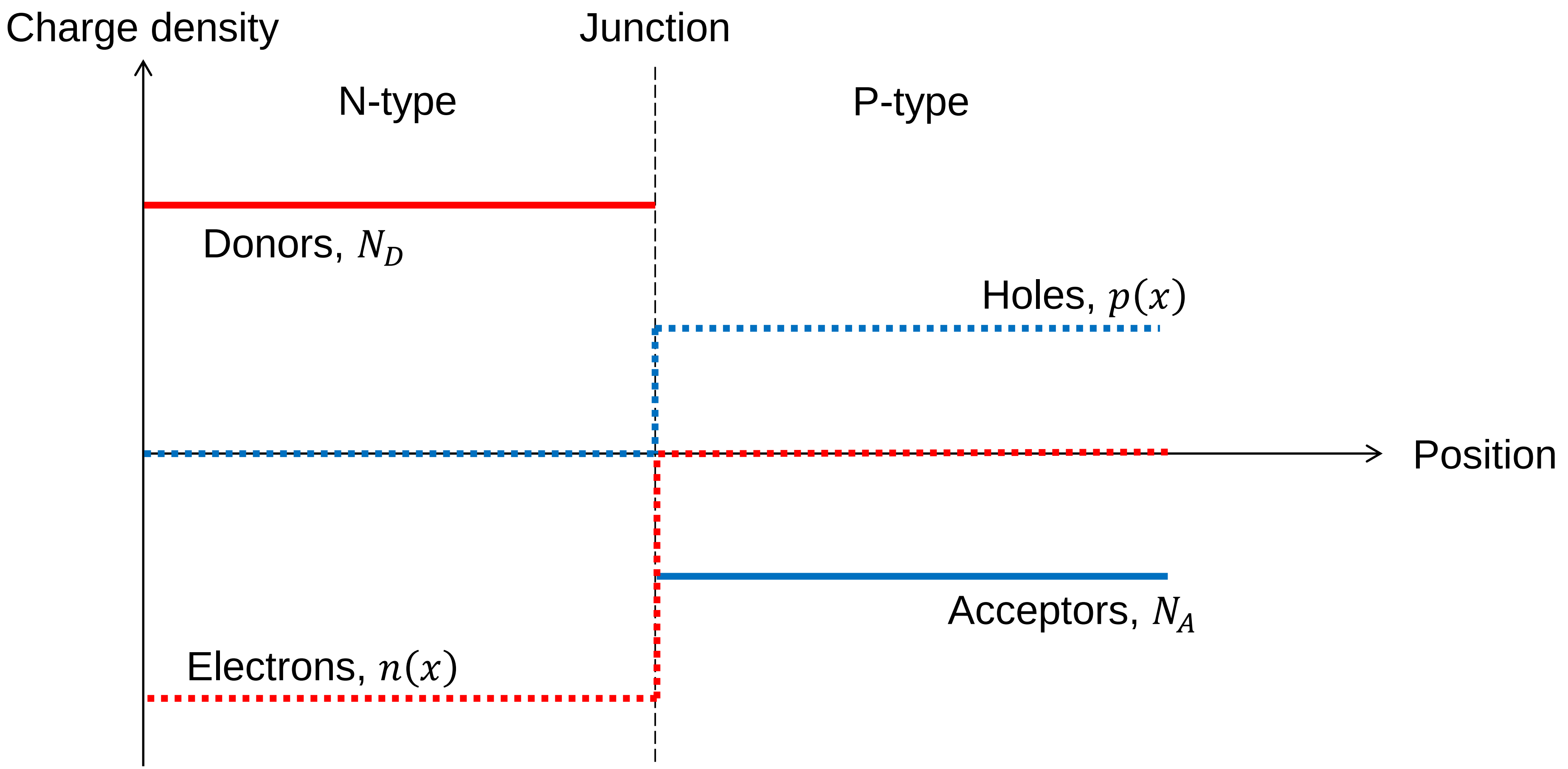
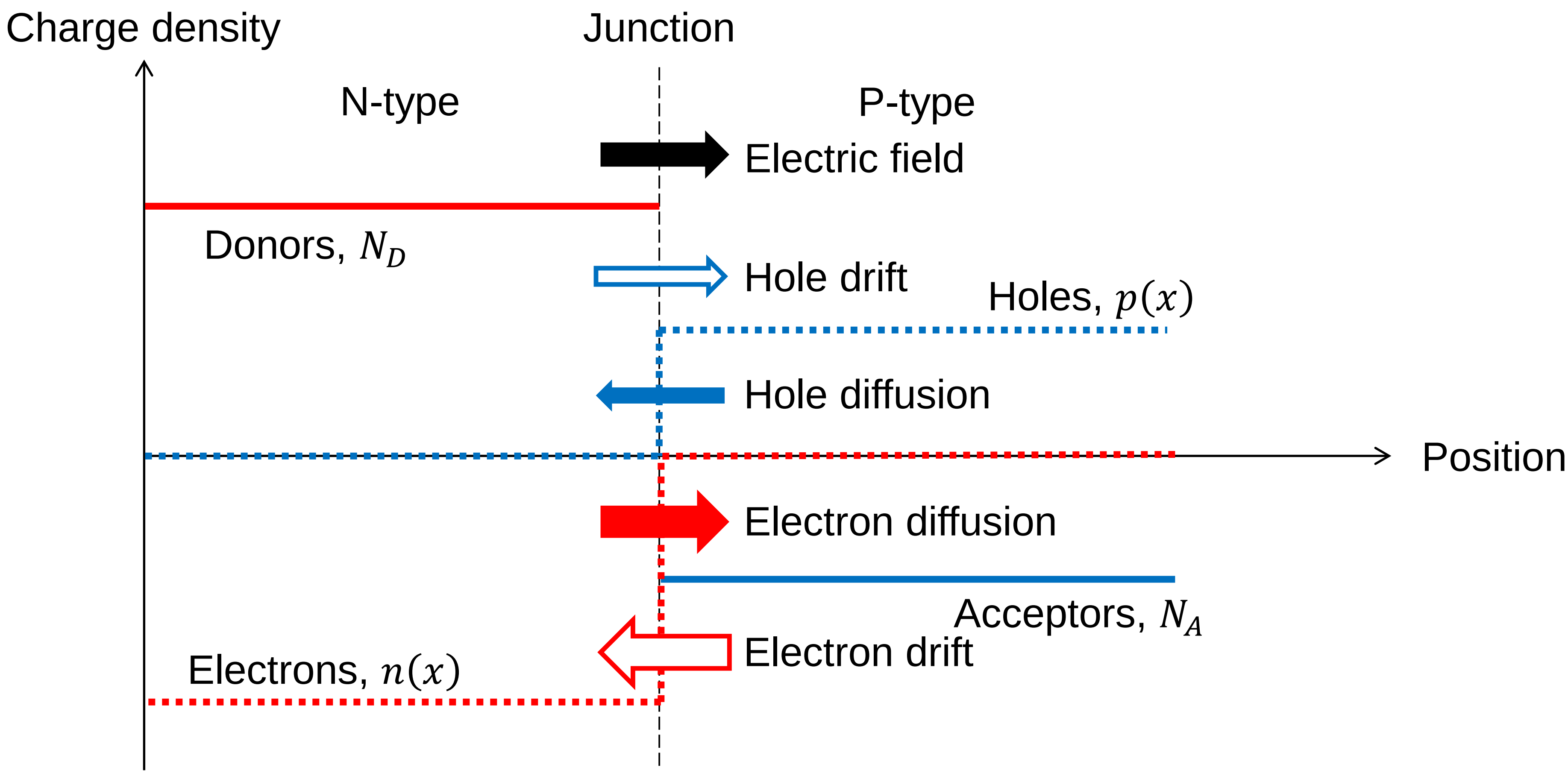
This is NOT a solution.

- $n = N_D$ in the N-type region and $p = N_A$ in the P-type
  - We need an electric field near the junction.



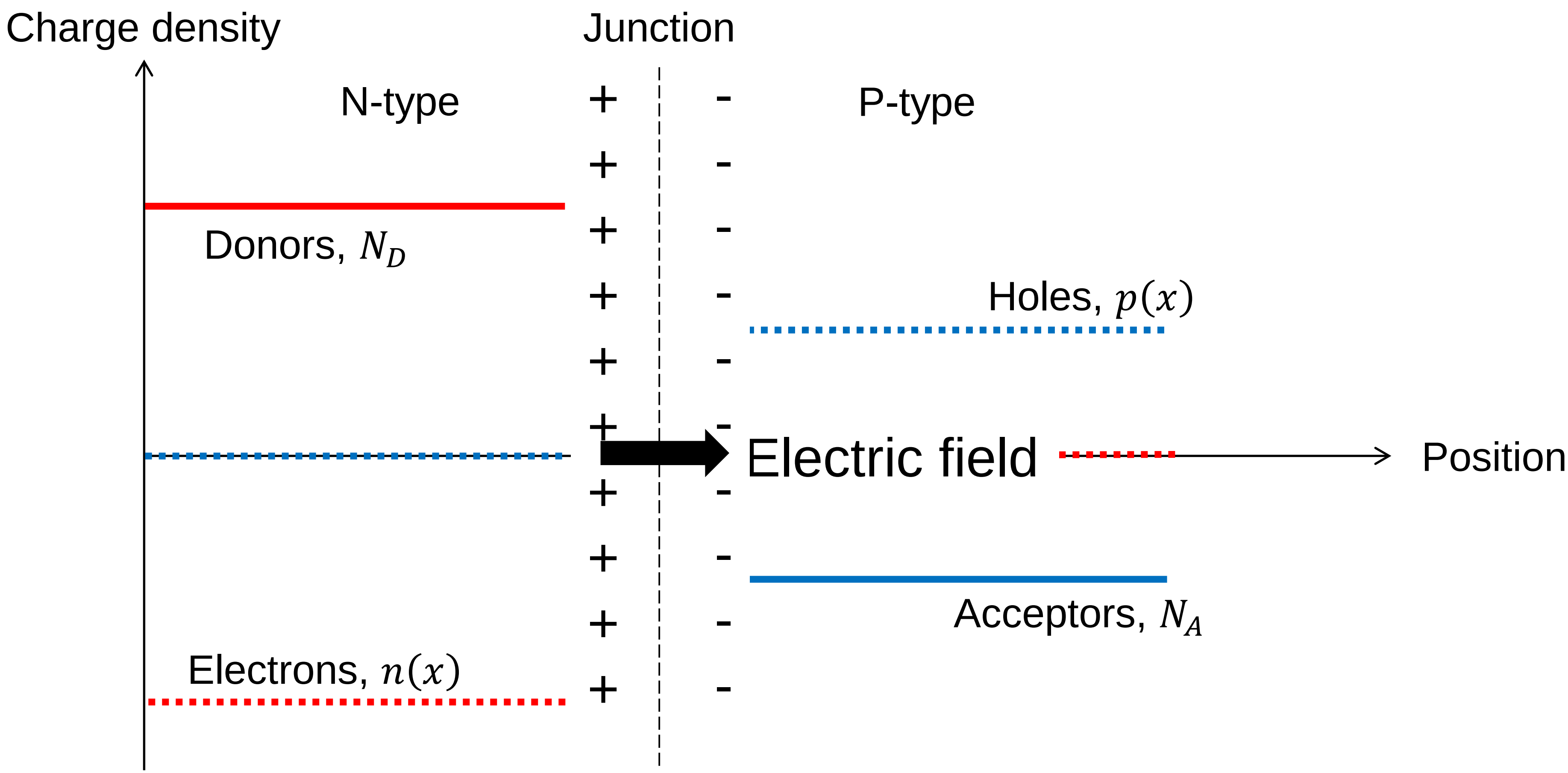
Direction and location of $\mathbf{E}$

- Electric field from the N-type to P-type
  - Only near the junction, we have the electric field.



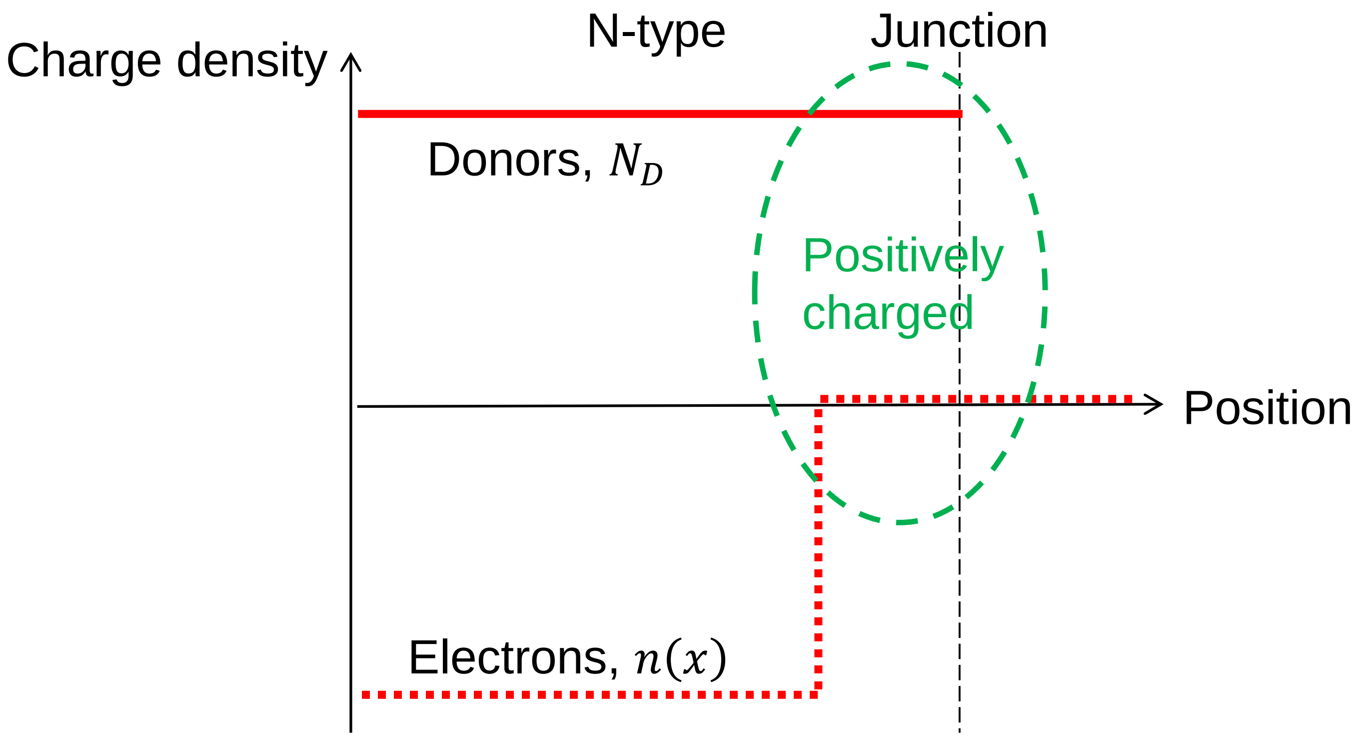
Localized E near junction

- (+) charges in the N-type region and (-) charges in the P-type region



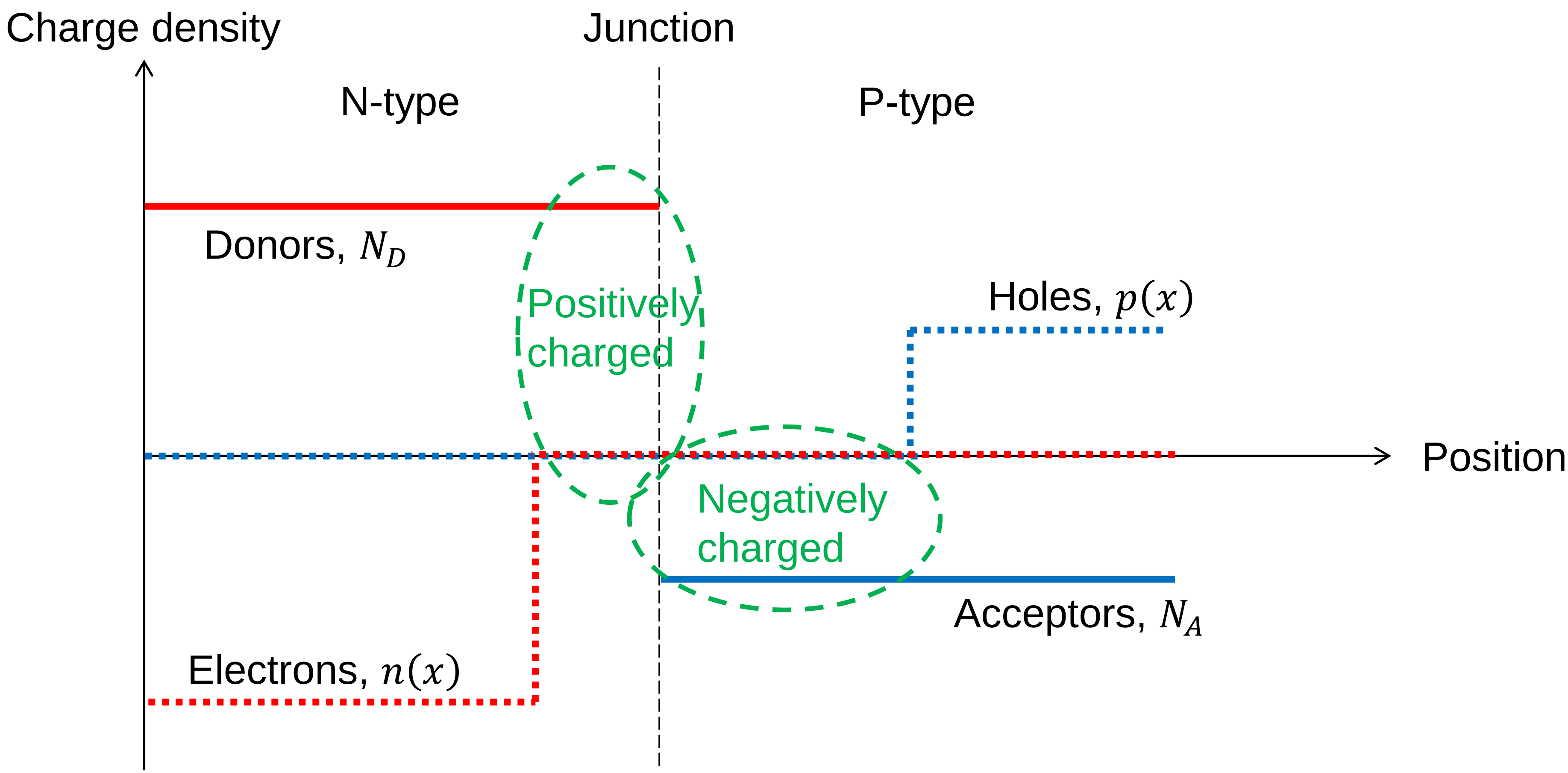
Space charge

- How can we have (+) charges in the N-type region?
  - Immobile donor atoms? (Positively charged)
  - Mobile electrons! (Negatively charged)



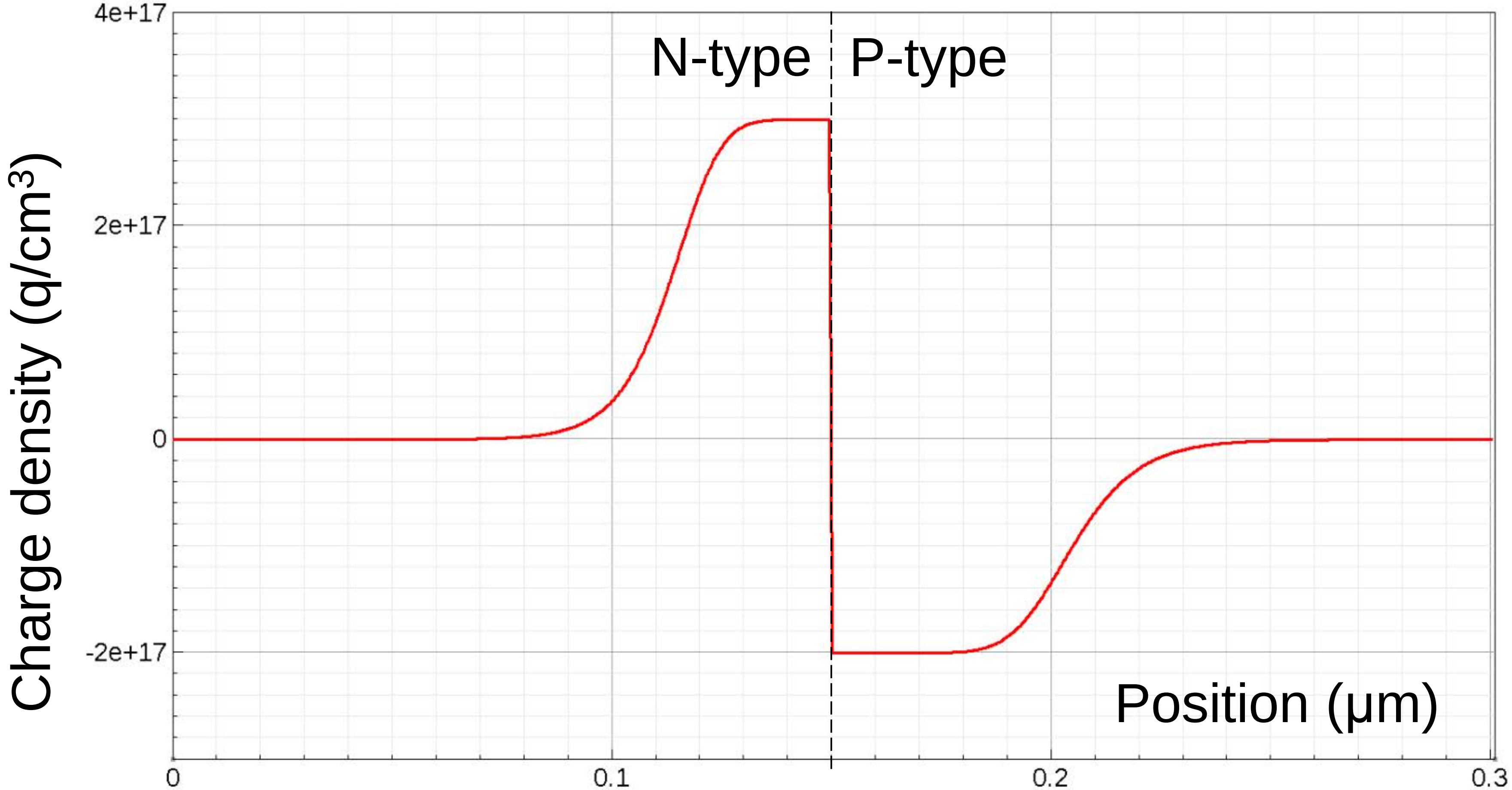
This is a solution.

- Depletion region
  - Calculation of the depletion width is of interest.



Numerical example

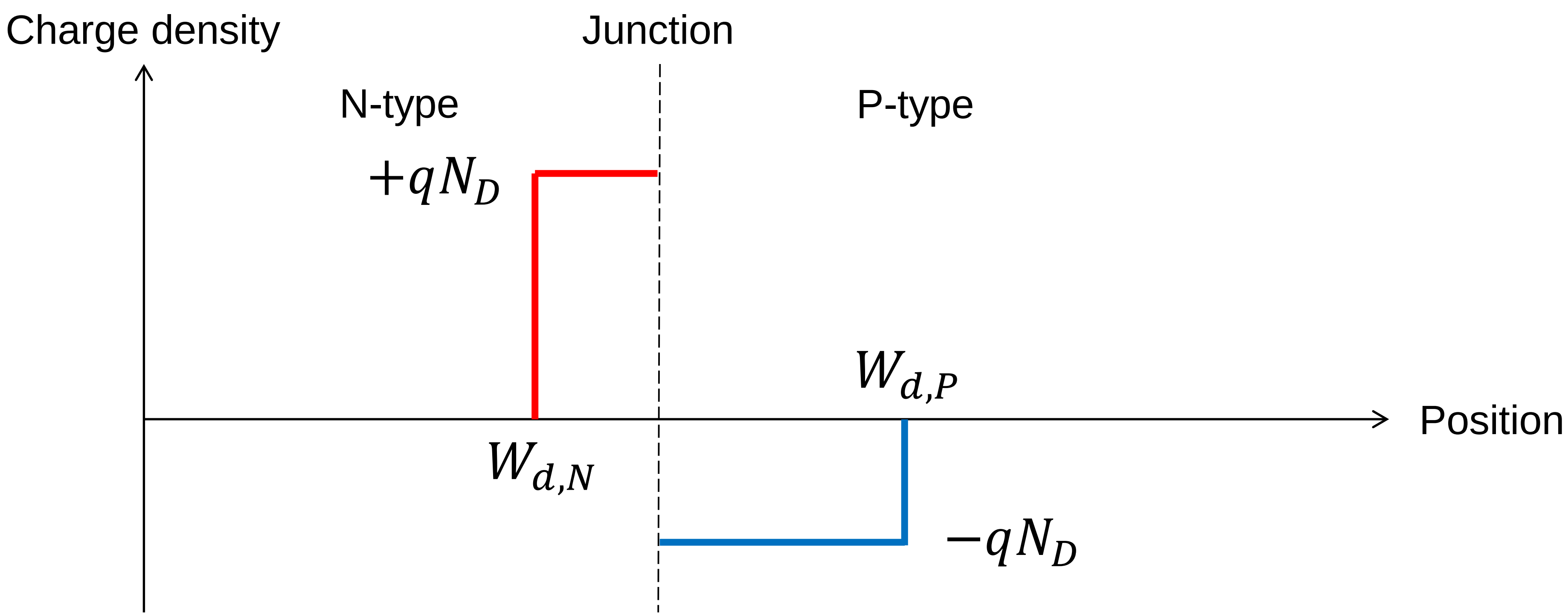
- An example of $N_D = 3 \times 10^{17}\ \mathrm{cm}^{-3}$ and $N_A = 2 \times 10^{17}\ \mathrm{cm}^{-3}$
  - Depletion approximation is not perfect, but quite good.



Depletion width

- Total depletion width, W_d
  - Sum of $W_{d,N}$ (N-type) and $W_{d,P}$ (P-type)
  - For the charge balance,

$$N_D W_{d,N} = N_A W_{d,P}$$



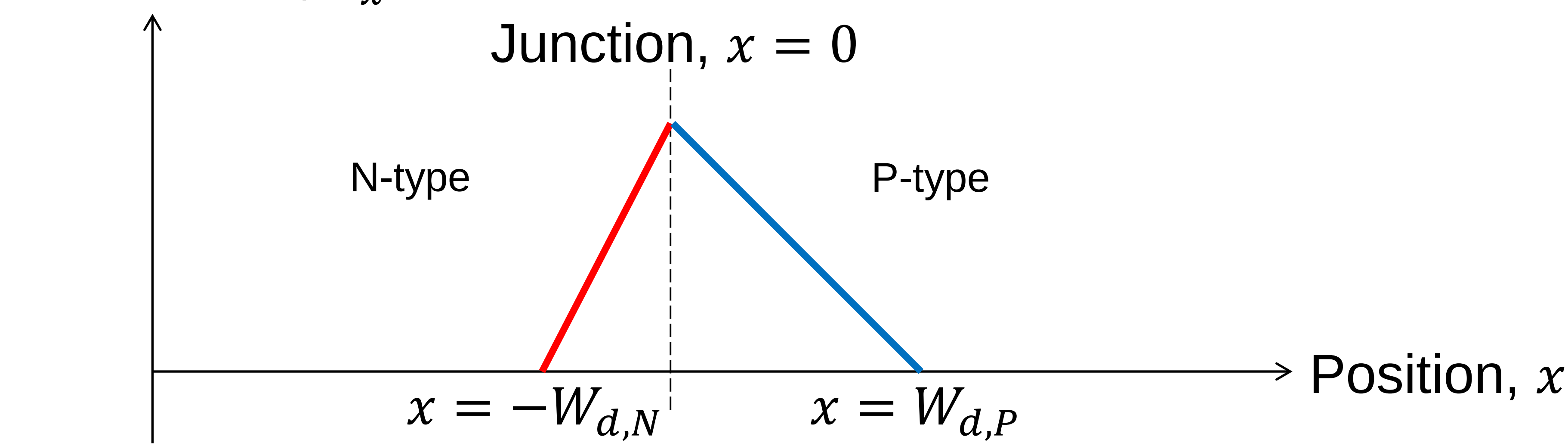
Electric field

- Solve $\frac{dE_x}{dx} = \frac{\rho}{\epsilon_{si}}$ where $\rho = +qN_D$ or $-qN_A$.
  - For the N-type region, $(-W_{d,N} \leq x \leq 0)$

$$E_x(x) = \frac{qN_D}{\epsilon_{si}}\left(x + W_{d,N}\right)$$

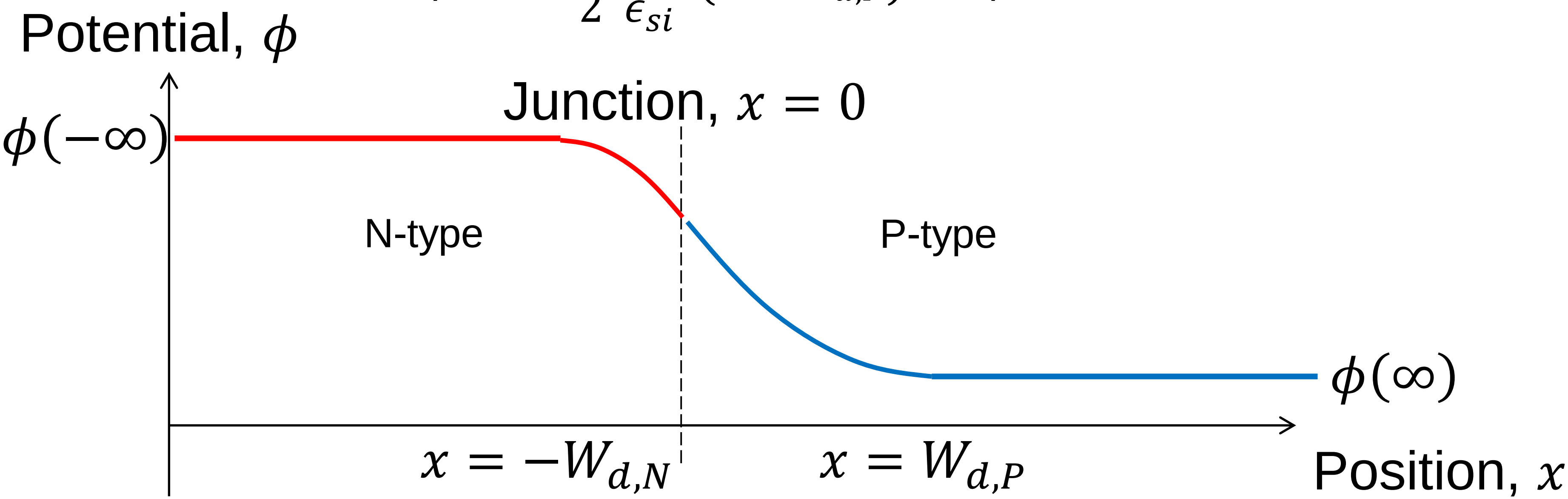
  - For the P-type region, $(0 \leq x \leq W_{d,P})$

$$E_x(x) = -\frac{qN_A}{\epsilon_{si}}\left(x - W_{d,P}\right)$$



Electrostatic potential

- Solve $-\frac{d\phi}{dx} = E_x$.
  - For the N-type region, $(-W_{d,N} \le x \le 0)$
$$\phi(x) = -\frac{1}{2}\frac{qN_D}{\epsilon_{si}}\left(x + W_{d,N}\right)^2 + \phi(-\infty)$$
  - For the P-type region, $(0 \le x \le W_{d,P})$
$$\phi(x) = \frac{1}{2}\frac{qN_A}{\epsilon_{si}}\left(x - W_{d,P}\right)^2 + \phi(\infty)$$



Depletion width

- Let us define that $V_{bi} \equiv \phi(-\infty) - \phi(\infty)$.
  - It is called the built-in potential.
  - At $x = 0$, two curves for the electrostatic potential must meet together.
  - Then, the depletion width, $W_d = W_{d,N} + W_{d,P}$, can be written as

$$W_d = \sqrt{\frac{2\epsilon_{si}}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)V_{bi}}$$

Built-in potential

- Remaining task is to identify V_{bi}.
  - At equilibrium, we have the following relation:

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

  - In the N-type region, far away from the junction,

$$n(-\infty) = N_D = n_i \exp\left(\frac{\phi(-\infty)}{V_T}\right)$$

  - In the P-type region, far away from the junction,

$$p(\infty) = N_A = n_i \exp\left(-\frac{\phi(\infty)}{V_T}\right)$$

  - The built-in potential becomes

$$V_{bi} = V_T \log \frac{N_D N_A}{n_i^2}$$

Hu, Example 4-1

- Assume that $N_D = 10^{20}\ \mathrm{cm}^{-3}$ and $N_A = 10^{17}\ \mathrm{cm}^{-3}$.
  - Remember that

$$V_{bi} = V_T \log \frac{N_D N_A}{n_i^2}$$

  - In this example, the built-in potential becomes about 1.012 V.
  - Then, the depletion width becomes

$$W_d = \sqrt{\frac{2\epsilon}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right) V_{bi}}$$

  - It is about 115 nm. Moreover, $W_{d,P} \gg W_{d,N}$.

Breathtaking balance

- Diffusion is suppressed by a repelling electric field (the built-in field)
  - In this case, the current density vanishes.
- Even stronger electric field?
- Weaker electric field?