Lecture4: Diode (2)

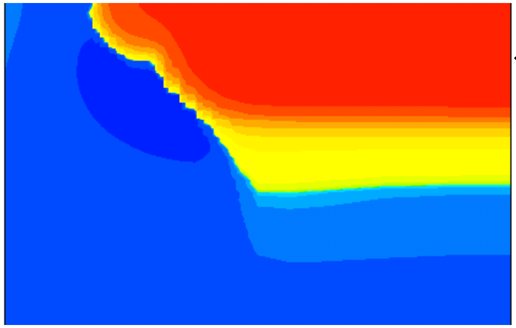
Sung-Min Hong (smhong@gist.ac.kr)

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

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.)

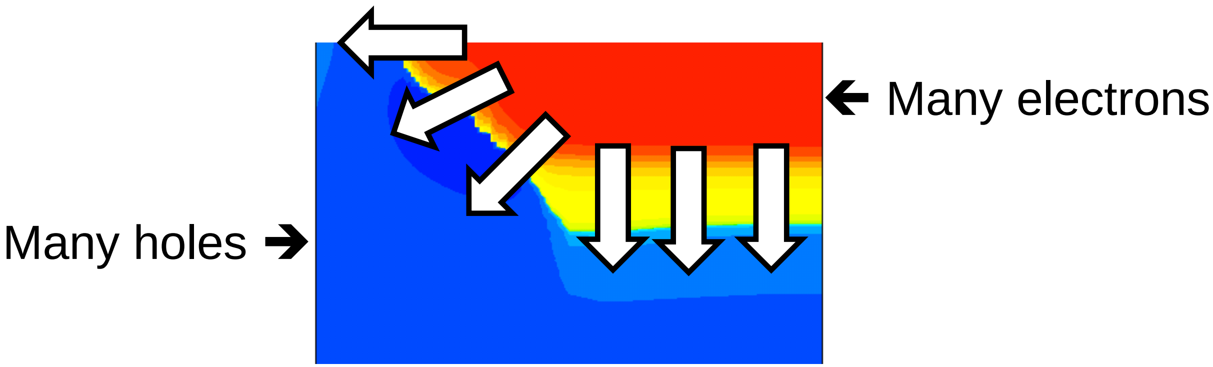
Many holes ➔ (Anode)



🡐 Many electrons (Cathode)

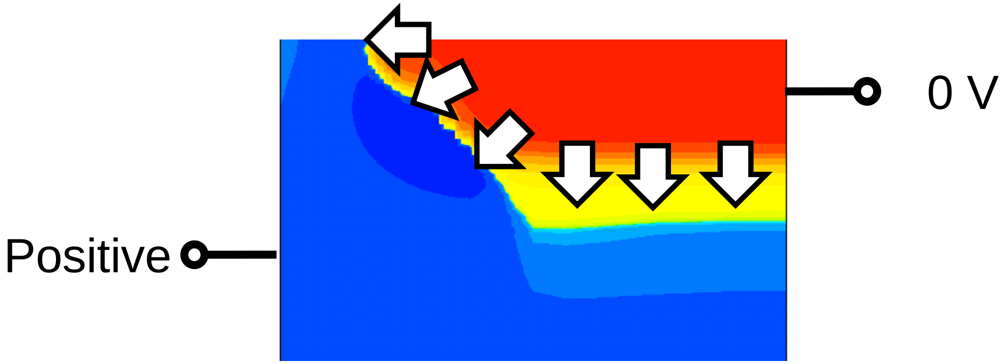
Equilibrium (2)

- 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.



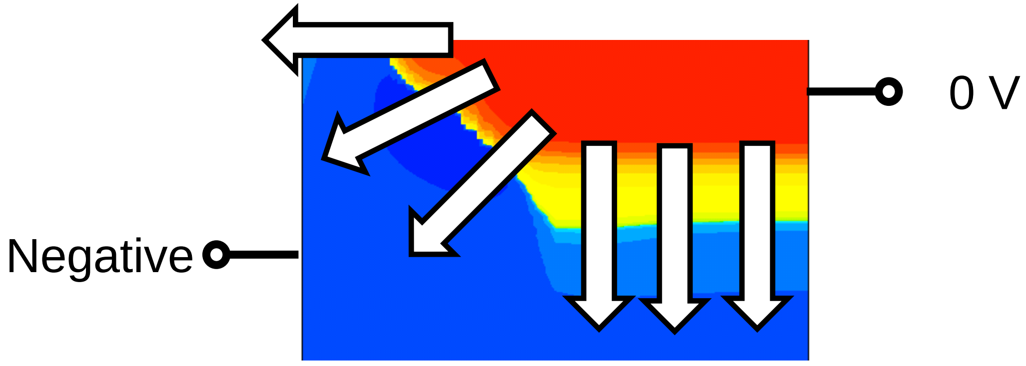
Forward bias

- 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, $\exp\frac{V_D}{V_T} \approx 1 + \frac{V_D}{V_T}$

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

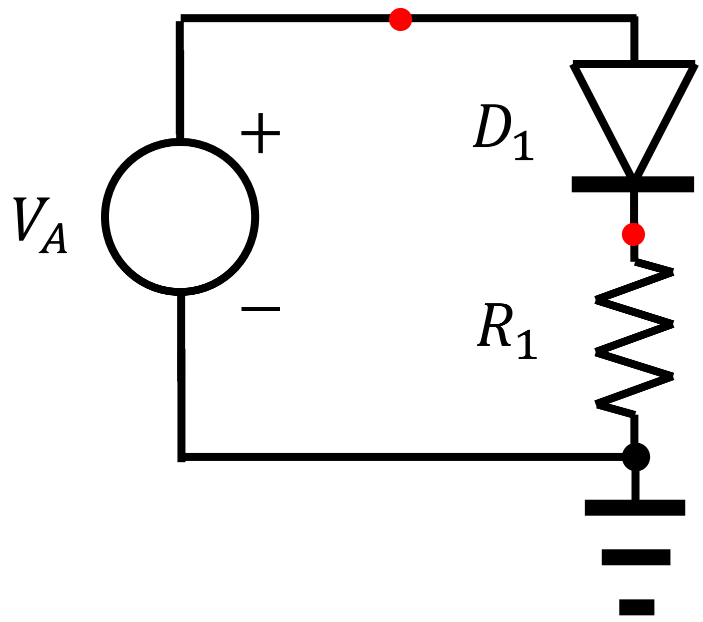
  - When V_D is negative and $V_D \ll -V_T$, $\exp\frac{V_D}{V_T} \approx 0$

$$I_D = -I_S$$

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

General solution (1)

- Analyze the following circuit. (A diode-resistor combination)
  - Calculation of node voltages and terminal currents



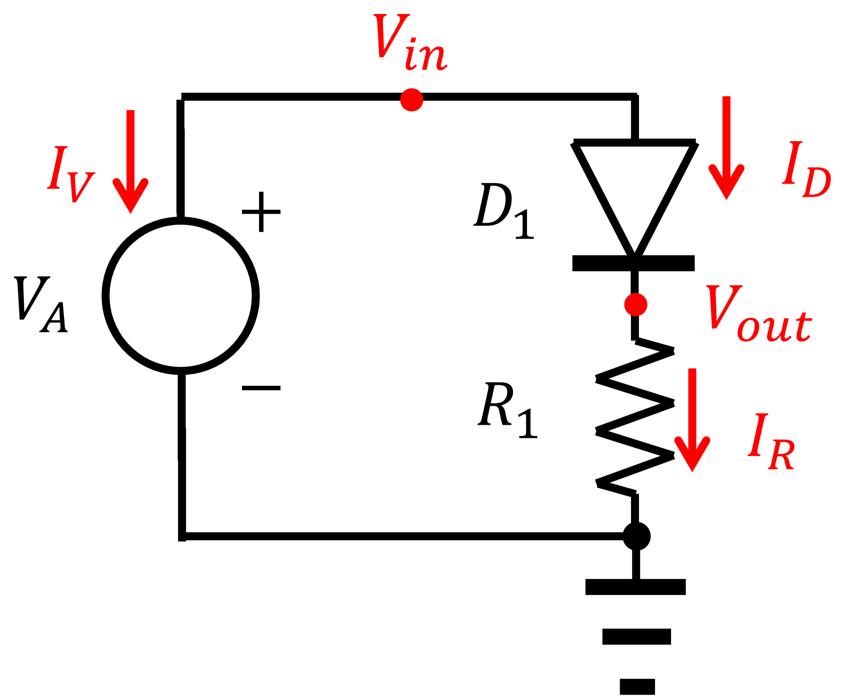
General solution (2)

- Identify the nodes and apply the KCL.
  - Two nodes (red dots) are found.

$$I_V + I_D = 0$$
$$-I_D + I_R = 0$$

  - Equations for terminal IVs

$$V_{in} = V_A$$
$$I_D = I_S\left(\exp\left(\frac{V_{in} - V_{out}}{V_T}\right) - 1\right)$$
$$I_R = \frac{V_{out}}{R_1}$$



General solution (3)

- Solve the set of equations.
  - After simple manipulation, it is easily found that

$$-I_S\left(\exp\left(\frac{V_A - V_{out}}{V_T}\right) - 1\right) + \frac{V_{out}}{R_1} = 0$$

  - An nonlinear equation for V_{out} is obtained.
  - The solution, V_{out}, can be visualized by drawing the following two curves.

$$y = I_S\left(\exp\left(\frac{V_A - x}{V_T}\right) - 1\right)$$

$$y = \frac{x}{R_1}$$

Graphical solution (1)

- Assume that V_A = 2 V, I_s = 0.5 fA, and R_1 = 270 Ω.
  - Draw two curves:

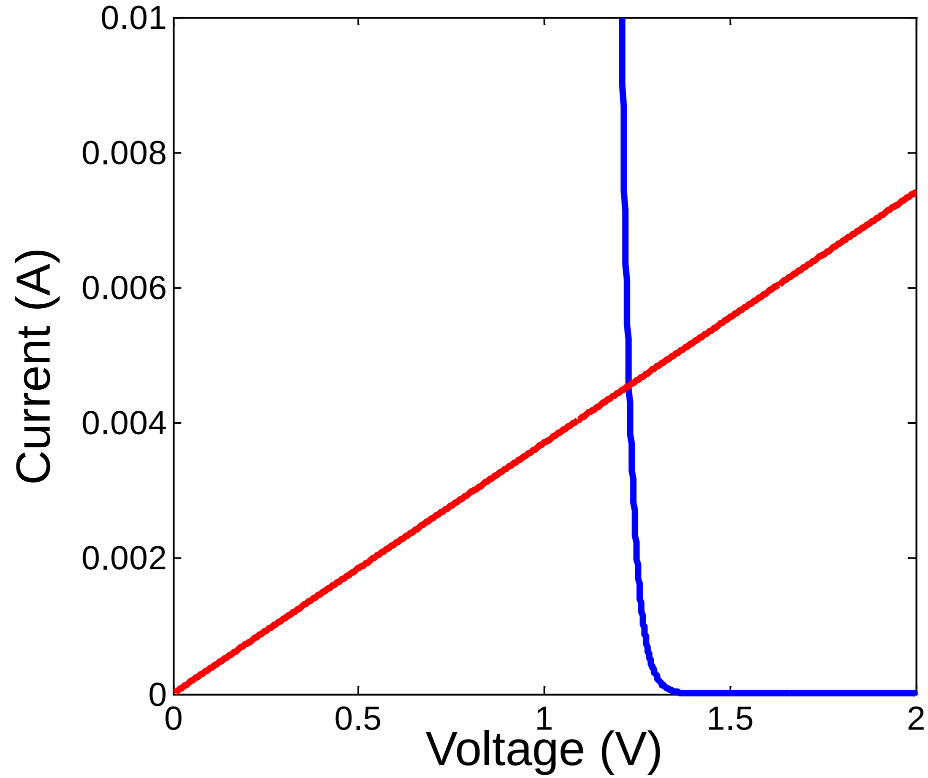
$$y = I_S\left(\exp\left(\frac{V_A - x}{V_T}\right) - 1\right)$$

$$y = \frac{x}{R_1}$$

  - The answer is

V_{out} = 1.2287 V.

  - 0.77 V is applied to the diode.



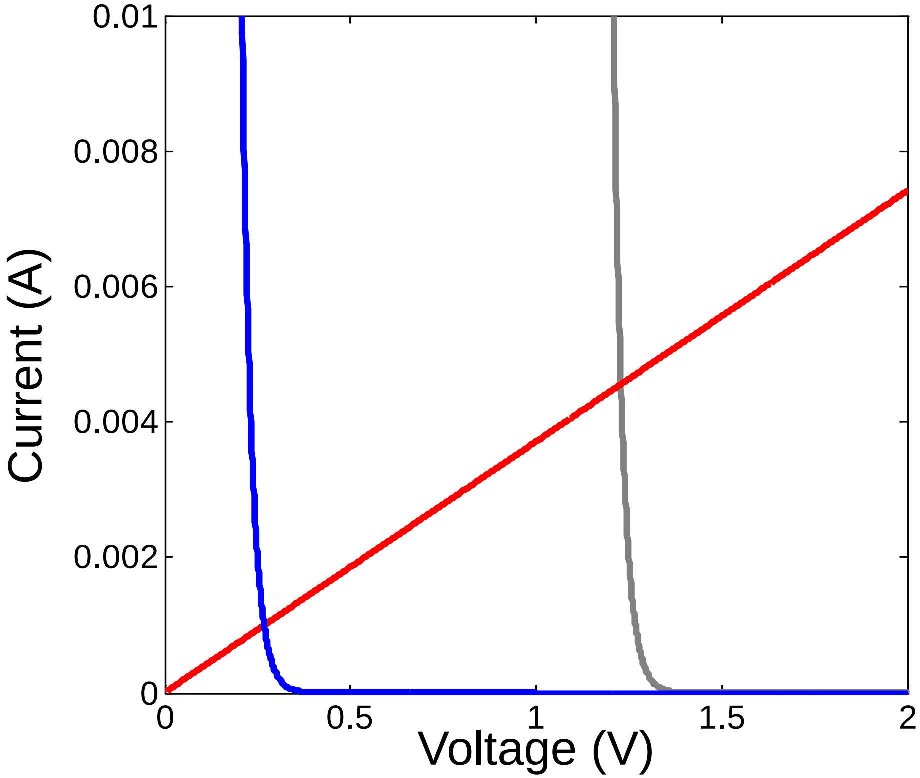
Graphical solution (2)

- Reduce V_A to 1 V.
  - The answer is

V_{out} = 0.2687 V.

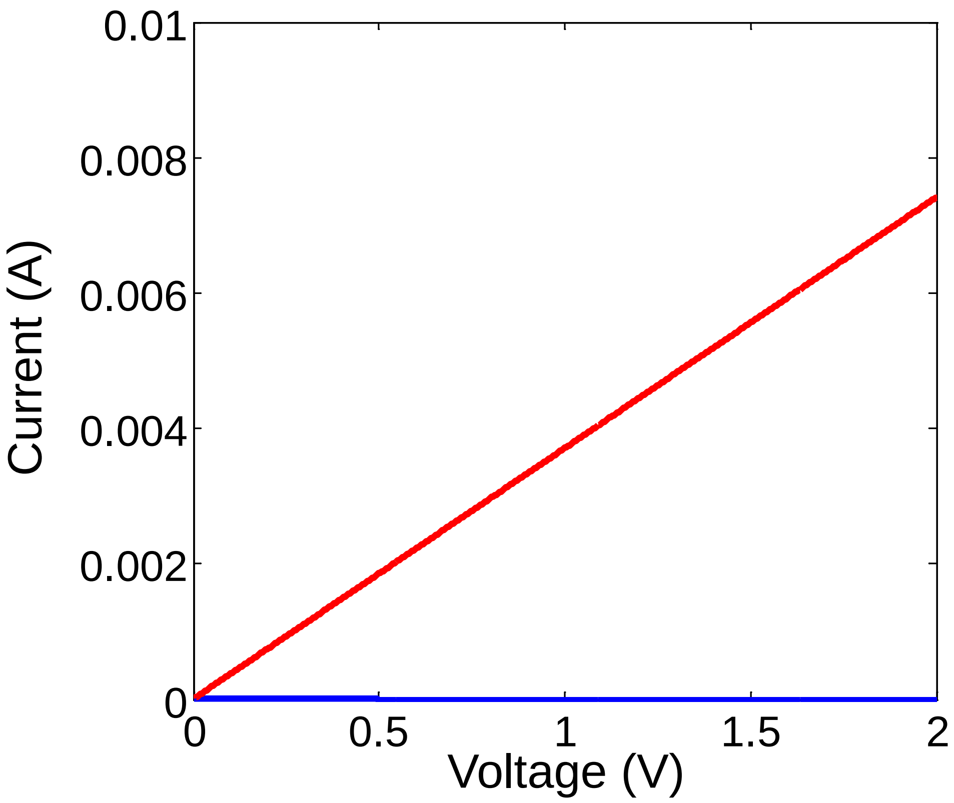
  - 0.73 V is applied to the diode.

- Even smaller V_A?
  - For example, 0.5 V?



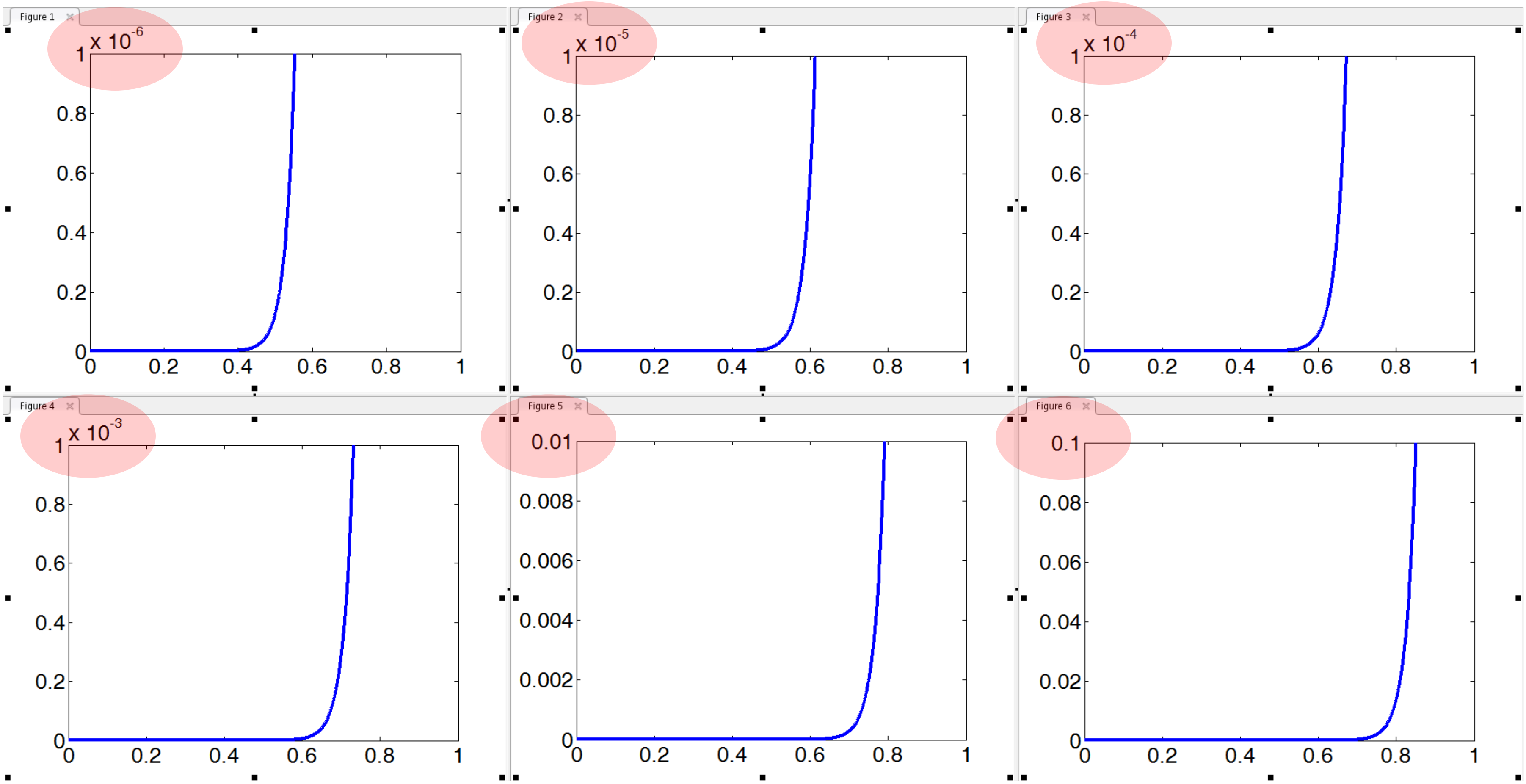
When V_A = 0.5 V

- The same scale as before.
  - ???
  - What is V_{out}?
- Not enough V_A
  - No current conduction



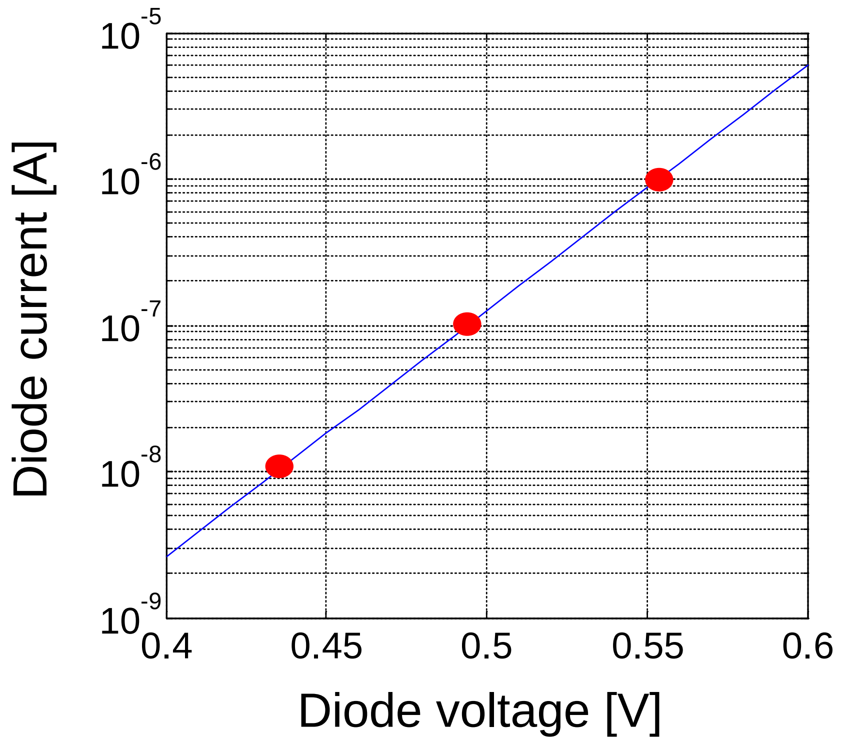
Dioide IV curves

- A diode with $I_S = 5 \times 10^{-16}$A (Only different y scales)



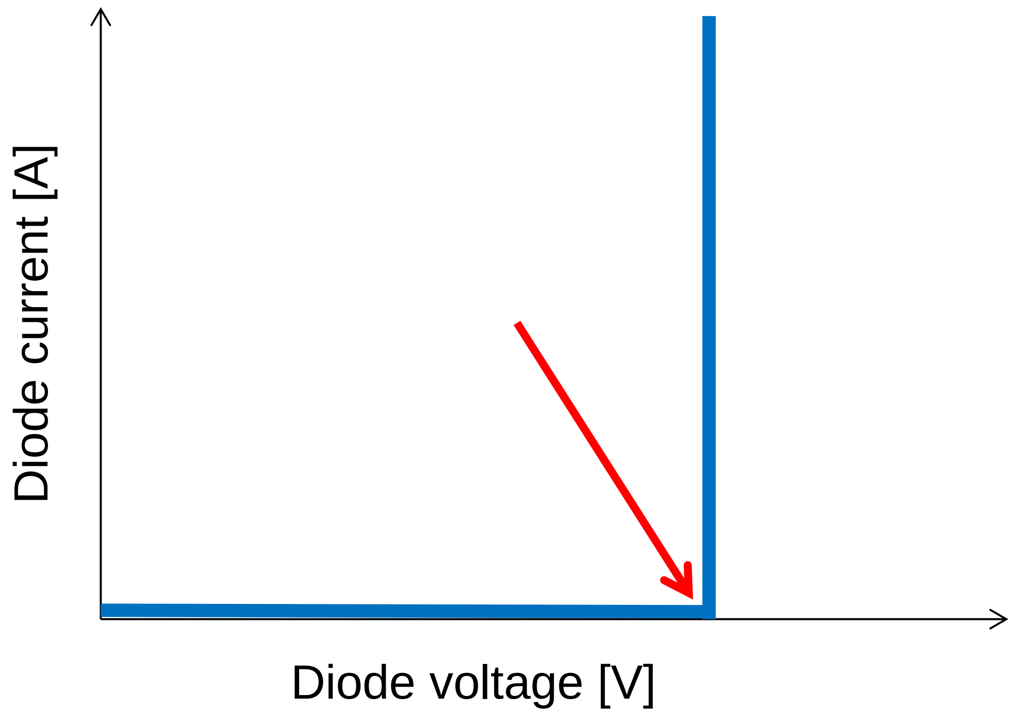
Important observation

- In order to obtain 10x large current,
  - We must apply only 60 mV additionally. (300K)



Diode model

- Two phases



Homework#2

- Due: 09:00, March 18
  - Submit your Homework answer sheet (hardcopy) directly to Mr. Suhyeong Cha, our TA.
  - His office: EECS building C-411
- Solve following problems of the 2018 mid-term exam.
  - P8
  - P9
  - P11
- Solve following problems of the 2017 mid-term exam.
  - P10
  - P11
  - P14
  - P17