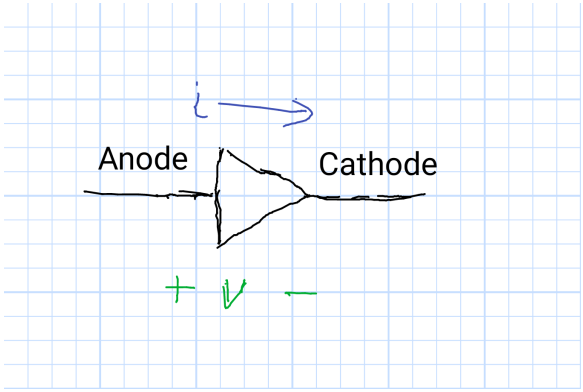
Fundamentals of Electronics
Week 4

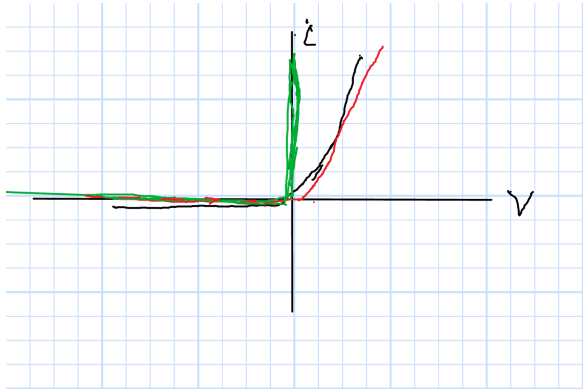
Charles A. DiMarzio
EECE–2412
Northeastern University

Sep 2024

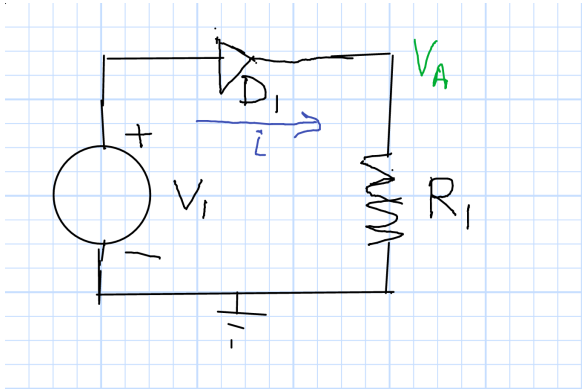
Diodes, Briefly



Diode Symbol



I–V Curves



Circuit

- Diodes are Pretty Good Conductors One Way
- Diodes are Pretty Good Insulators the Other Way
- Light Emitting Diodes Emit Light When they Conduct
- They are Nonlinear
- There are Several Piecewise–Linear Approximations
- The Details Can Get Messy

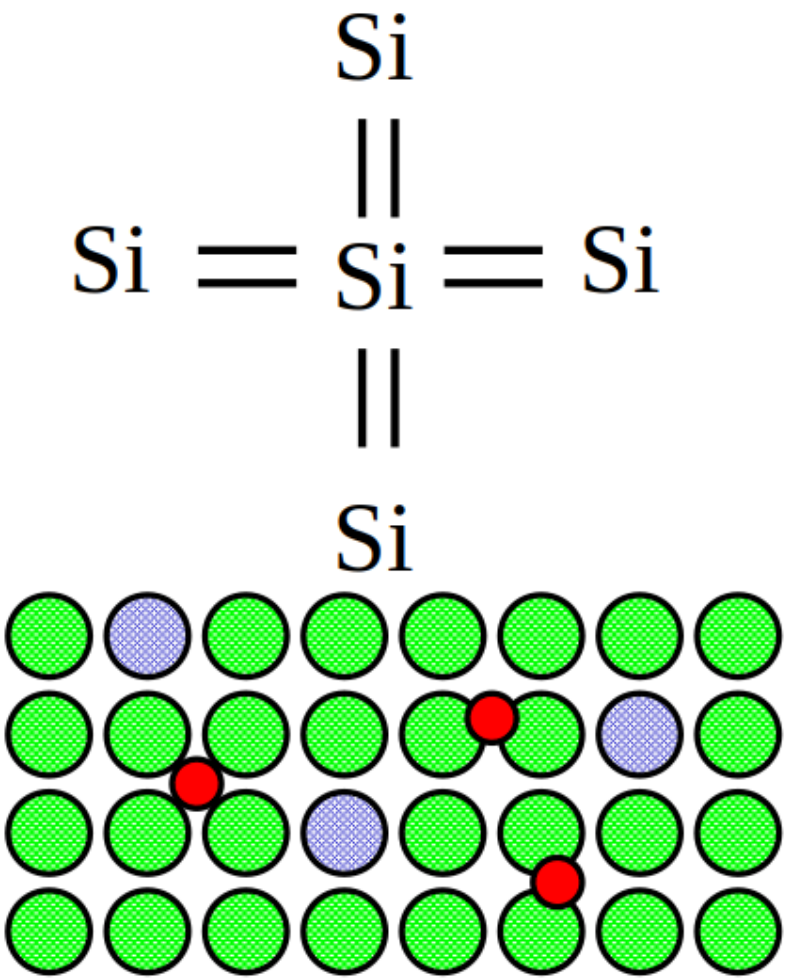
Week 4 Agenda

- Basic Physics in Intrinsic Silicon
  - Semiconductors
  - Diffusion Current
  - Drift Current
- Semiconductor Doping
- Junction
  - Open–Circuit
  - Reverse Bias and Breakdown
  - Forward Bias
- Photodiodes

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Intrinsic Silicon (1)



- Free Electron Density Depends on Temperature
- Charge-Neutral

$$n = p = n_i = BT^3 e^{-E_g/kT}$$

$$= BT^3 e^{-qV/kT} = BT^3 e^{-V/V_T}$$

Intrinsic Silicon (2)

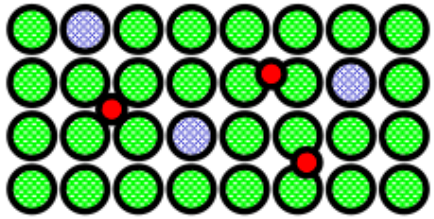
$$n = p = n_i = BT^3 e^{-E_g/kT}$$

$$B = 5.4 \times 10^{31} / (\text{cmK})^3 \text{ for Silicon}$$

$$kT/q = 25\text{mV}$$

$$n_i \approx 1.5 \times 10^{10} / \text{cm}^3$$

Compare 5 X 10^{22} Atoms/cm^3
Moderate σ
"Σεμιχονδυχτορ"



- Two Current Mechanisms
  - Drift
    - in Applied Field
  - Diffusion
    - "Just Because"

Electrons and Holes

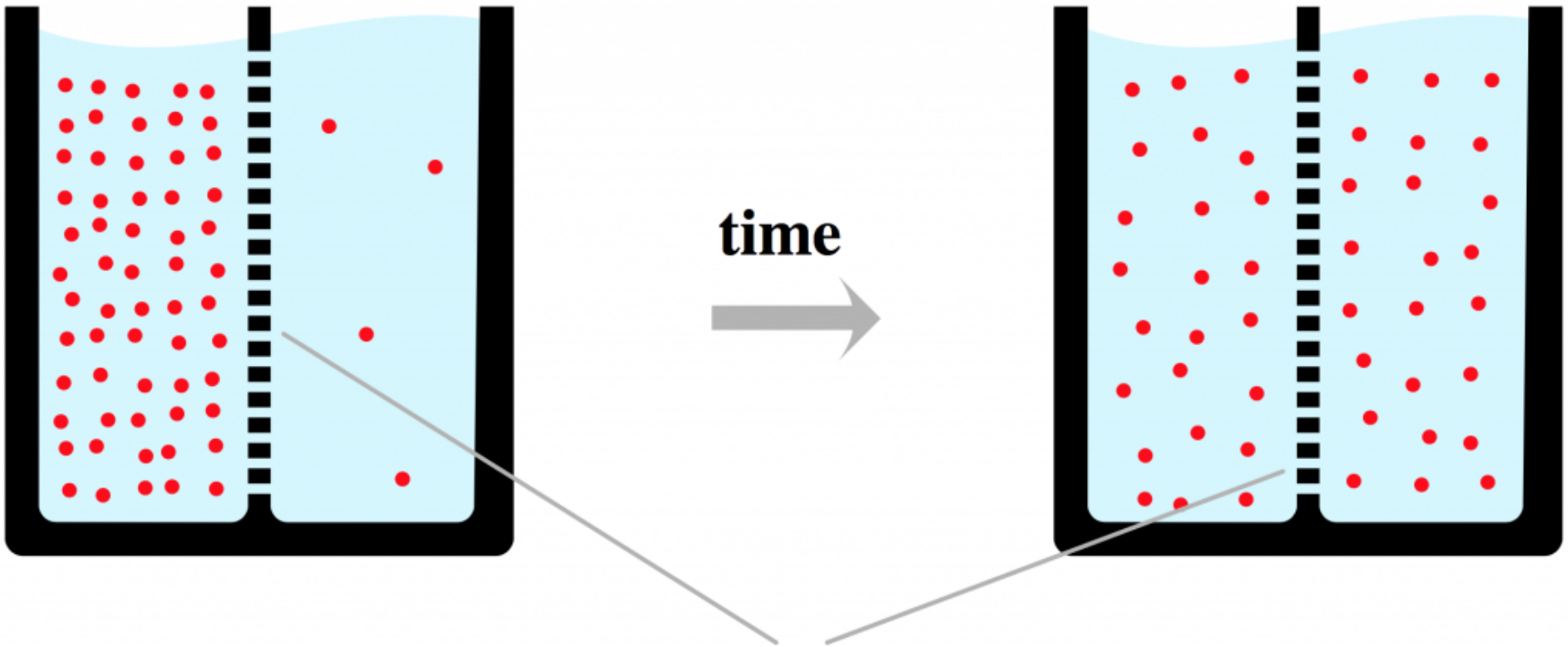
- A Hole Can Move
- An Electron Recombines
- Holes Move More Slowly than Electrons
- Hole Moves to Right $\rightarrow$ Current to the Right
- Electron Moves to Left $\rightarrow$ Current to the Right

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Diffusion Demonstration

No Applied Force
Thermal Energy
Uncorrelated Random Motion
Average Result: $\vec{v} = D\nabla n$



https://teachwithfergy.com/diffusion-demonstration/

Hole and Electron Diffusion Currents

Hole-Current Density
"High to Low"
Hole Charge
HoleDiffusivity
Hole Density
Gradient

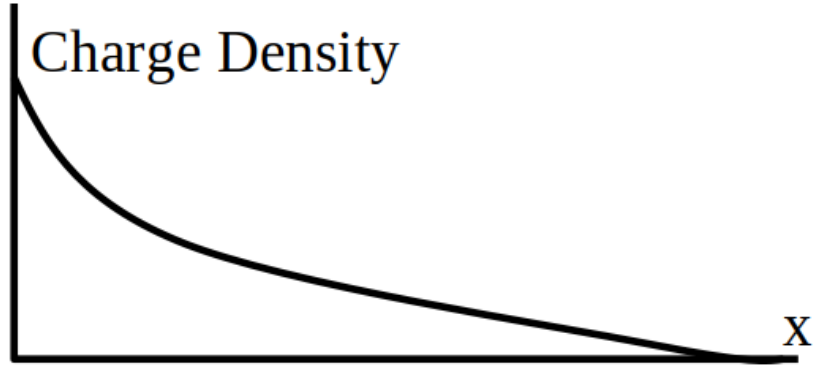
$$J_p = -qD_p \frac{dp}{dx}$$

$$J_n = qD_n \frac{dn}{dx}$$

$$J_p = -1.6 \times 10^{-19}\,\text{Coul} \times 12 \frac{\text{cm}^2}{\text{sec}} \times \frac{dp}{dx}$$

$$J_n = -1.6 \times 10^{-19}\,\text{Coul} \times 34 \frac{\text{cm}^2}{\text{sec}} \times \frac{dn}{dx}$$

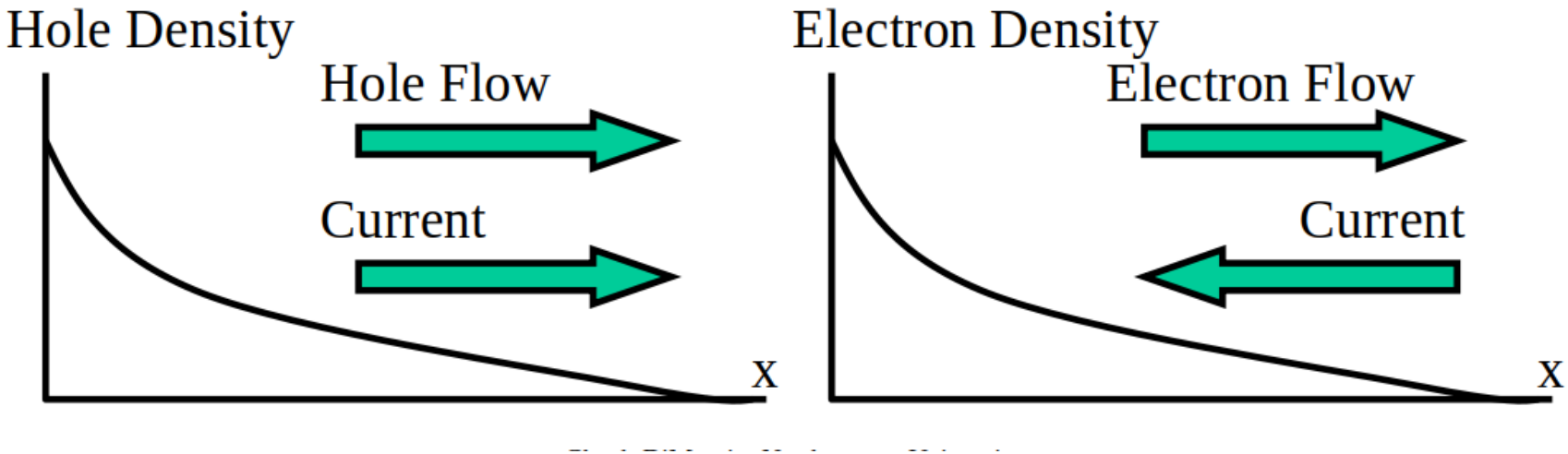
$$\frac{\text{Coul/sec}}{\text{cm}^2} = \text{Coul} \frac{\text{cm}^2}{\text{sec}} \frac{\text{cm}^{-3}}{\text{cm}}$$



Diffusion Currents

$$J_p = -qD_p \frac{dp}{dx} \qquad J_p \approx -1.6\times10^{-19}\,\text{Coul}\times 12\,\frac{\text{cm}^2}{\text{sec}}\times\frac{dp}{dx}$$

$$J_n = qD_n \frac{dn}{dx} \qquad J_n \approx -1.6\times10^{-19}\,\text{Coul}\times 34\,\frac{\text{cm}^2}{\text{sec}}\times\frac{dn}{dx}$$



Drift

Velocity $v \propto E$

Hole Velocity

$v = \mu_p E$

- v: Velocity (cm/s)
- μ: Mobility
- E: Field (V/m)

$$v \approx 480 \frac{\text{cm}^2}{\text{Vs}} E$$

Electron Velocity

$$v = -\mu_n E$$

$$v \approx -1350 \frac{\text{cm}^2}{\text{Vs}} E$$

Velocities are Average
Collisions are Important

Drift Current

Hole Velocity

$$v = \mu_p E$$

Electron Velocity

$$v = -\mu_n E$$

$$J_{drift} = q(p\mu_p + n\mu_n)E$$

$$J_{drift} = \sigma E$$

Conductivity

Note: Resistance is $R = \ell / (\sigma A)$

Current Summary

Diffusion

$$J_{diffusion} = -q\left(D_p \frac{dp}{dx} + D_n \frac{dn}{dx}\right)$$

Drift

$$J_{drift} = q(p\mu_p + n\mu_n)E$$

Relationship

$$\frac{D_p}{\mu_p} = \frac{D_n}{\mu_n} = V_T$$

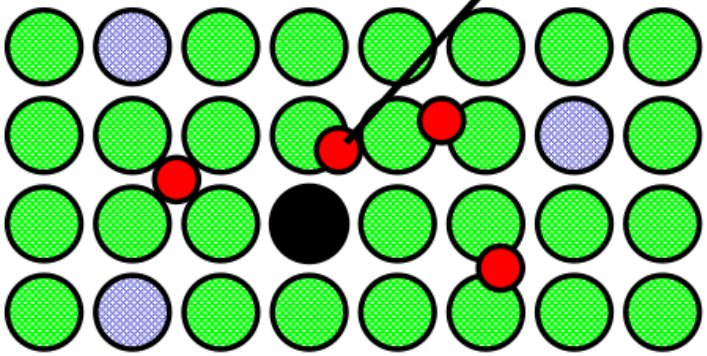
$$J = q\left(\mu_p\left(pE + V_T \frac{dp}{dx}\right) + \mu_n\left(nE + V_T \frac{dn}{dx}\right)\right)$$

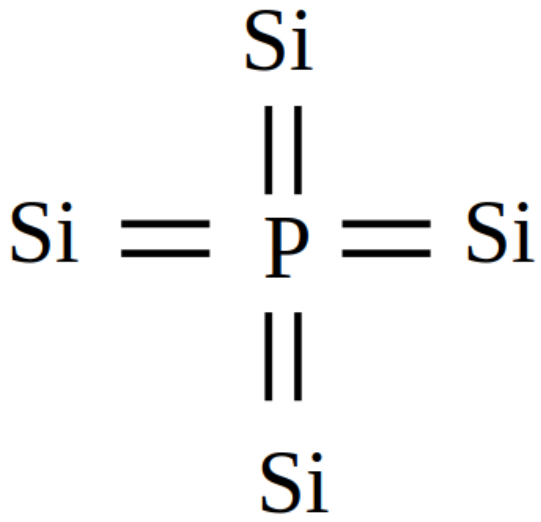
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N Doping

N-Doping
Phosphorus has Valence=5
One Extra Valence Electron
One Extra Proton
Still Charge Neutral

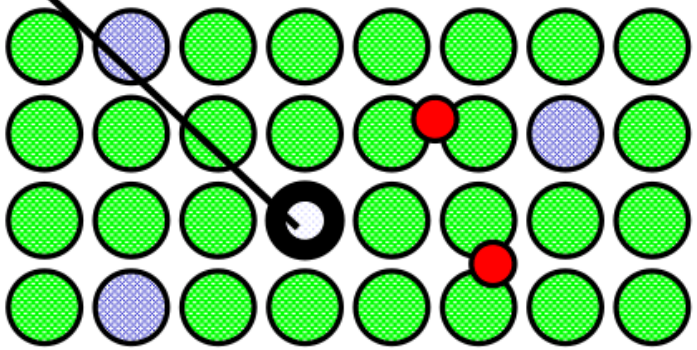


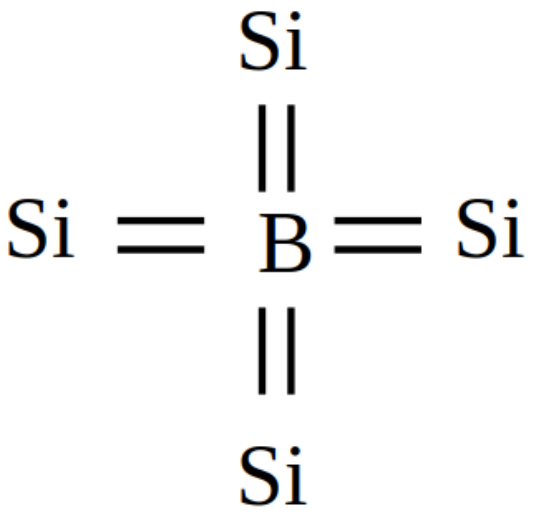


Electrons Are Majority Carriers

P Doping

P-Doping
Boron has Valence=3
Short One Valence Electron
One Free Electron Replaces It
Short One Proton
Still Charge Neutral





Holes Are Majority Carriers

Doping Numbers

$$n_{n0} = N_D$$

- n_{n0}: Density of Free Electrons
- in N-Doped Material
- Equilibrium
- N_D: Number Density of Donors

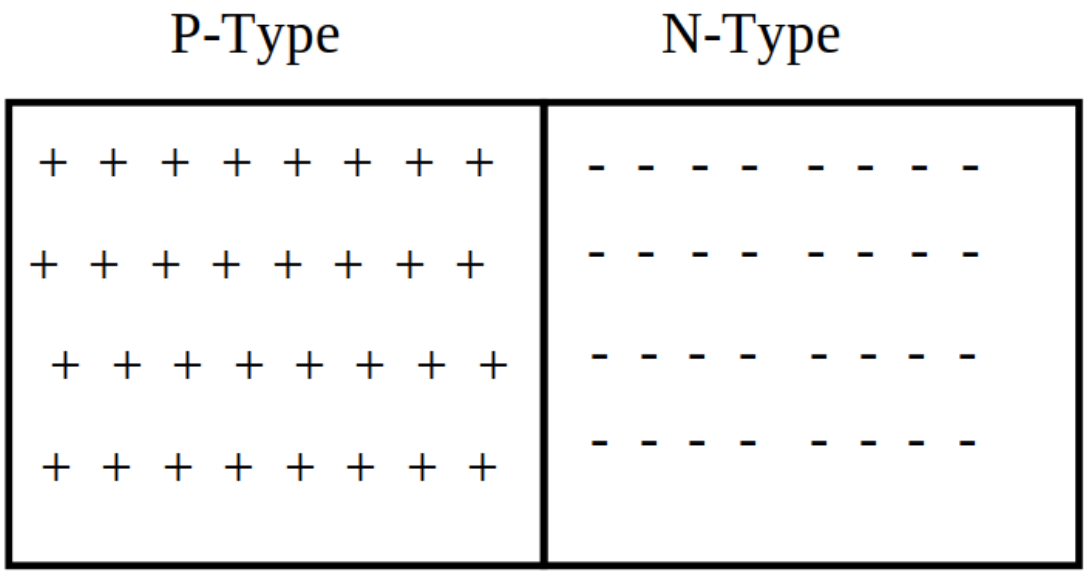
Relationship $$n_{n0}\, p_{n0} = n_i^2 = \left(BT^3 e^{-V/V_T}\right)^2$$

$$p_{n0} = \frac{n_i^2}{n_{n0}}$$

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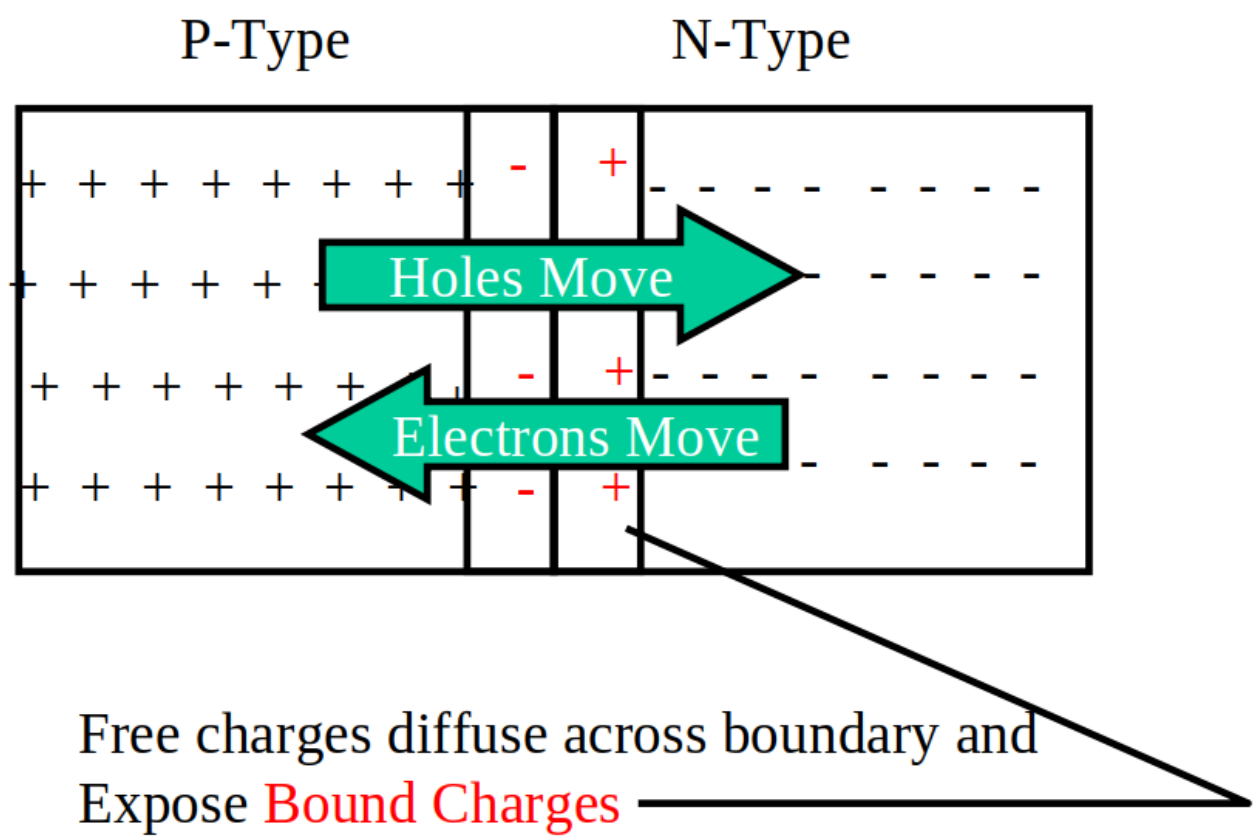
Open–Circuit P–N Junction



Both Sides are Charge Neutral
Gradient of Charge Exists at Junction
"Diffusion Happens"

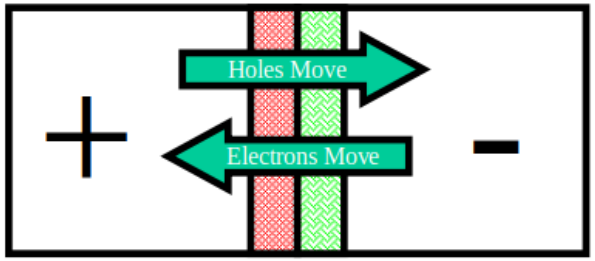
+ are holes and - are electrons

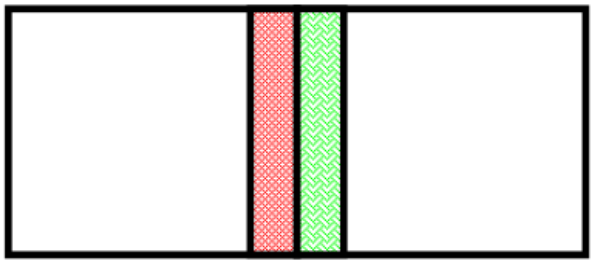
Diffusion Moves Free Charges



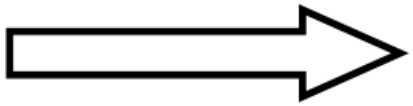
+ are holes and - are electrons

Drift Moves them the Other Way

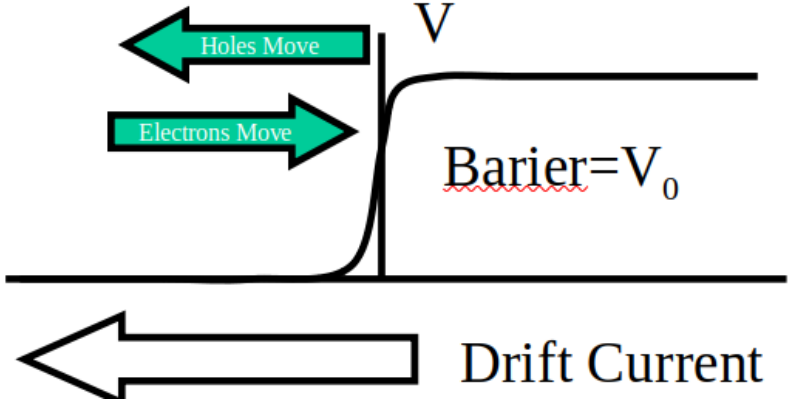




Bound Charge Produces Field and Thus Voltage Barrier



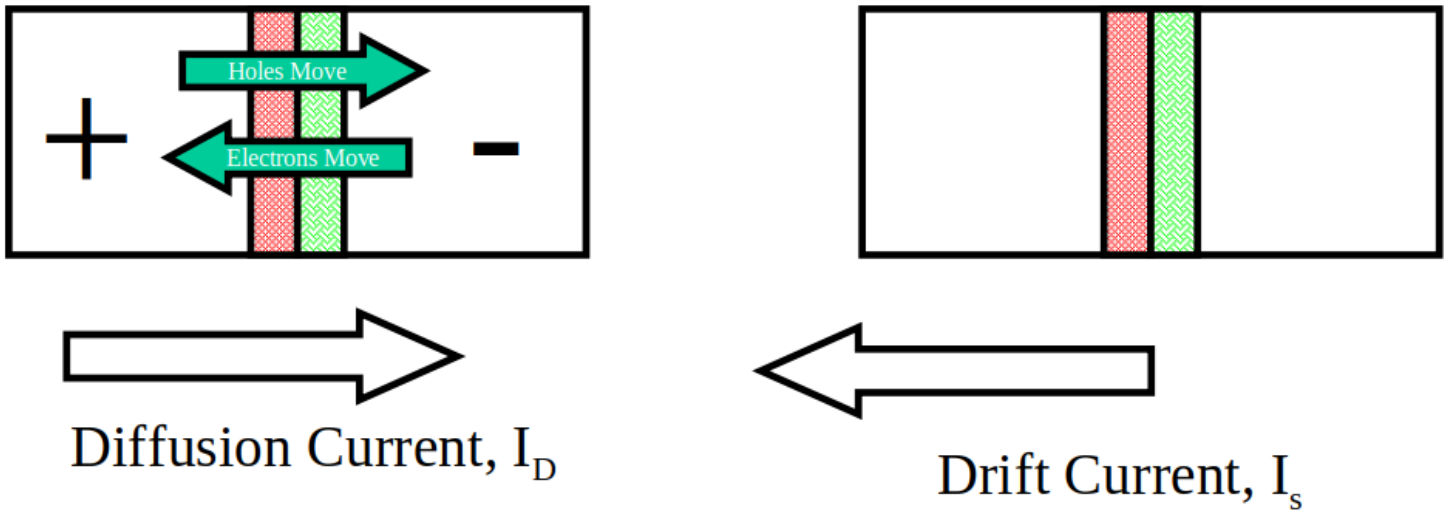
Diffusion Current



red electrons and green holes

Open–Circuit Junction (1)

$$I = 0$$



$$I_D = I_S$$

red electrons and green holes

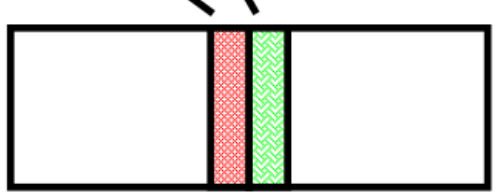
Open–Circuit Junction (2)

Barrier Voltage

$$v_0 = V_T \ln\left(\frac{N_A N_D}{n_i^2}\right) \approx 0.7\text{V for Silicon}$$

Size of Depletion Region (Important for Capacitance)

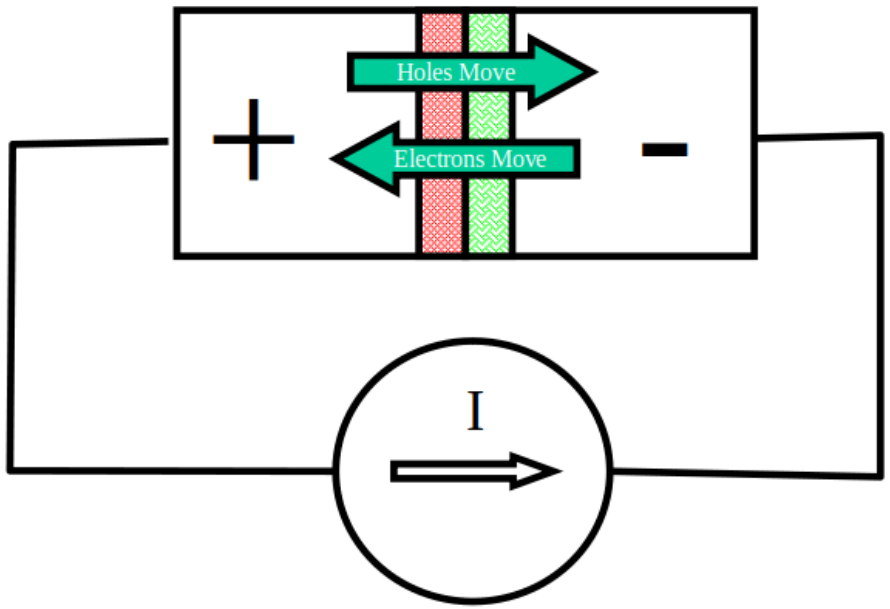
$$W_{Depl} = x_d + x_n = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)V_0} \qquad \varepsilon_s = 11.7\varepsilon_o = 104\text{F/cm}$$



$$0.1\mu\text{m} \le W_{Depl} \le 1\mu\text{m}$$

red electrons and green holes

Reverse Biased Junction



$$I = I_s - I_D$$

at Equilibrium

$$I_D \approx 0 \quad \Rightarrow \quad I \approx I_s$$

Size of Depletion Region

$$W_{Depl} = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{1}{N_A} + \frac{1}{N_D}\right)(V_0 + V_R)}$$

red electrons and green holes

Reverse Bias Capacitance

$$W_{Depl} = \sqrt{\frac{2\varepsilon_s}{q}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)(V_0 + V_R)}$$

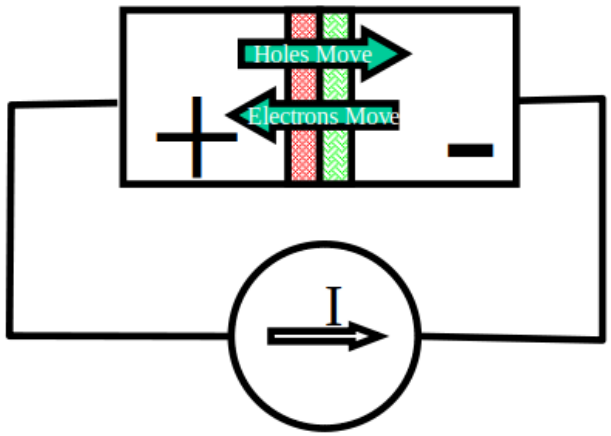
$$\text{Theoretical Expression } C_j = \frac{dq_j}{dV_R} = AW_{Depl}\,(V_R = 0)$$

Empirical Result

$$C_j = \frac{\sqrt{\frac{\varepsilon_s q}{2}\left(\frac{1}{N_A}+\frac{1}{N_D}\right)\frac{1}{V_0}}}{\left(1+\frac{V_R}{V_0}\right)^m} = \frac{C_0}{\left(1+\frac{V_R}{V_0}\right)^m}$$

Grading Coefficient $\frac{1}{3} \le m \le \frac{1}{2}$

Breakdown

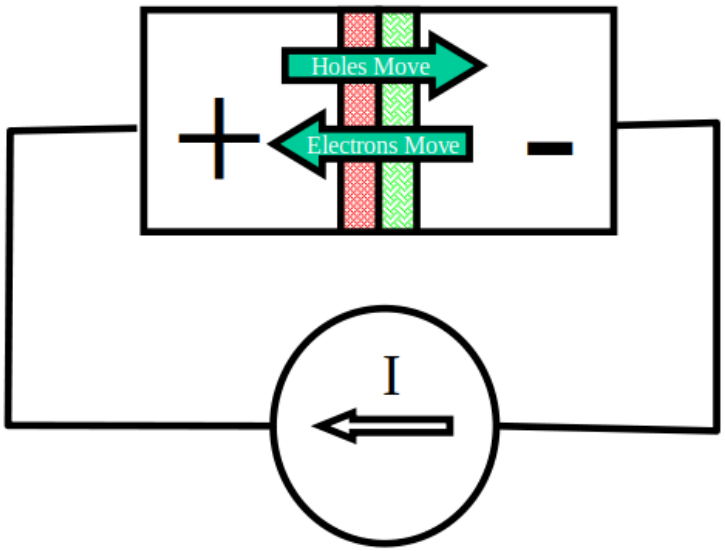


- Breakdown Condition

$$I >> I_S$$

- Zener Effect
  - Based on Field
- Avalanche Effect
  - Based on Minority Carriers

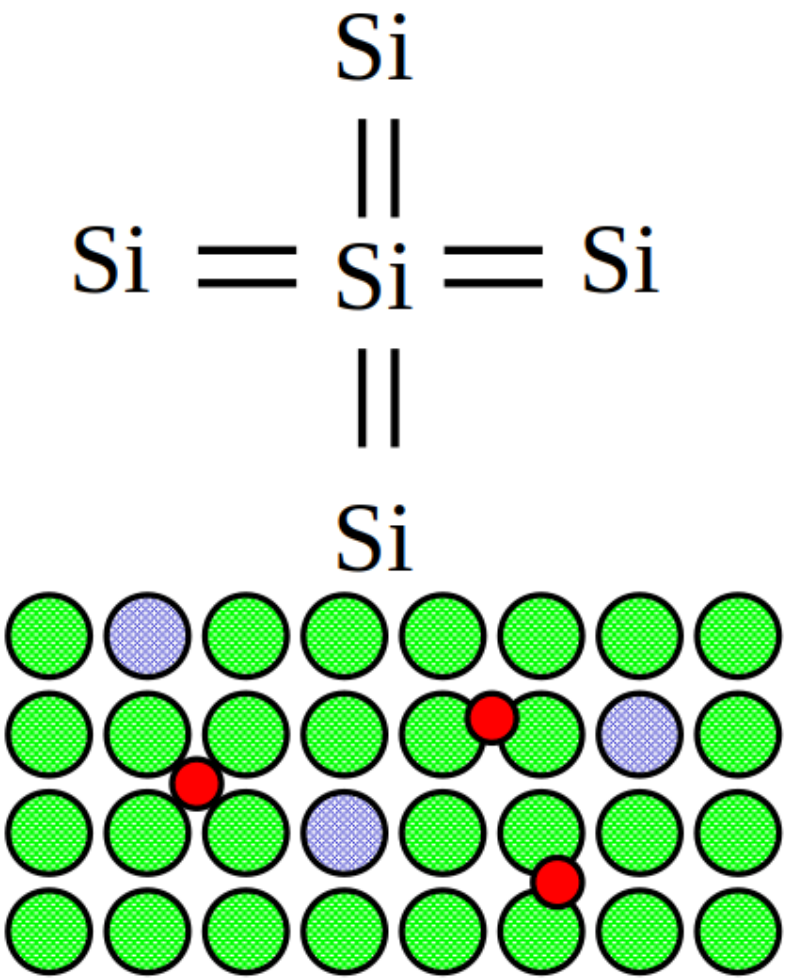
Forward Biased Junction (1)



- Majority Carriers Flow
  - Cover Bound Charge
- Diffusion Current Increases
- Barrier Voltage Decreases

$$I = I_D - I_S$$

Forward Biased Junction (2)



- Free Electron Density Depends on Temperature
- Charge-Neutral

$$n = p = n_i = BT^3 e^{-E_g/kT}$$

$$= BT^3 e^{-qV/kT} = BT^3 e^{-V/V_T}$$

Shockley Equation

- Previous Page: $n = p = BT^3 e^{-v_d/V_T}$
- More Carriers: More Current
- Forward Current

$$i_d = I_s e^{v_d/(nV_T}$$

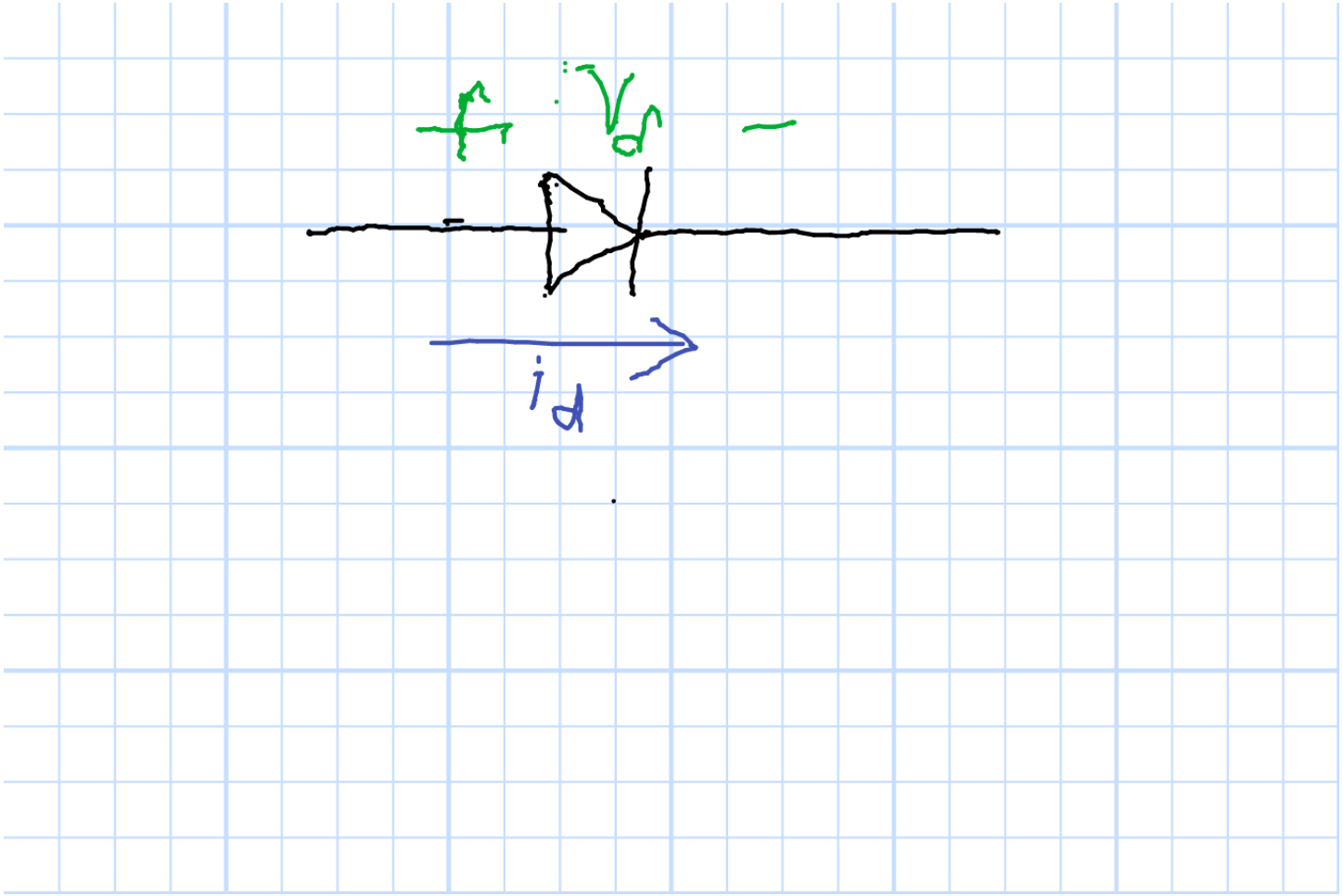
- Shockley Equation

$$i_d = I_s \left[e^{v_d/(nV_T} \right]$$

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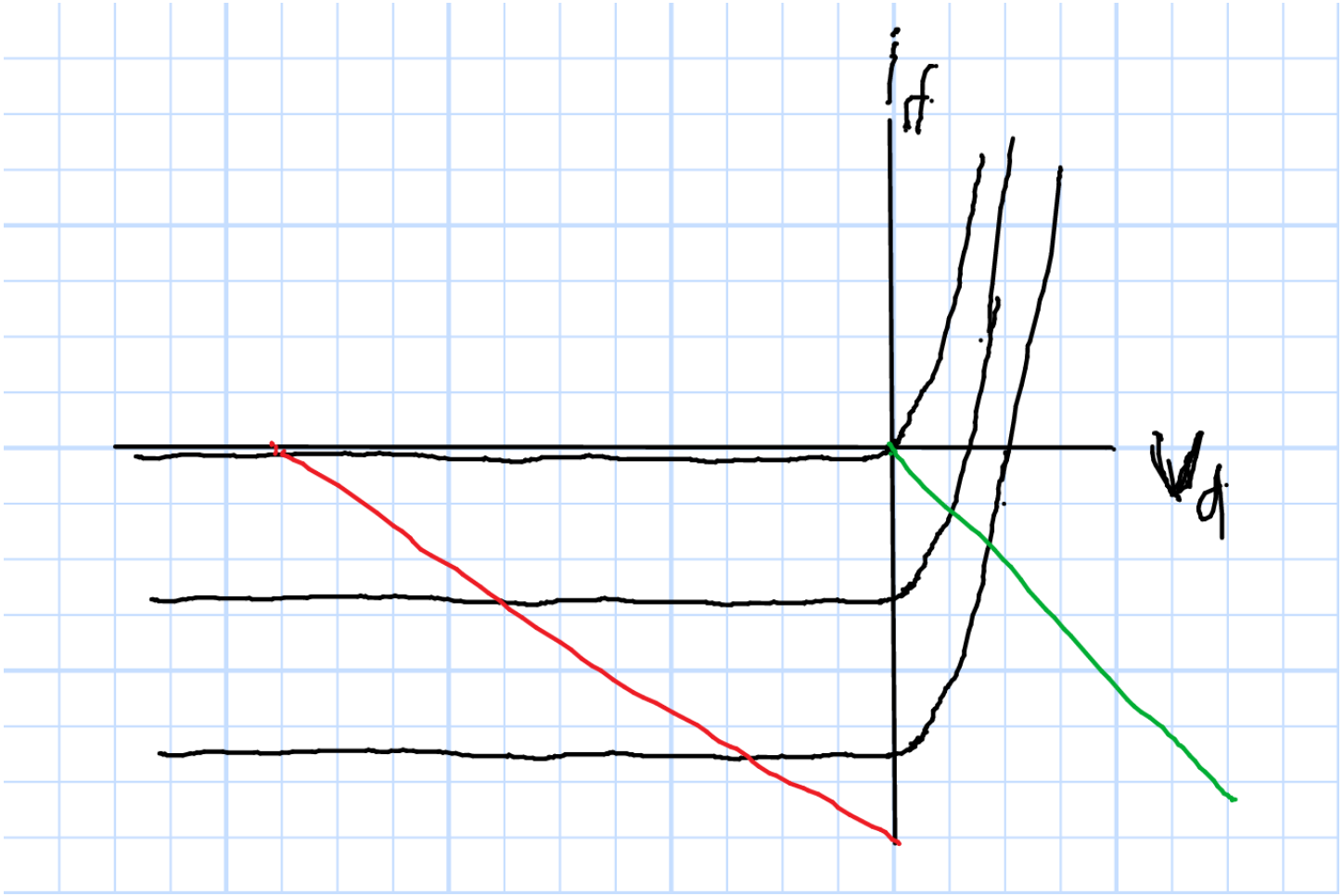
Photodiodes. . .



Diode: Small reverse current & Large forward current

Photodiode: Reverse current increases with optical power.

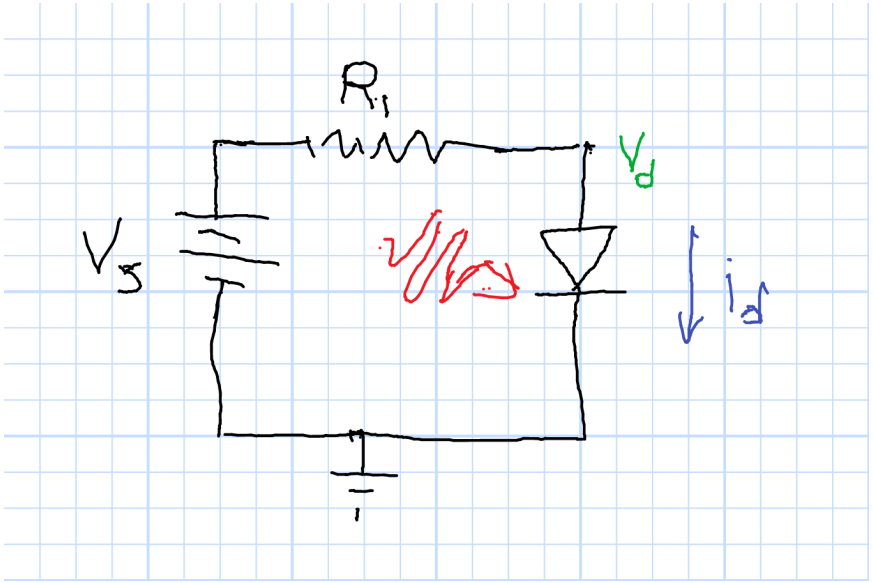
Photodiode Curves

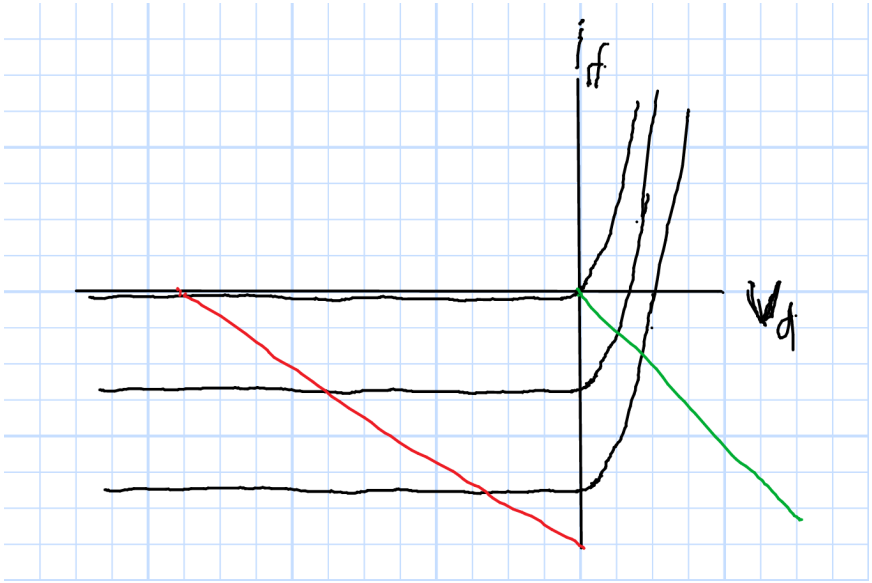


Diode (Top Curve); $i_d = I_s\left(-1 + e^{v_d/V_T}\right)$

Photocurrent adds: $i_{photo} = -\rho_i P_{optical}$ (Lower Lines).

Photodiode Circuit





$$v_d = v_s + \rho_i P_{optical} R_1$$

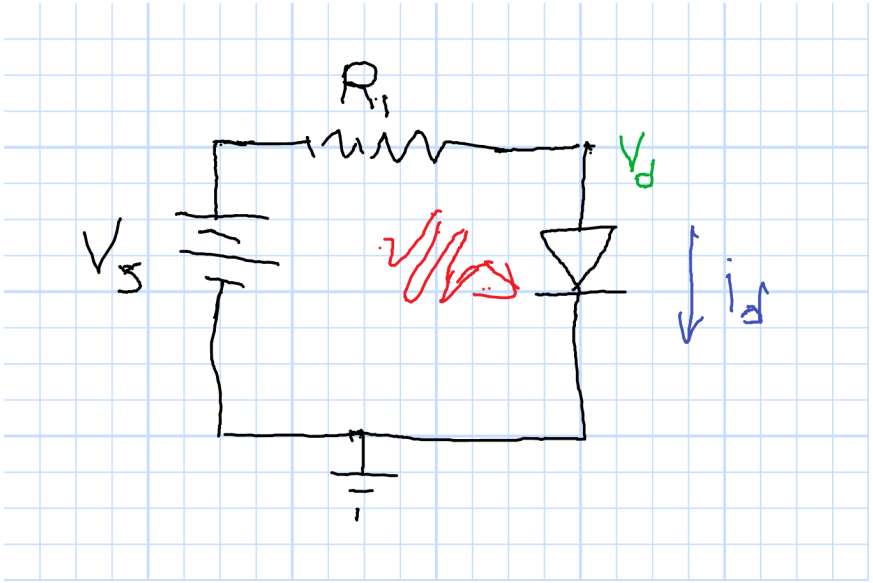
Photocurrent is Negative

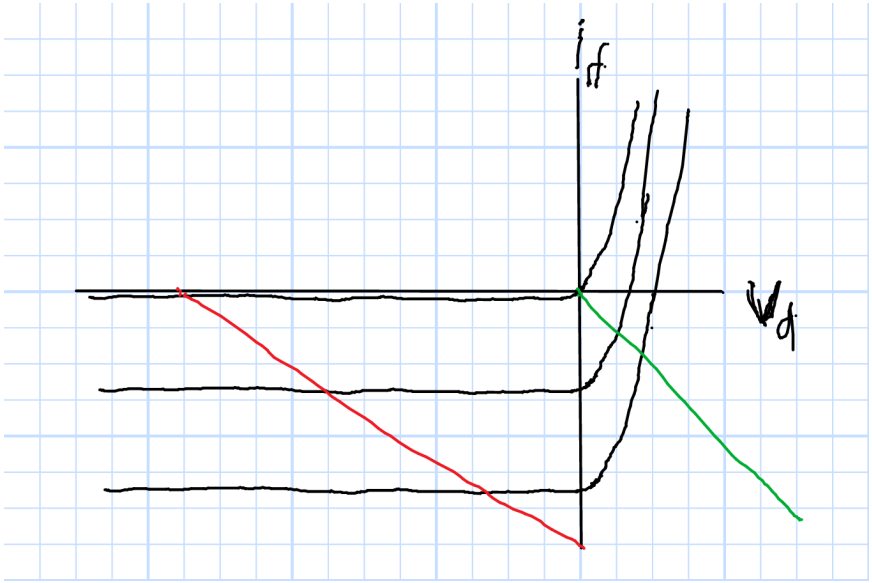
$$v_s < 0 \qquad \text{Red Line}$$

Useful as a detector of light.

Negative Bias also helps with speed.

Solar Cell





$v_s = 0$ $P_{diode} < 0$ Green Line

Diode is a source of power.

R_l is the load.

$$P_L = -P_{diode}$$