Semiconductor Diodes

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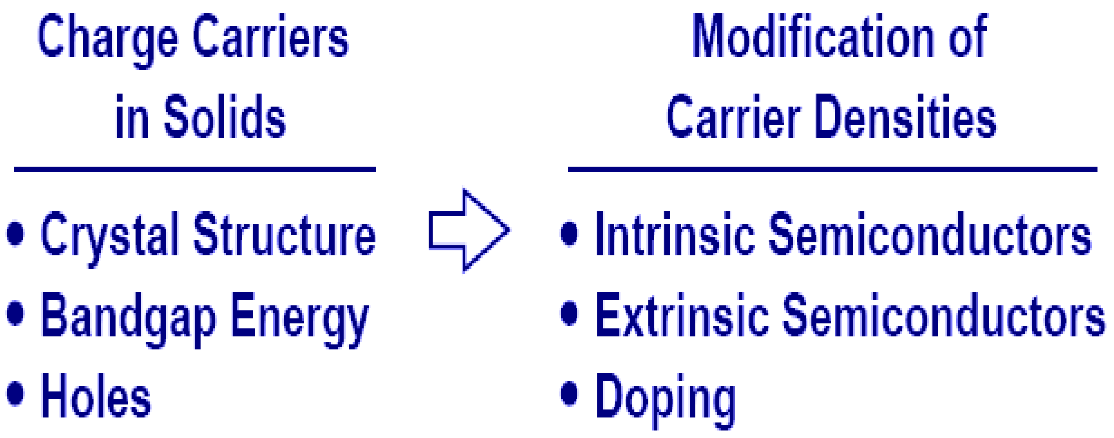
Chapter : Basic Physics of Semiconductors

2.1 Semiconductor materials and their properties

2.2 PN-junction diodes

2.3 Reverse Breakdown

Charge Carriers in Semiconductor



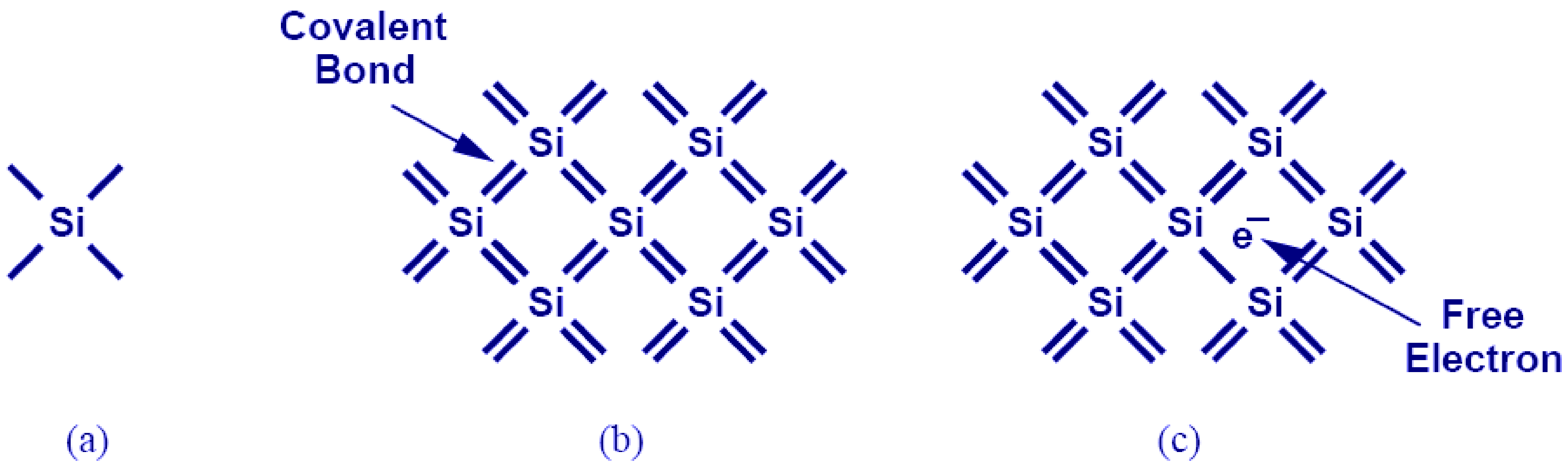
- To understand PN junction's IV characteristics, it is important to understand charge carriers' behavior in solids, how to modify carrier densities, and different mechanisms of charge flow.

Periodic Table

	III	IV	V	
	Boron (B)	Carbon (C)		
	Aluminum (Al)	Silicon (Si)	Phosphorous (P)	
	Galium (Al)	Germanium (Ge)	Arsenic (As)	

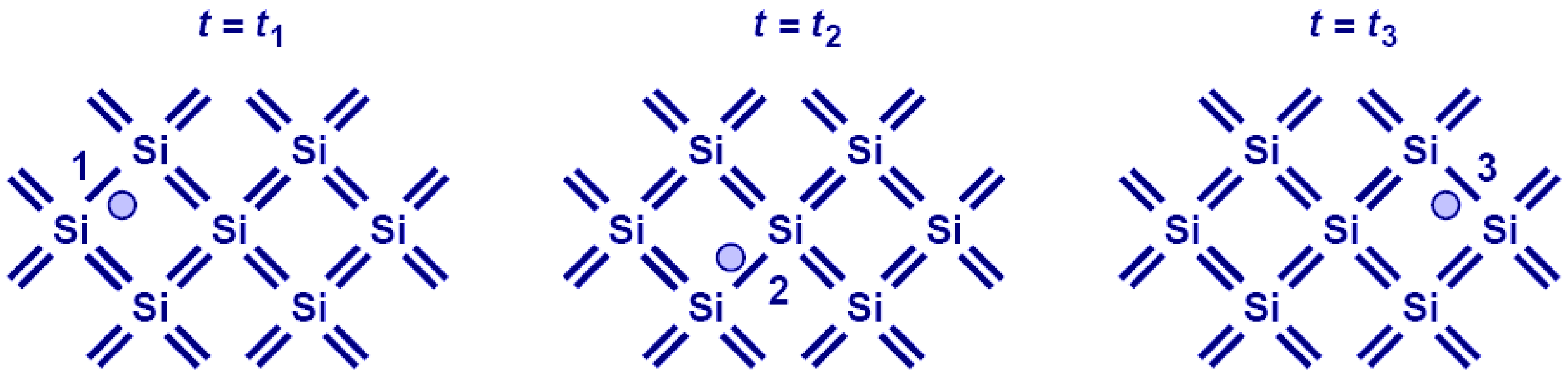
- This abridged table contains elements with three to five valence electrons, with Si being the most important.

Silicon



- Si has four valence electrons. Therefore, it can form covalent bonds with four of its neighbors.
- When temperature goes up, electrons in the covalent bond can become free.

Electron-Hole Pair Interaction

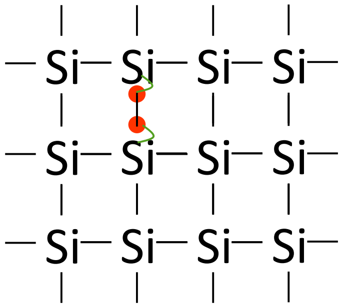


- With free electrons breaking off covalent bonds, holes are generated.
- Holes can be filled by absorbing other free electrons, so effectively there is a flow of charge carriers.

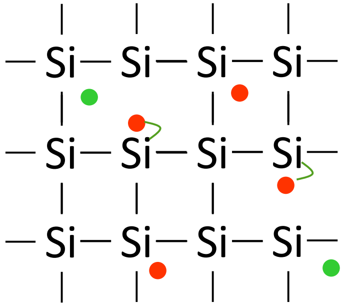
Free charged carriers in Si

Covalent bond

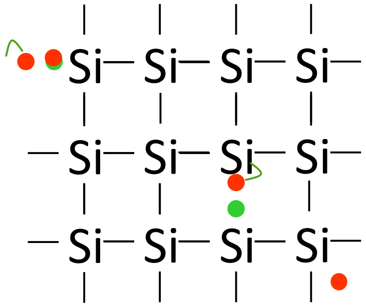
Intrinsic Si



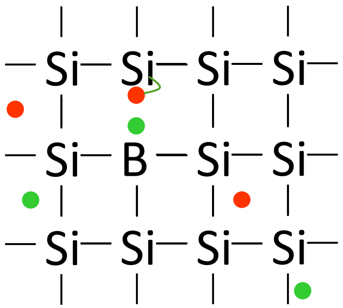
Thermal energy: kT



Movement: kT



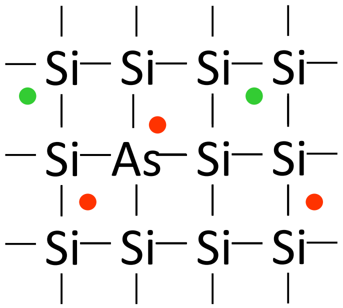
Extrinsic Si



N_A

p-type

Extrinsic Si

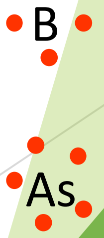


N_D

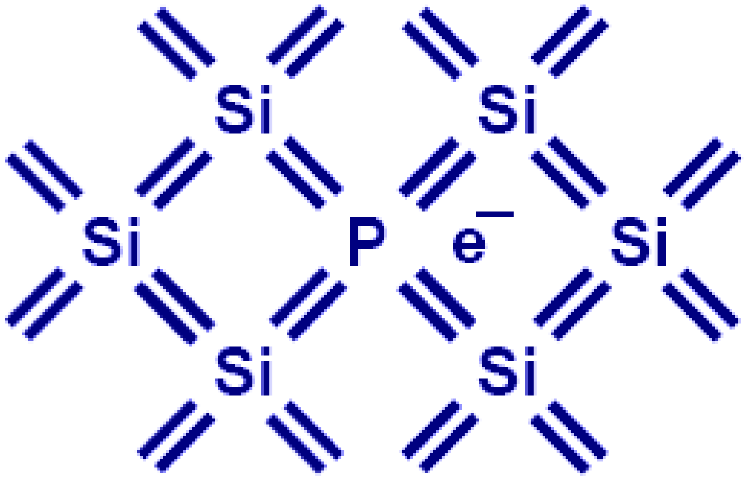
n-type

Extrinsic Si

Obtained by doping

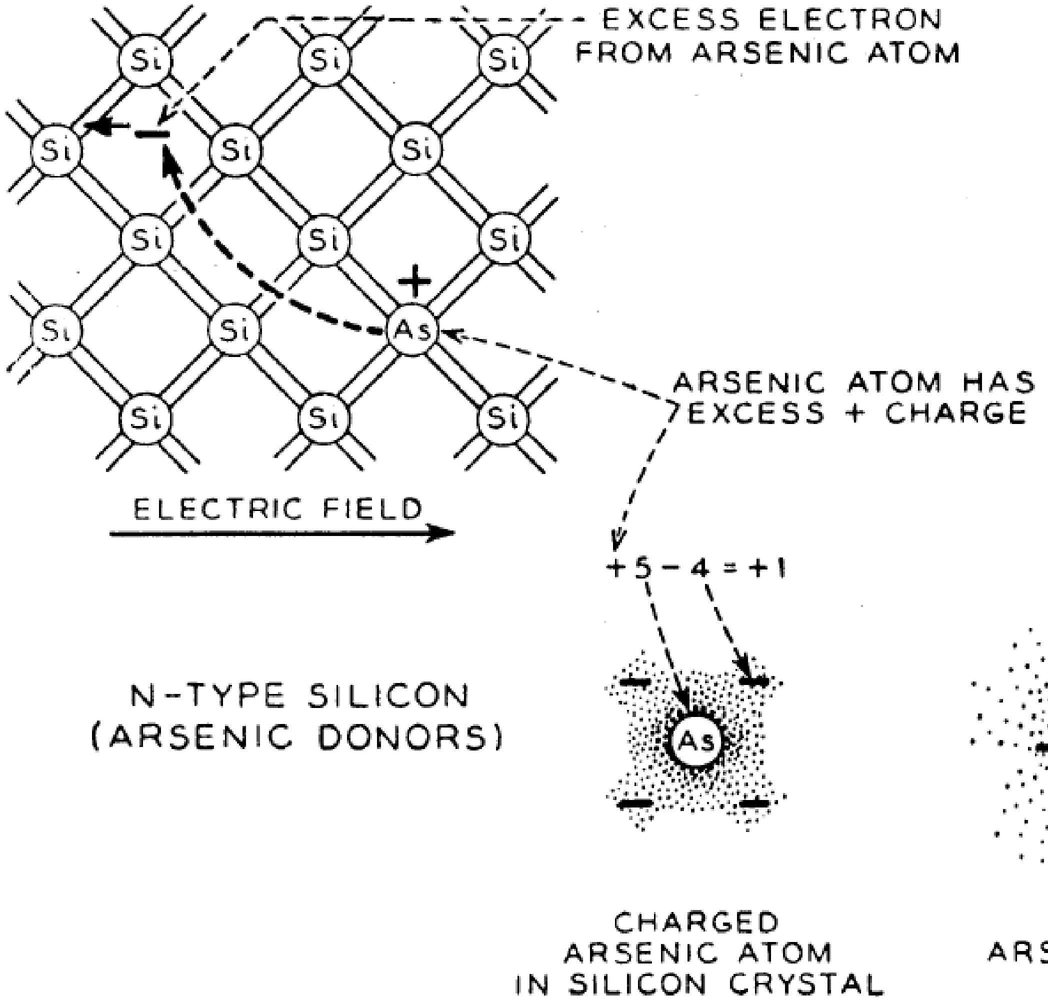


Doping (N type)

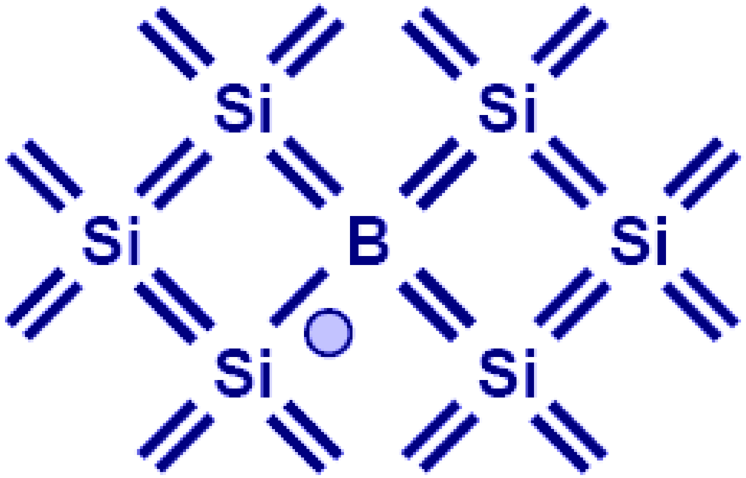


- Pure Si can be doped with other elements to change its electrical properties.
- For example, if Si is doped with P (phosphorous), then it has more electrons, or becomes type N (electron).

N-type


EXCESS ELECTRON
FROM ARSENIC ATOM
Si
As
+
ARSENIC ATOM HAS
EXCESS + CHARGE
ELECTRIC FIELD
N-TYPE SILICON
(ARSENIC DONORS)
+5 − 4 = +1
+5 − 5 = 0
+4 − 4 = 0
CHARGED
ARSENIC ATOM
IN SILICON CRYSTAL
FREE
ARSENIC ATOM
NEUTRAL
SILICON ATOM
IN CRYSTAL

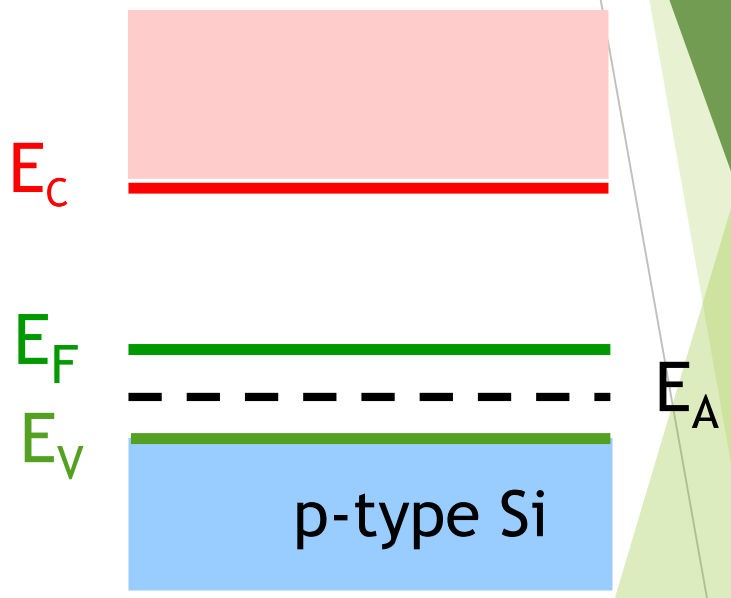
Doping (P type)



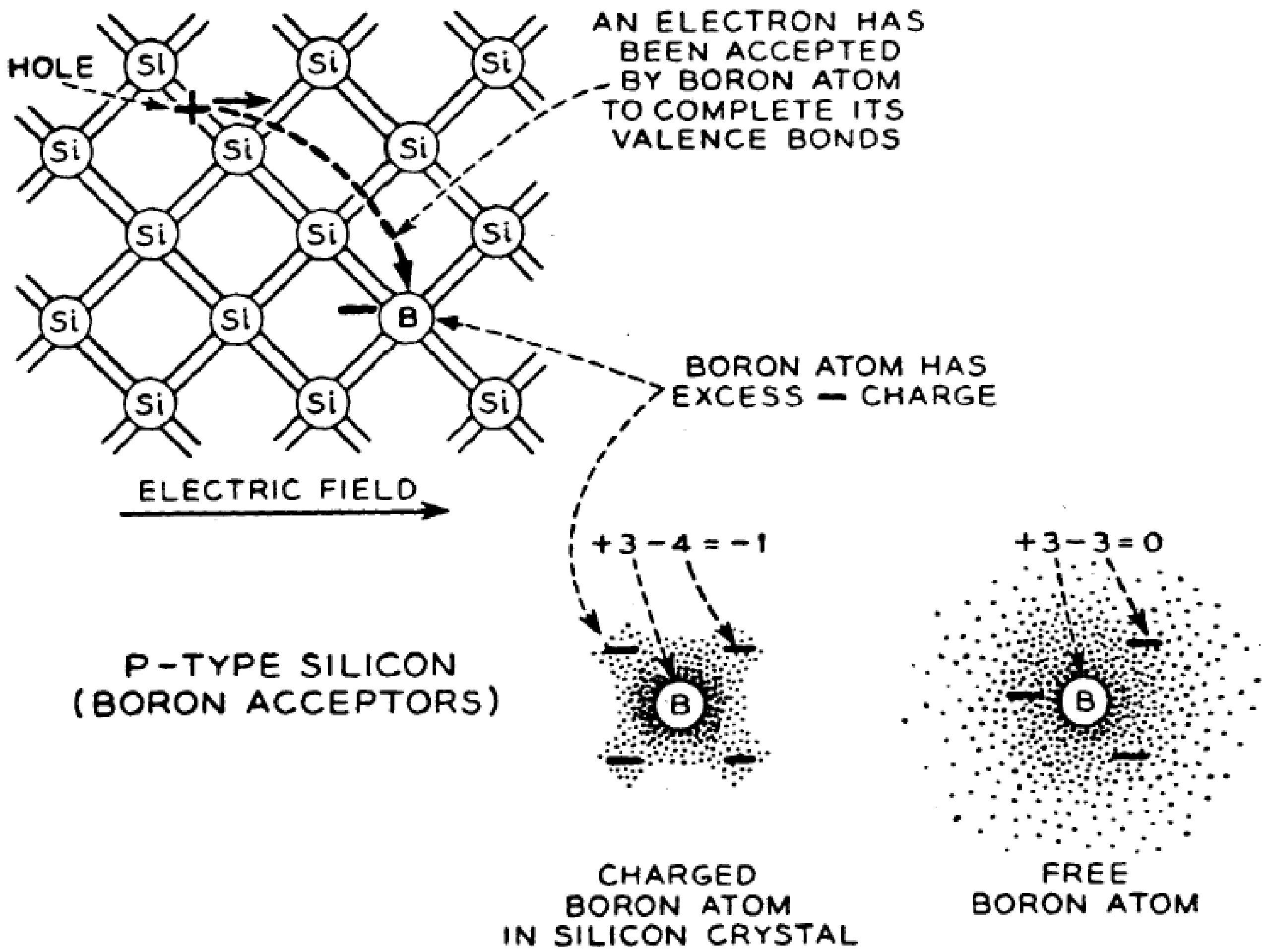
- If Si is doped with B (boron), then it has more holes, or becomes type P.

Band Diagram: Acceptor Dopant in Semiconductor

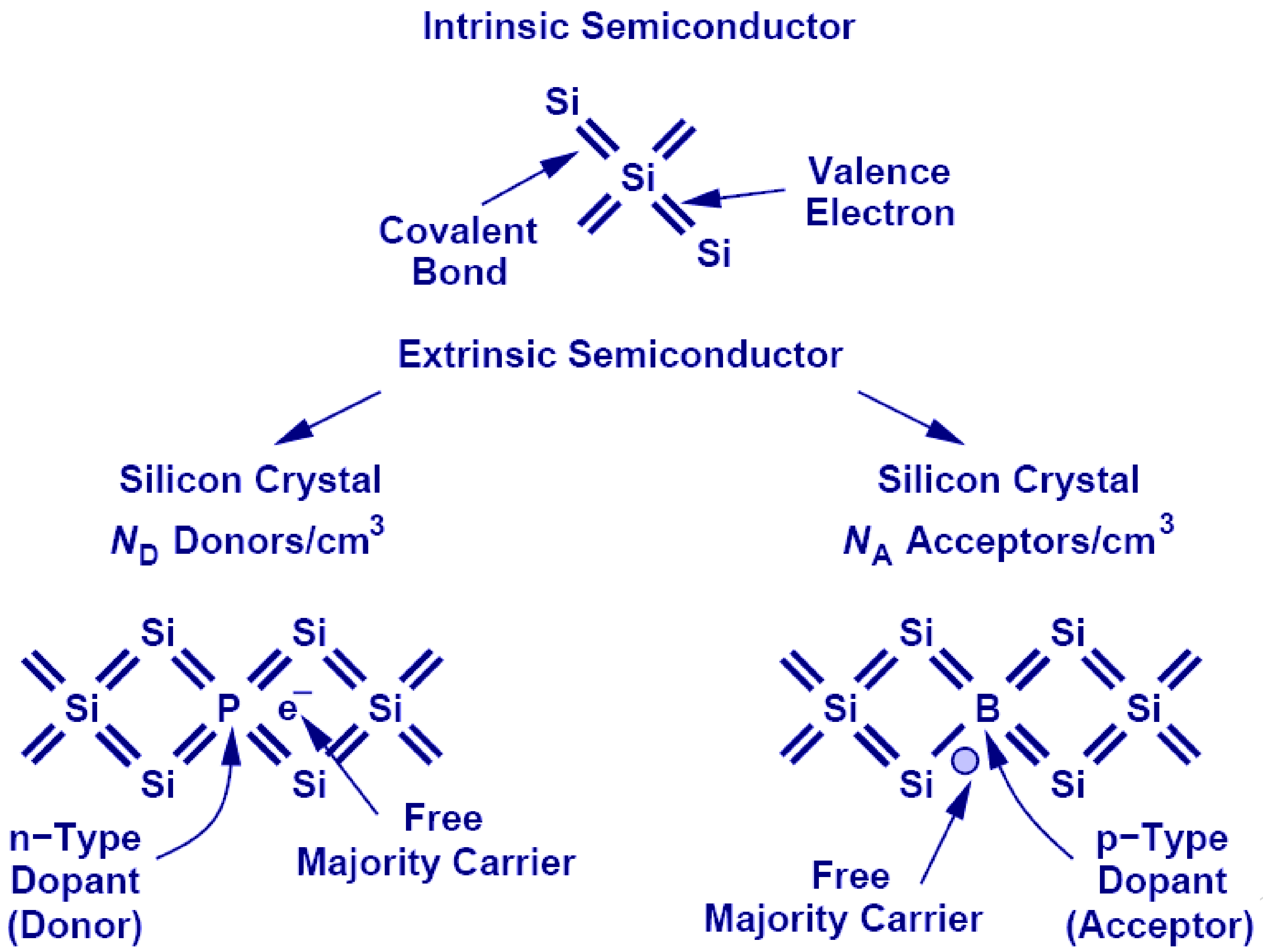
- For Si, add a group III element to "accept" an electron and make p-type Si (more positive "holes").
- "Missing" electron results in an extra "hole", with an acceptor energy level E_A just above the valence band E_V.
  - Holes easily formed in valence band, greatly increasing the electrical conductivity.
- Fermi level E_F moves down towards E_V.



P-type


HOLE
Si
B
AN ELECTRON HAS BEEN ACCEPTED BY BORON ATOM TO COMPLETE ITS VALENCE BONDS
BORON ATOM HAS EXCESS — CHARGE
ELECTRIC FIELD
P-TYPE SILICON (BORON ACCEPTORS)
+3 −4 = −1
+3 − 3 = 0
+4 − 4 = 0
CHARGED BORON ATOM IN SILICON CRYSTAL
FREE BORON ATOM
NEUTRAL SILICON ATOM IN CRYSTAL

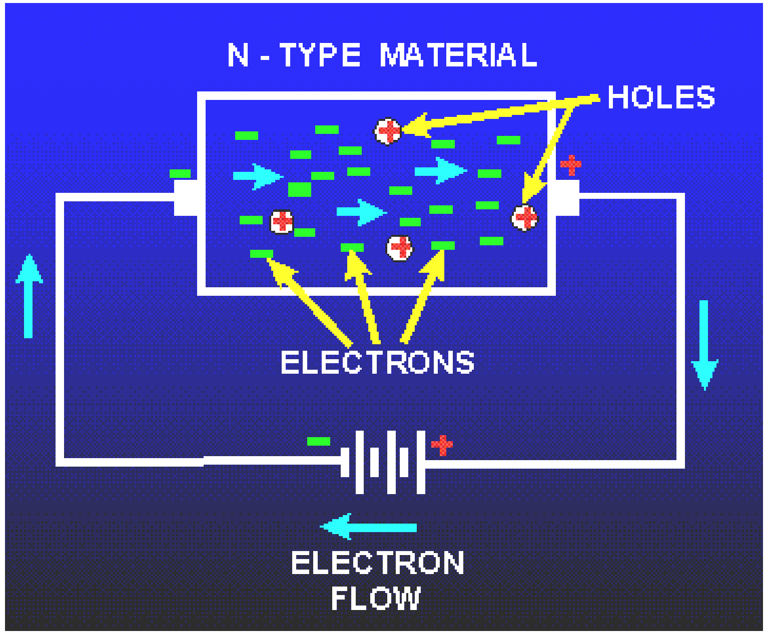
Summary of Charge Carriers

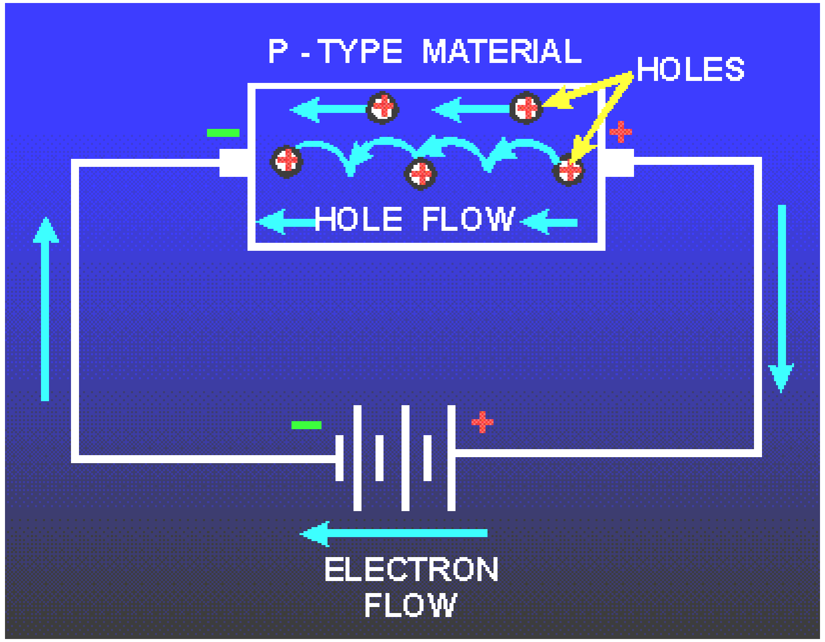


P-N Junction Review

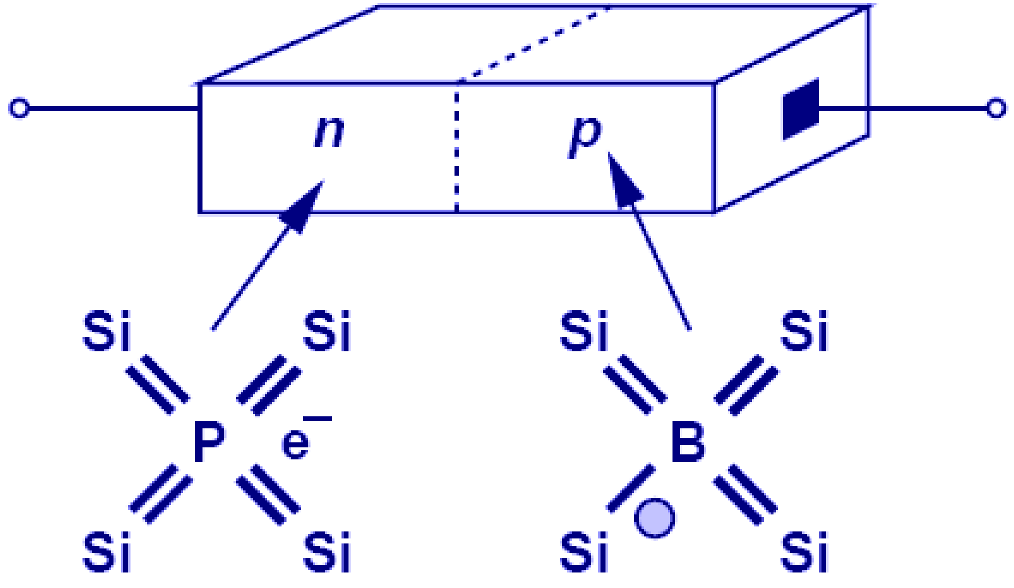
- PN junctions are fabricated from a monocrystalline piece of semiconductor with both a P-type and N-type region in proximity at a junction.
- The transfer of electrons from the N side of the junction to holes annihilated on the P side of the junction produces a barrier voltage. This is 0.6 to 0.7 V in silicon, and varies with other semiconductors.
- A forward biased PN junction conducts a current once the barrier voltage is overcome. The external applied potential forces majority carriers toward the junction where recombinetion takes place, allowing current flow.
- A reverse biased PN junction conducts almost no current. The applied reverse bias attracts majority carriers away from the junction. This increases the thickness of the nonconducting depletion region.
- Reverse biased PN junctions show a temperature dependent reverse leakage current. This is less than a µA in small silicon diodes.

Conduction in p/n-type Semiconductors

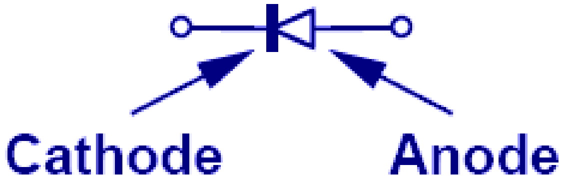




PN Junction (Diode)

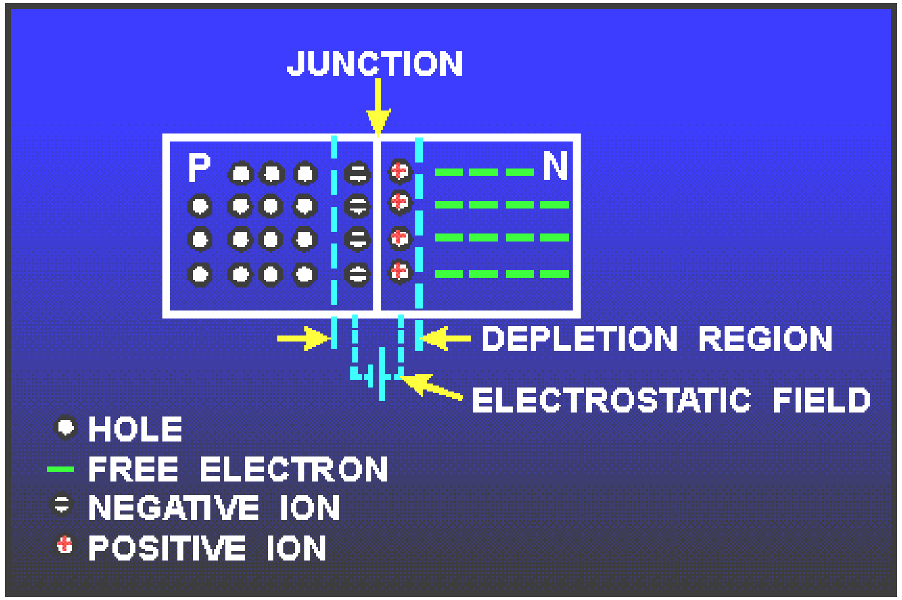


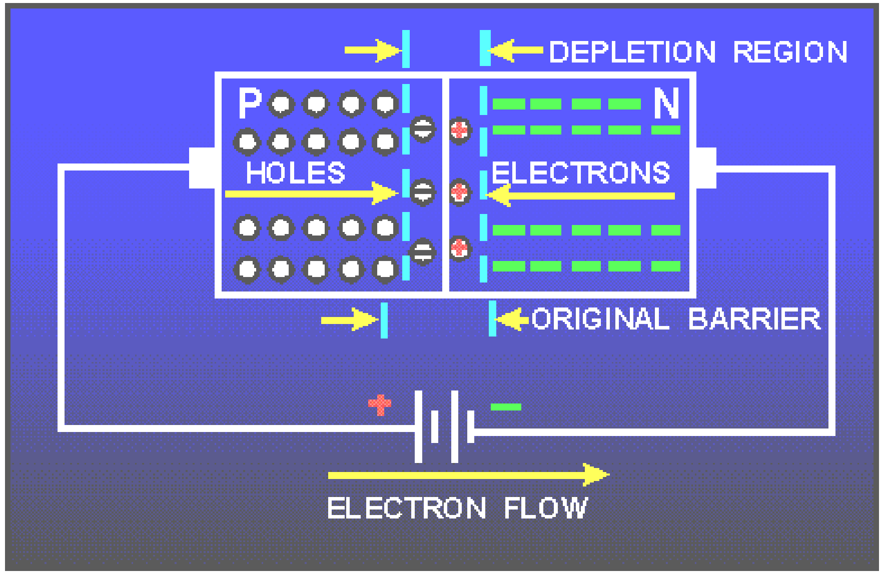
(a)

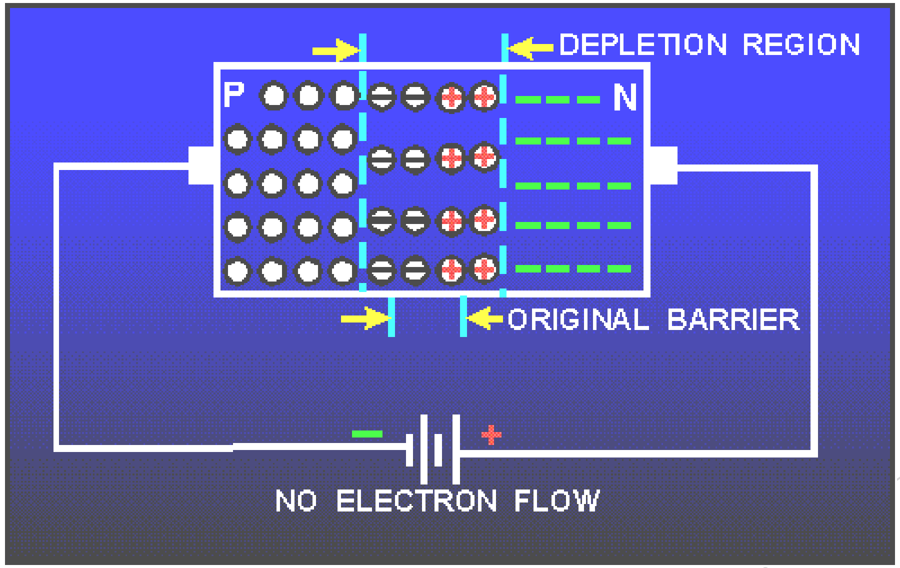


(b)

- When N-type and P-type dopants are introduced side-by-side in a semiconductor, a PN junction or a diode is formed.


JUNCTION
P
N
DEPLETION REGION
ELECTROSTATIC FIELD
HOLE
FREE ELECTRON
NEGATIVE ION
POSITIVE ION


DEPLETION REGION
P
N
HOLES
ELECTRONS
ORIGINAL BARRIER
ELECTRON FLOW


DEPLETION REGION
P
N
ORIGINAL BARRIER
NO ELECTRON FLOW

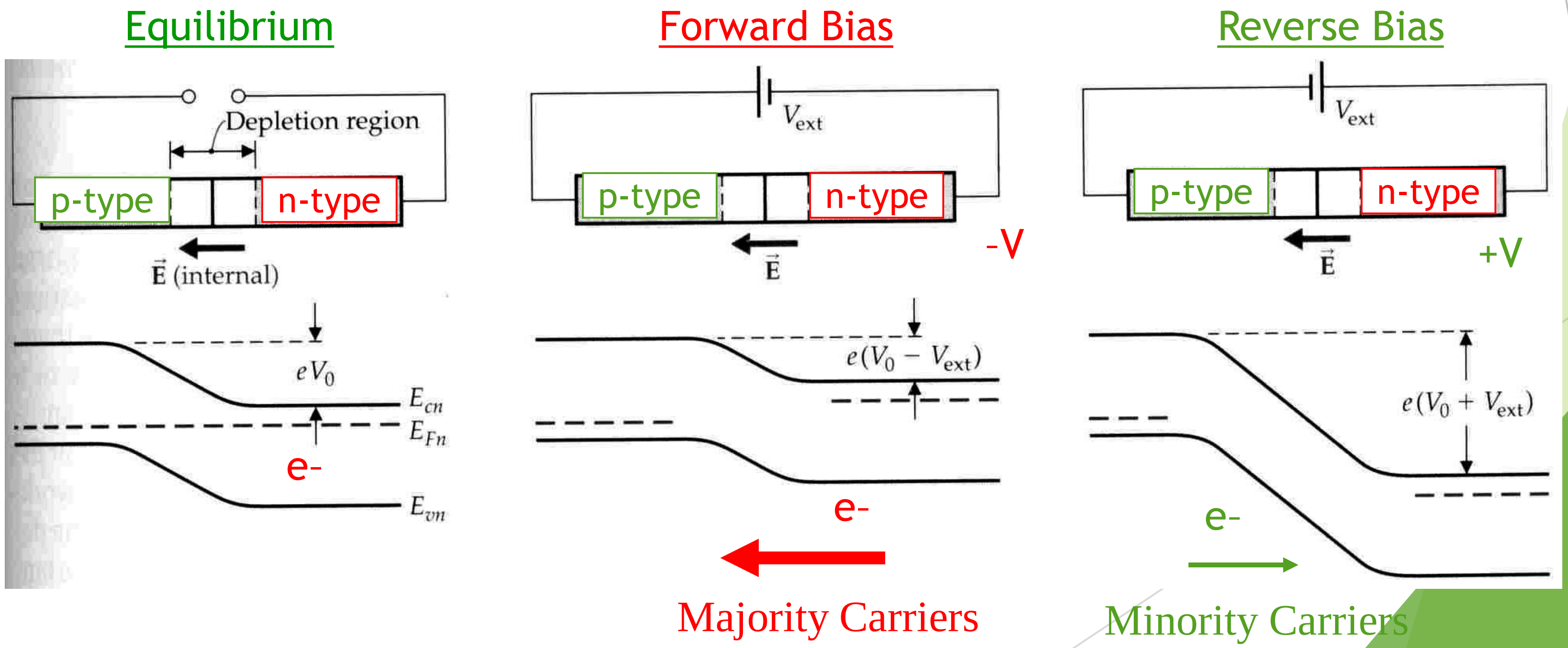
Diode's Three Operation Regions

PN Junction in Equilibrium		PN Junction Under Reverse Bias		PN Junction Under Forward Bias
• Depletion Region • Built-in Potential	⇨	• Junction Capacitance	⇨	• I/V Characteristics

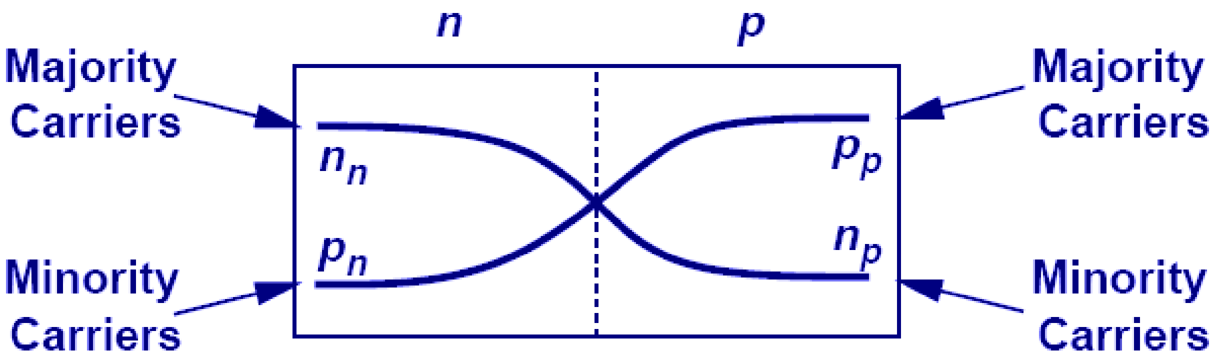
- In order to understand the operation of a diode, it is necessary to study its three operation regions: equilibrium, reverse bias, and forward bias.

PN Junction: Band Diagram under Bias

- Forward Bias: negative voltage on n-side promotes diffusion of electrons by decreasing built-in junction potential → higher current.
- Reverse Bias: positive voltage on n-side inhibits diffusion of electrons by increasing built-in junction potential → lower current.



Current Flow Across Junction: Diffusion



n_n : Concentration of electrons on n side

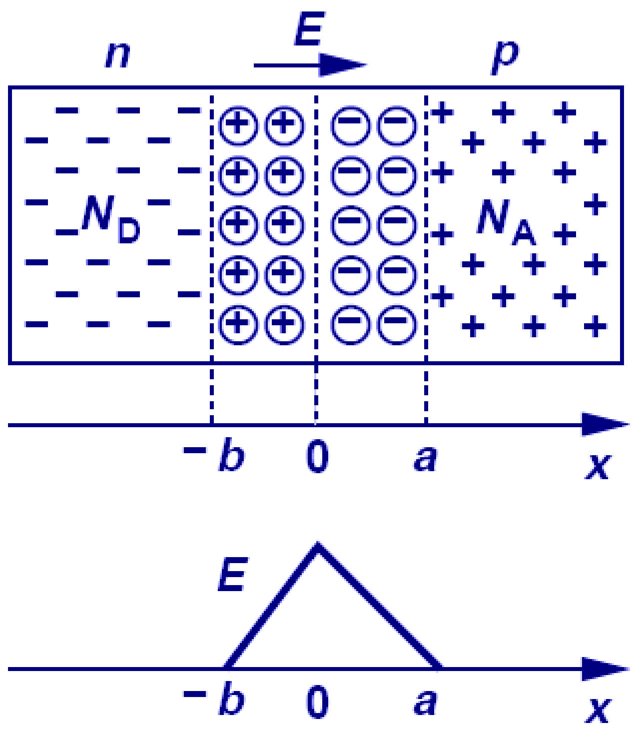
p_n : Concentration of holes on n side

p_p : Concentration of holes on p side

n_p : Concentration of electrons on p side

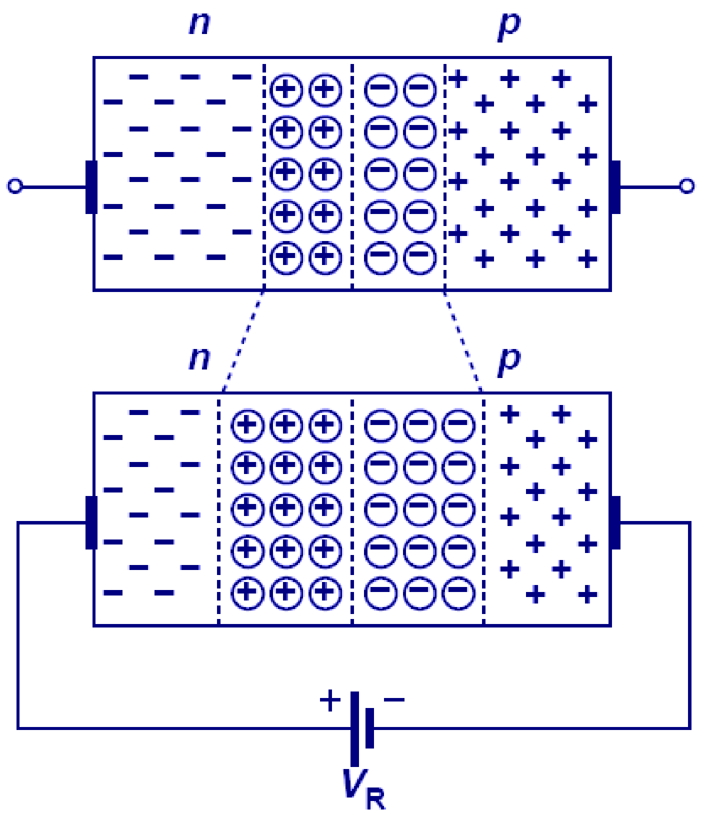
- Because each side of the junction contains an excess of holes or electrons compared to the other side, there exists a large concentration gradient. Therefore, a diffusion current flows across the junction from each side.

Current Flow Across Junction: Drift



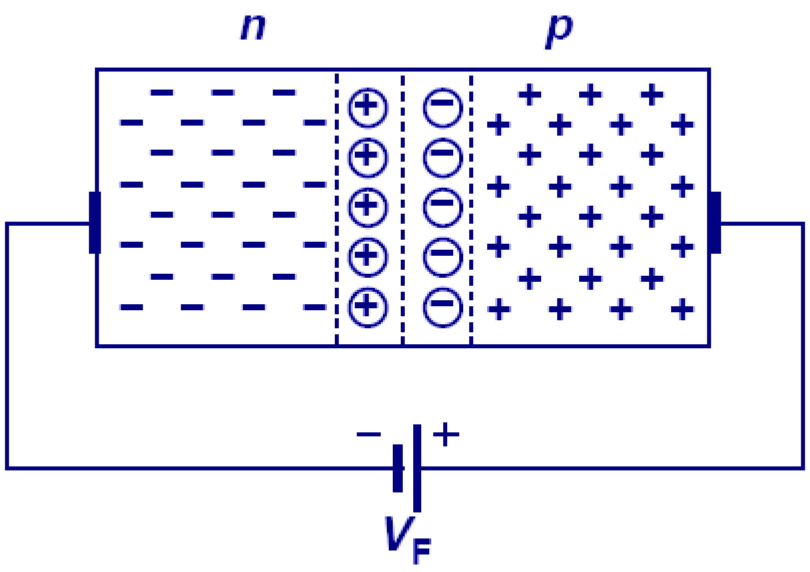
- The fixed ions in depletion region create an electric field that results in a drift current.

Diode in Reverse Bias



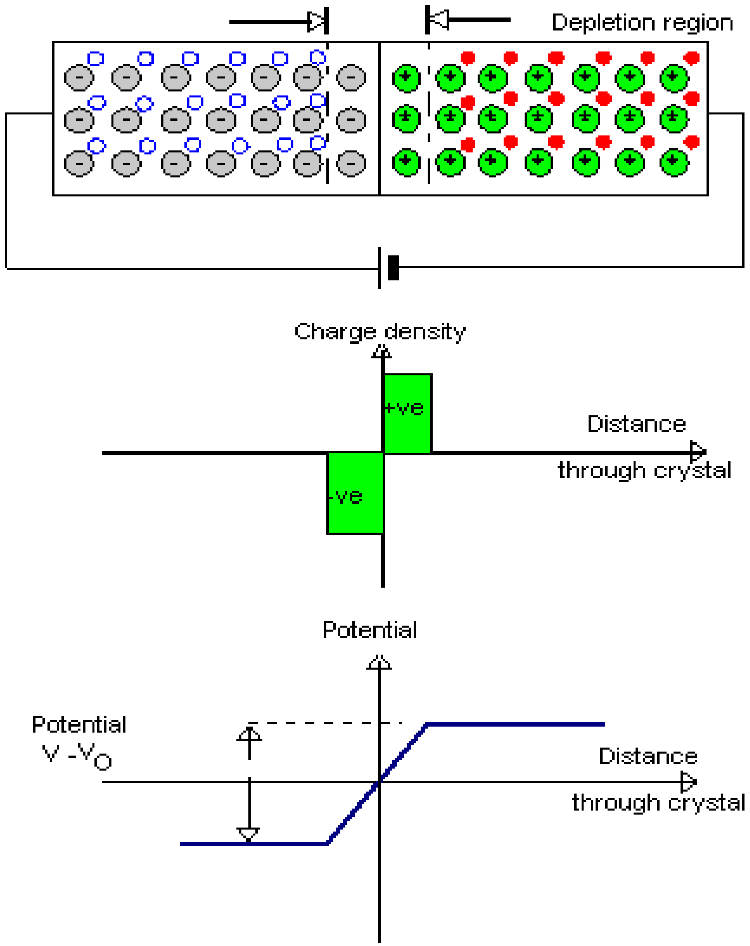
- When the N-type region of a diode is connected to a higher potential than the P-type region, the diode is under reverse bias, which results in wider depletion region and larger built-in electric field across the junction.

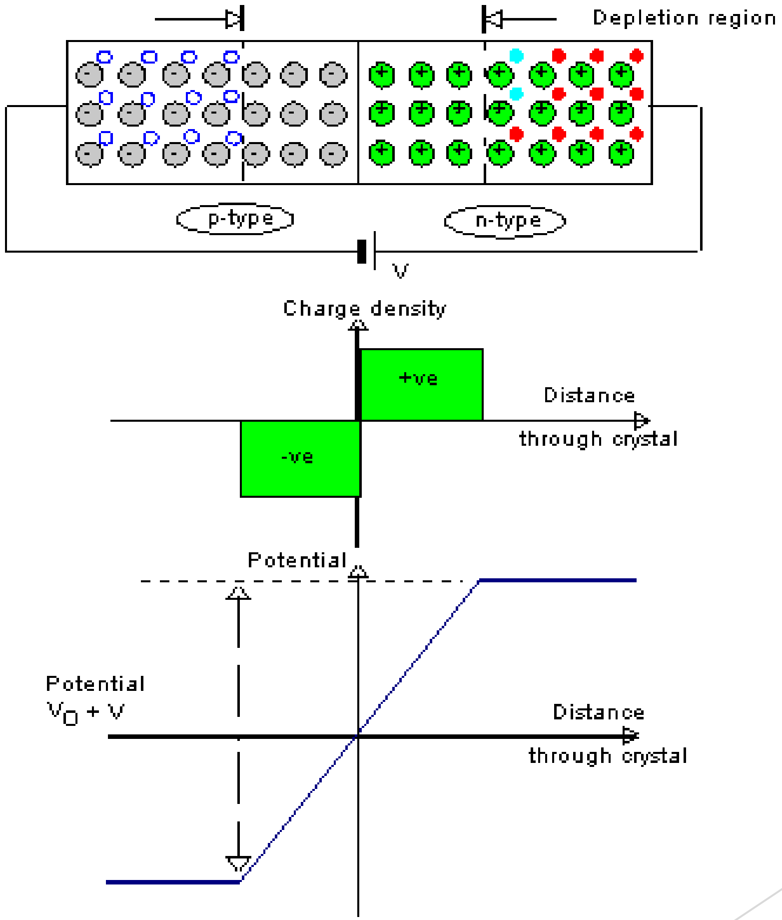
Diode in Forward Bias



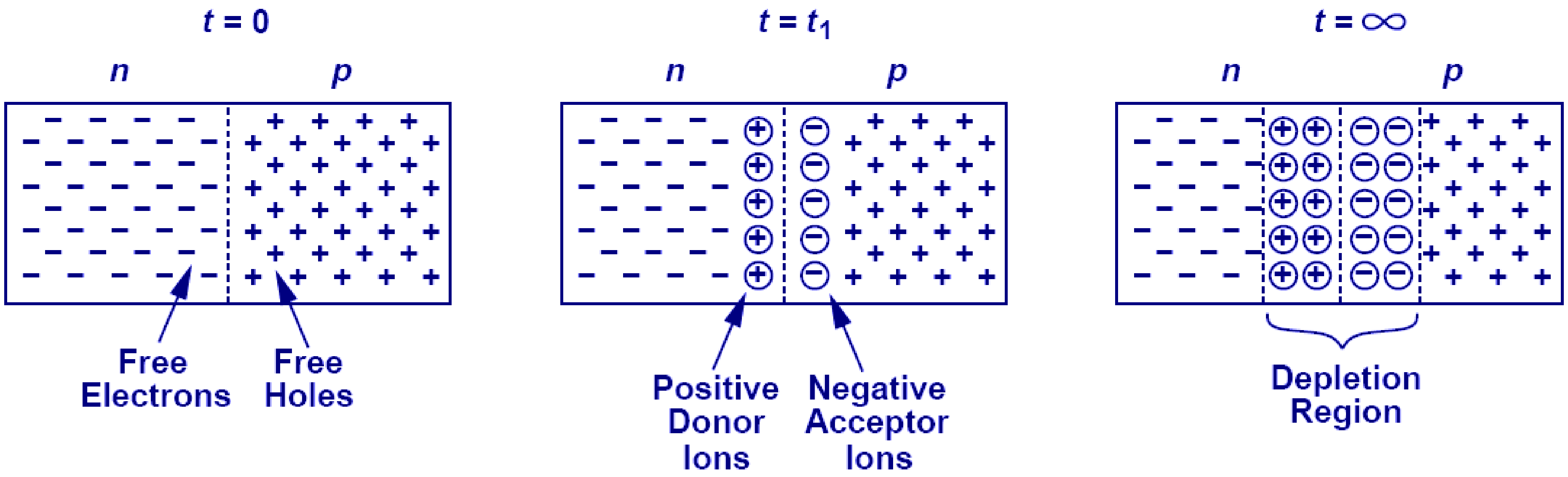
- When the N-type region of a diode is at a lower potential than the P-type region, the diode is in forward bias.
- The depletion width is shortened and the built-in electric field decreased.

Forward & Reverse Biased





Depletion Region

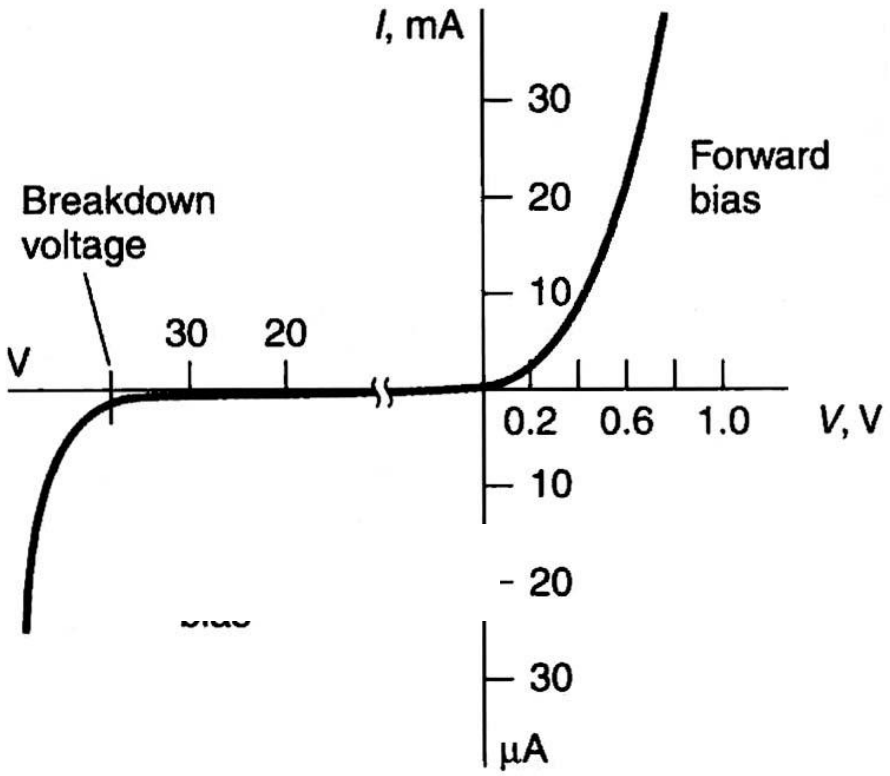


- As free electrons and holes diffuse across the junction, a region of fixed ions is left behind. This region is known as the "depletion region."

PN Junction: IV Characteristics

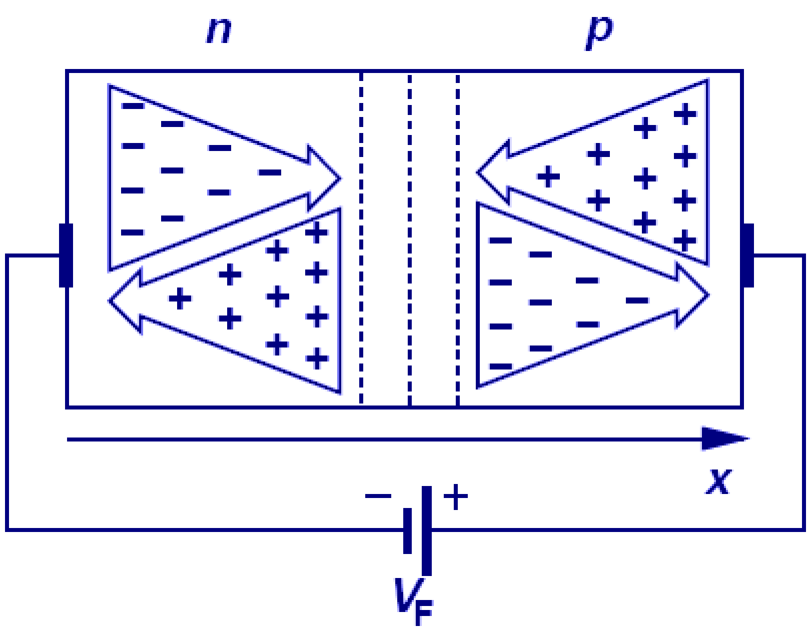
$$I = I_o[e^{eV/kT} - 1]$$

- Current-Voltage Relationship



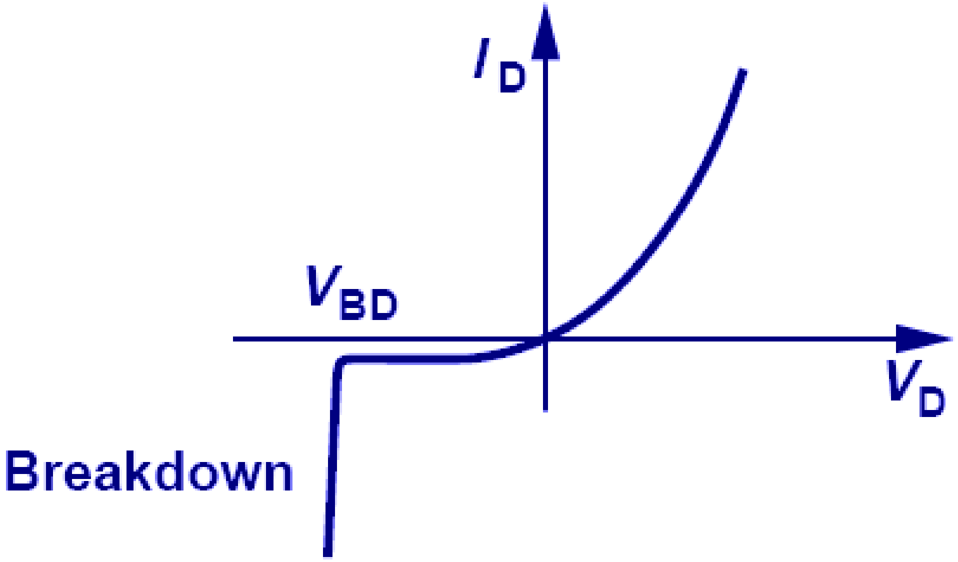
- Forward Bias: current exponentially increases.
- Reverse Bias: low leakage current equal to ~I_o.
- Ability of pn junction to pass current in only one direction is known as "rectifying" behavior.

Forward Bias Condition: Summary



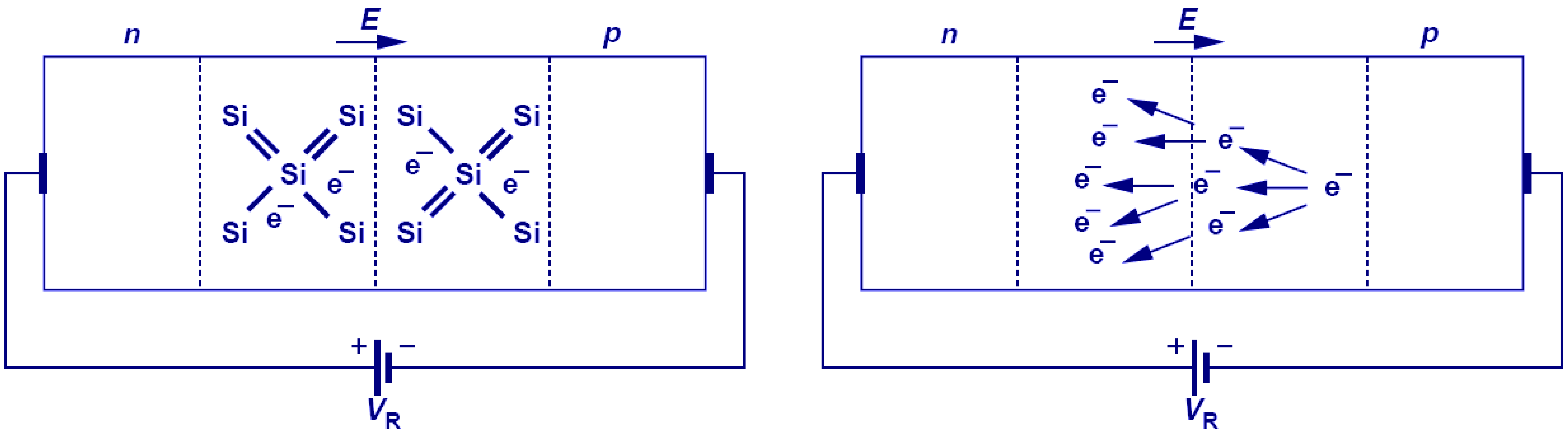
- In forward bias, there are large diffusion currents of minority carriers through the junction. However, as we go deep into the P and N regions, recombination currents from the majority carriers dominate. These two currents add up to a constant value.

Reverse Breakdown



- When a large reverse bias voltage is applied, breakdown occurs and an enormous current flows through the diode.

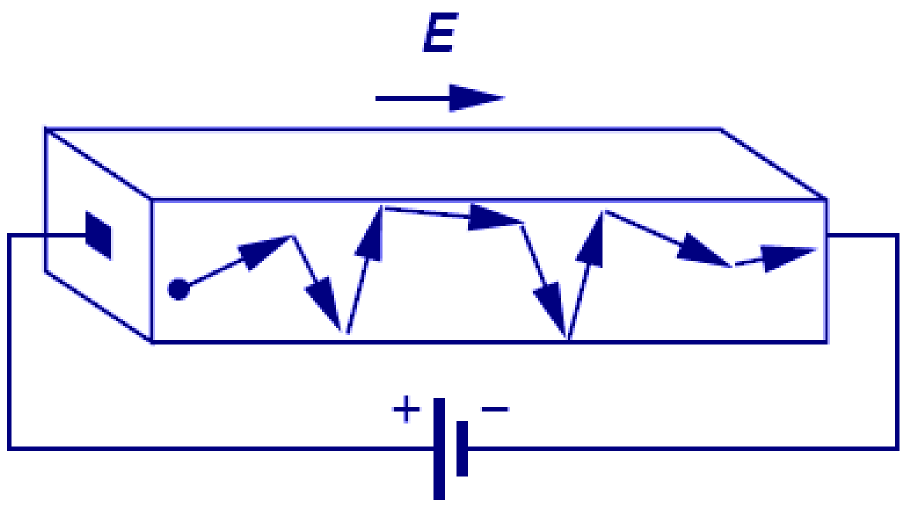
Zener vs. Avalanche Breakdown



(a) (b)

- Zener breakdown is a result of the large electric field inside the depletion region that breaks electrons or holes off their covalent bonds.
- Avalanche breakdown is a result of electrons or holes colliding with the fixed ions inside the depletion region.

First Charge Transportation Mechanism: Drift

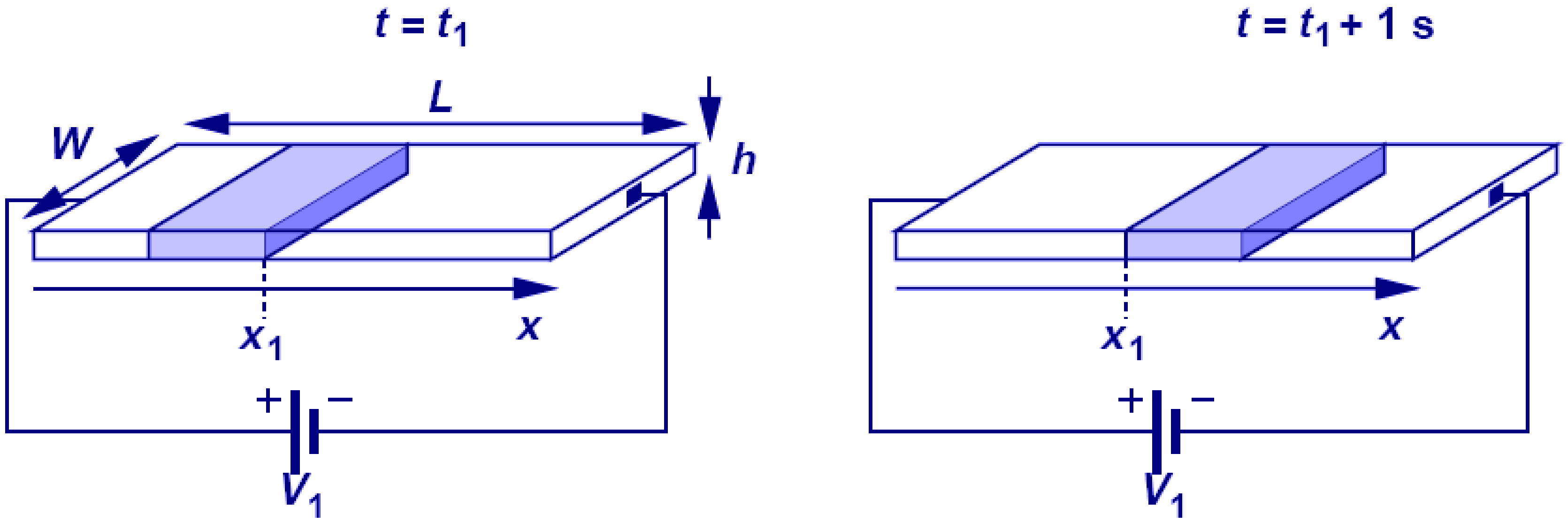


$$\vec{v}_h = \mu_p \vec{E}$$

$$\vec{v}_e = -\mu_n \vec{E}$$

- The process in which charge particles move because of an electric field is called drift.
- Charge particles will move at a velocity that is proportional to the electric field.

Current Flow: General Case



$$I = -v \cdot W \cdot h \cdot n \cdot q$$

- Electric current is calculated as the amount of charge in *v* meters that passes thru a cross-section if the charge travel with a velocity of *v* m/s.

Current Flow: Drift

$$J_n = \mu_n E \cdot n \cdot q$$

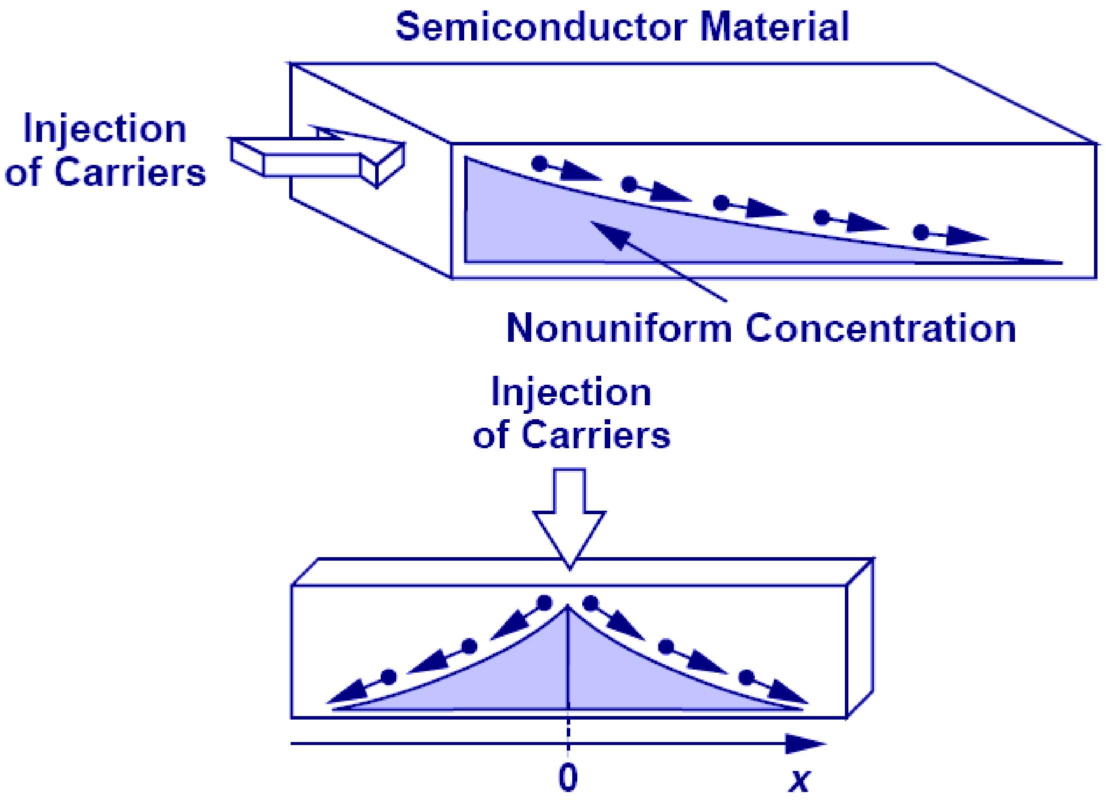
$$J_{tot} = \mu_n E \cdot n \cdot q + \mu_p E \cdot p \cdot q$$

$$= q(\mu_n n + \mu_p p)E$$

- Since velocity is equal to μE, drift characteristic is obtained by substituting V with μE in the general current equation.
- The total current density consists of both electrons and holes.

CH2 Basic Physics of Semiconductors

Second Charge Transportation Mechanism: Diffusion



- Charge particles move from a region of high concentration to a region of low concentration. It is analogous to an every day example of an ink droplet in water.

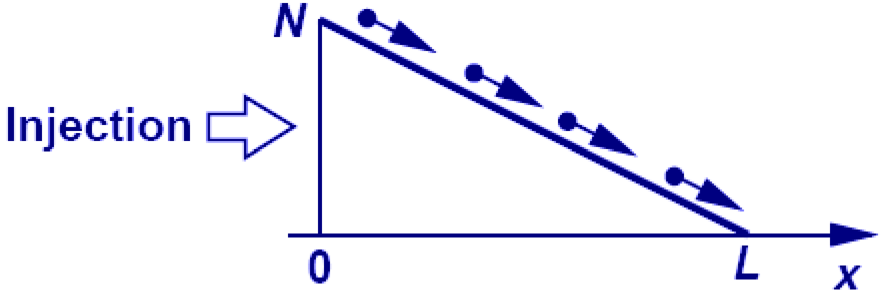
Current Flow: Diffusion

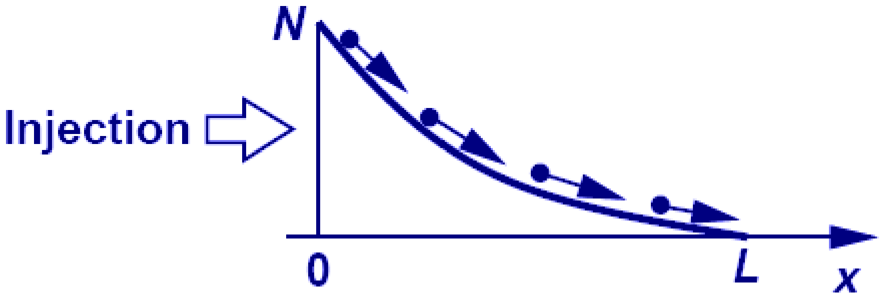
$$I = AqD_n \frac{dn}{dx} \qquad J_p = -qD_p \frac{dp}{dx}$$

$$J_n = qD_n \frac{dn}{dx} \qquad J_{tot} = q(D_n \frac{dn}{dx} - D_p \frac{dp}{dx})$$

- Diffusion current is proportional to the gradient of charge (dn/dx) along the direction of current flow.
- Its total current density consists of both electrons and holes.

Example: Linear vs. Nonlinear Charge Density Profile





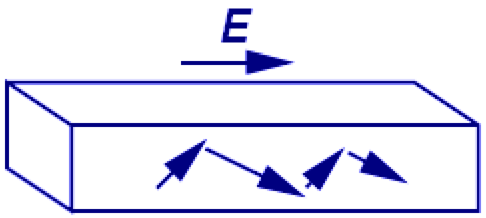
$$J_n = qD_n \frac{dn}{dx} = -qD_n \cdot \frac{N}{L}$$

$$J_n = qD \frac{dn}{dx} = \frac{-qD_n N}{L_d} \exp \frac{-x}{L_d}$$

- Linear charge density profile means constant diffusion current, whereas nonlinear charge density profile means varying diffusion current.

Einstein's Relation

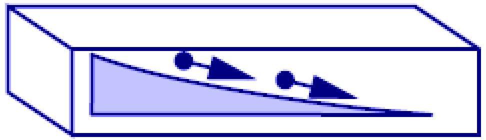
Drift Current



$$J_n = q \mu_n E$$

$$J_p = q \mu_p$$

Diffusion Current



$$J_n = q D_n \frac{dn}{dx}$$

$$J_n = -q D_p \frac{dp}{dx}$$

$$\frac{D}{\mu} = \frac{kT}{q}$$

- While the underlying physics behind drift and diffusion currents are totally different, Einstein's relation provides a mysterious link between the two.