Basic electronics circuits

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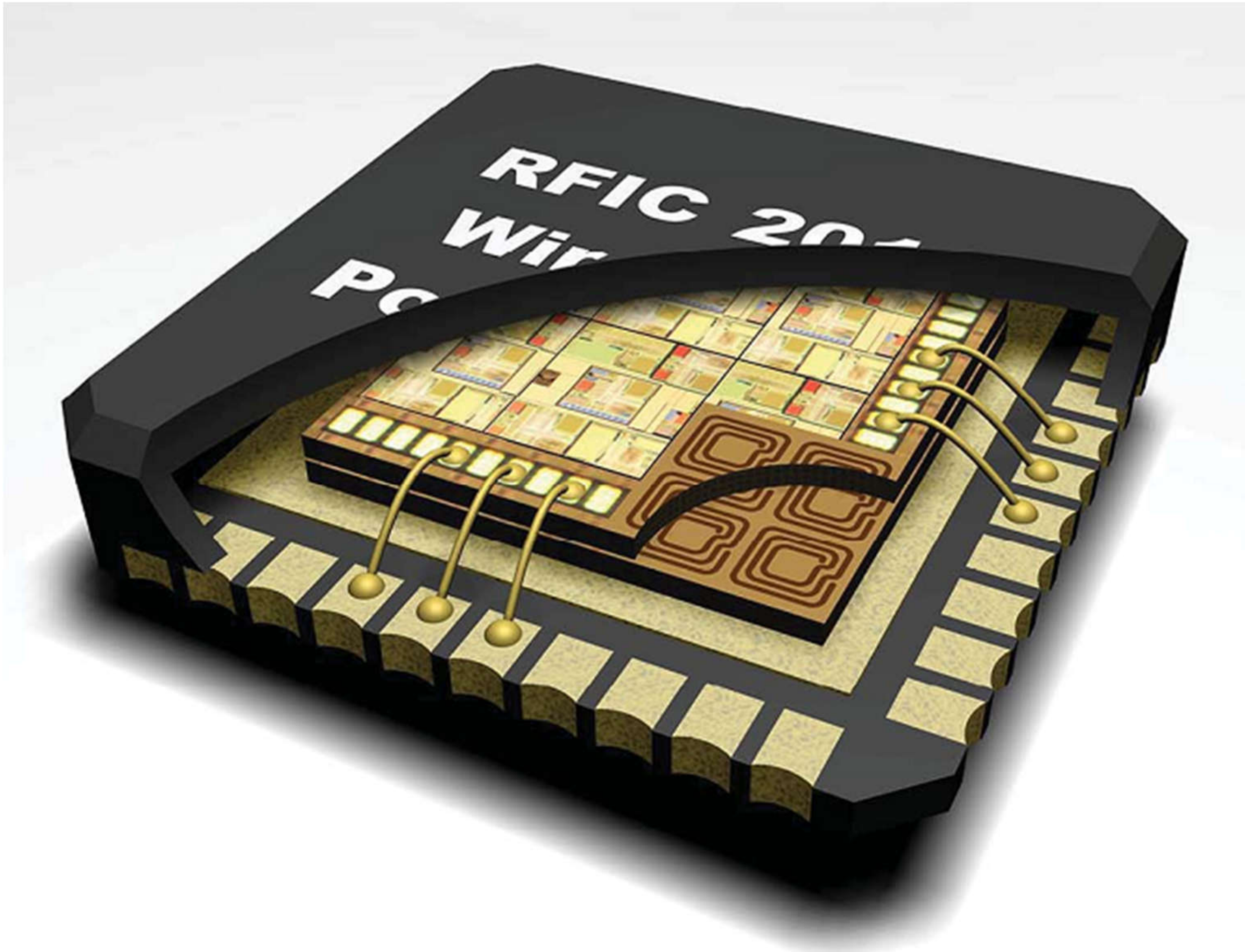


SEDRA/SMITH

Microelectronic Circuits

Syllabus

- Semiconductor devices, diode and BJT
- Operational amplifier
- Filters
- Waveform generators
- ADC and DAC

Syllabus

- **Semiconductor diode and rectifier:** Diode characteristics, half-wave and full wave rectifiers, shunt capacitor filter, voltage regulator, regulated D-C power supply

- **Bipolar junction transistor**: npn and pnp, modes of operation, I-V characteristics

- **Op-Amp (operational amplifier):** Amplifier parameters, controlled source models, classification, the operational amplifier (OP-AMP) as a linear active device, the VCVS model of an op-amp, different amplifier configurations using op-amp (open loop-closed loop), frequency response of op-amp and op-amp based amplifiers. Calculation of CMRR, Gain Band width product. Op-Amp as integrator, differentiator, addition, subtraction etc.

Syllabus

- **Passive and active filters:** Concepts of low-pass, high-pass and band-pass filters, ideal (brick-wall) filter response, frequency response of simple RC filters, active RC filters using Op-amp.

- **Oscillator:** Effects of negative and positive feedback of an amplifier, condition of harmonic oscillation, RC and LC oscillator circuits, Phase shift oscillator, Wien bridge oscillator.

Syllabus

- **Comparator:** Op-amp as a comparator, digital inverters (TTL/CMOS) as comparators, comparator with hysteresis, Schmitt trigger using Op-amp. Concept of bistable, monostable and astable circuits using opamp (multi vibrators)

- **Waveform generators (555 Timer):** Concept of bistable, monostable and astable circuits using 555 timer and relaxation oscillator based on comparator and RC timing circuit, square wave generator using 555 timer, crystal clock generator. 555 timer as a two dimensional comparator.

Syllabus

- **Analog-Digital conversion:** Digital to Analog Converter (DAC) using binary resistor scheme, R-2R ladder DAC, DAC using switched current resources, Analog to Digital converter (ADC) using capacitor charge/discharge: single-slope and dual-slope ADCs, ADC using counter and DAC, ADC using successive approximation

Text books

- **TEXT BOOKS:**
  - Microelectronic Circuits by Sedra and Smith, Oxford University Press, Fifth Edition, 2010.
  - Linear integrated circuits, Roy choudary
- **REFERENCE BOOKS:**
  - Integrated Electronics by Millman and Halkias, Tata McGraw Hill, 2009.
  - Microelectronics by Millman and Grabel, Tata McGraw Hill, 2008.

Elements

- Passive elements
  - Resistor
  - Inductor
  - Capacitor
- Active elements
  - Transistor
  - Operational amplifier

Laws & analyses

- Ohm’s law
- KCL
- KVL
- Mesh analysis
- Nodal analysis

Sources

- Independent sources
  - Independent voltage source
  - Independent current source
- Dependent sources
  - Dependent voltage source
  - Dependent current source
- Ideal sources
- Practical sources

Divider circuits

- Voltage divider
- Current divider

Material classification

- Material classification based on conductivity (σ)/resistivity (ρ)
  - Conductors
  - Semiconductors
  - Insulators

$$\sigma = \frac{1}{\rho}$$

Atomic arrangement

- Periodic
- Lattice constant

General constants and conversion factors

Angstrom	Å	$1\ \text{Å} = 10^{-4}\ \mu\text{m} = 10^{-8}\ \text{cm} = 10^{-10}\ \text{m}$
Boltzmann's constant	k	$k = 1.38 \times 10^{-23}\ \text{J/K} = 8.6 \times 10^{-5}\ \text{eV/K}$
Electron–volt	eV	$1\ \text{eV} = 1.6 \times 10^{-19}\ \text{J}$
Electronic charge	e or q	$q = 1.6 \times 10^{-19}\ \text{C}$
Micron	μm	$1\ \mu\text{m} = 10^{-4}\ \text{cm} = 10^{-6}\ \text{m}$
Mil		$1\ \text{mil} = 0.001\ \text{in.} = 25.4\ \mu\text{m}$
Nanometer	nm	$1\ \text{nm} = 10^{-9}\ \text{m} = 10^{-3}\ \mu\text{m} = 10\ \text{Å}$
Permittivity of free space	ε_o	$\varepsilon_o = 8.85 \times 10^{-14}\ \text{F/cm}$
Permeability of free space	μ_o	$\mu_o = 4\pi \times 10^{-9}\ \text{H/cm}$
Planck's constant	h	$h = 6.625 \times 10^{-34}\ \text{J–s}$
Thermal voltage	V_T	$V_T = kT/q \cong 0.026\ \text{V at } 300\ \text{K}$
Velocity of light in free space	c	$c = 2.998 \times 10^{10}\ \text{cm/s}$

Semiconductor constants

	Si	Ge	GaAs	SiO_2
Relative dielectric constant	11.7	16.0	13.1	3.9
Bandgap energy, E_g(eV)	1.1	0.66	1.4	
Intrinsic carrier concentration, n_i (cm^{-3} at 300 K)	1.5×10^{10}	2.4×10^{13}	1.8×10^{6}	

Outline: Semiconductor Materials and Diodes

- Semiconductor material properties
- Two types of charged carriers exist in a semiconductor
- Two mechanisms generate currents in a semiconductor
- Current–voltage characteristics of the pn junction diode

Valence electrons

- An atom is composed
  - nucleus
    - positively charged protons
    - neutral neutrons
  - electrons
    - negatively charged
- The electrons are distributed in various “shells” at different distances from the nucleus,
  - electron energy increases as shell radius increases
- Electrons in the outermost shell are called **valence electrons**
  - **the chemical activity of a material is determined primarily by the number of valence electrons**

Elemental and compound semiconductors

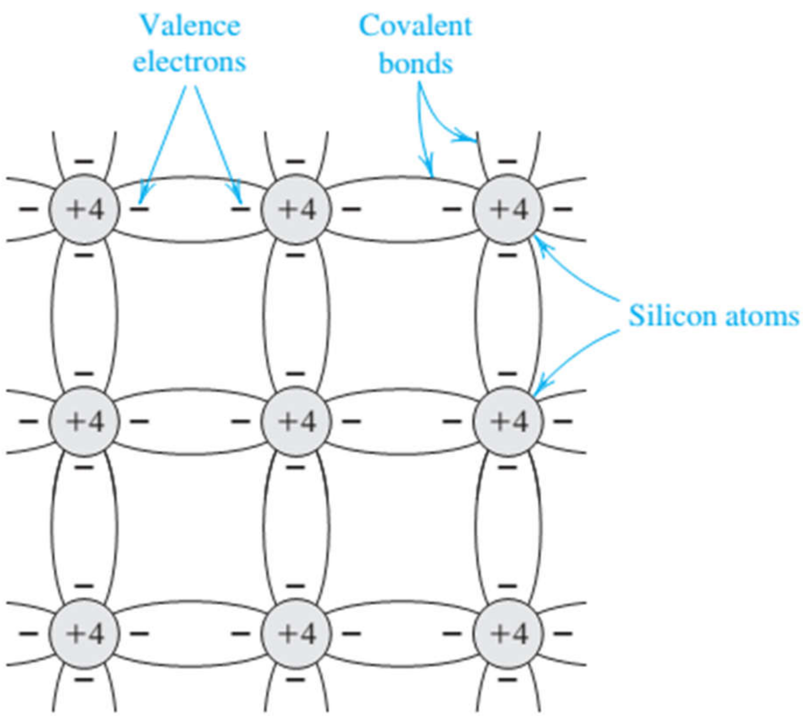
- Elements in the periodic table can be grouped according to the number of valence electrons
- **elemental semiconductors** (group IV)
  - Silicon (Si)
  - Germanium (Ge)
- **compound semiconductor** (group III–V)

GaAs	Gallium arsenide
GaP	Gallium phosphide
AlP	Aluminum phosphide
AlAs	Aluminum arsenide
InP	Indium phosphide

III	IV	V
5 B Boron	6 C Carbon	
13 Al Aluminum	14 Si Silicon	15 P Phosphorus
31 Ga Gallium	32 Ge Germanium	33 As Arsenic
49 In Indium		51 Sb Antimony

Periodic table

Single crystal silicon at T = 0 K



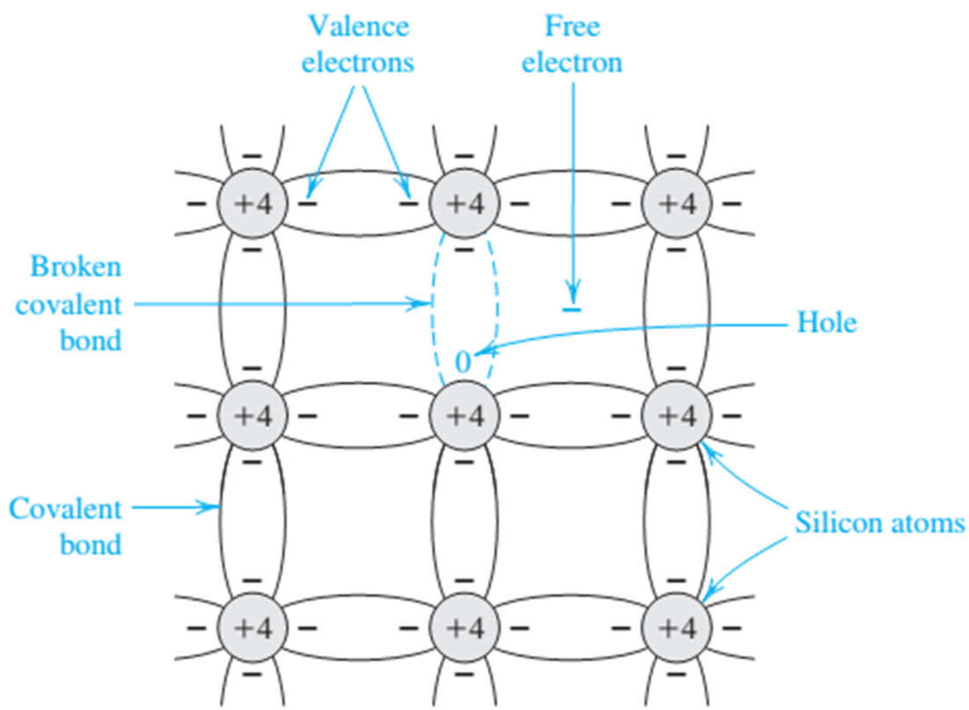
Silicon Lattice constant 5.43 Å

Two-dimensional representation of single crystal silicon at T = 0 K; all valence electrons are bound to the silicon atoms by covalent bonding

Silicon at T = 0 K

- at T = 0 K, silicon is an **insulator**
  - that is, no charge flows (Current) through semiconductor
- each electron is in its lowest possible energy state
- Electrons are bound to their individual atoms

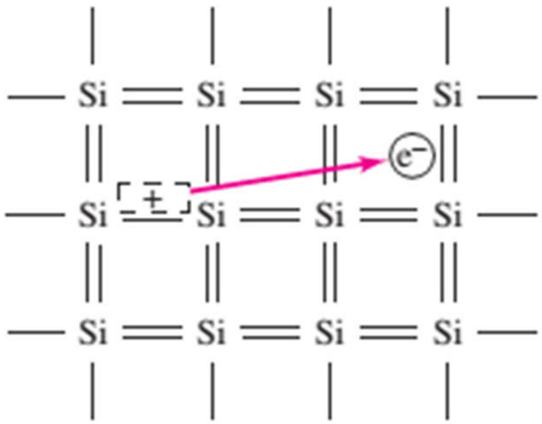
Silicon at *T* > 0 K



The breaking of a covalent bond for *T* > 0 K creating an electron in the conduction band and a positively charged "empty state"

Silicon at $T > 0$ K

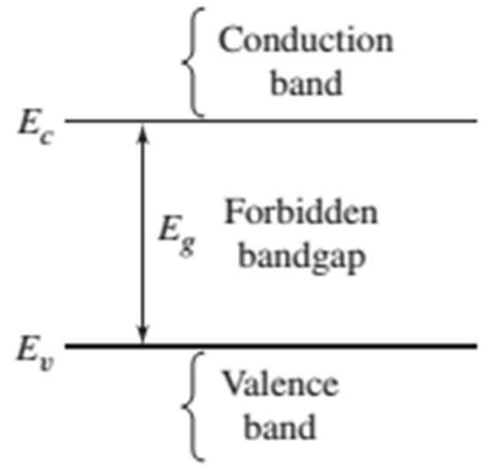
- the valence electrons will gain thermal energy
- Once the electron gains enough thermal energy, it will break the covalent bond
- Results in free electron/mobile carrier
- **Bandgap energy (E_g):** The minimum energy required for an electron to break covalent bond
- The electrons that gain E_g now exist in conduction band
- The free electrons in conduction band can move throughout the crystal (silicon)
- The net movement of the electrons in conduction band generates current



The breaking of a covalent bond for $T > 0$ K

Energy band diagram

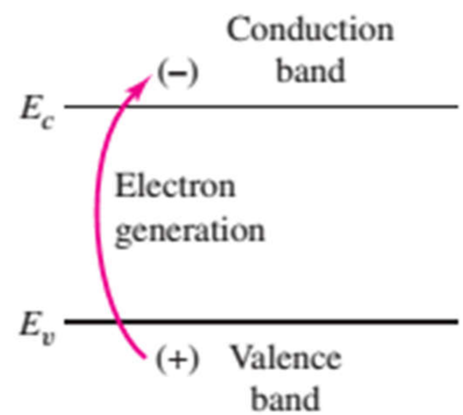
- The energy E_v is the maximum energy of the valence energy band
- Energy E_c is the minimum energy of the conduction energy band.
- The bandgap energy E_g is the difference between E_c and E_v, and the region between these two energies is called the **forbidden bandgap.**
- Electrons cannot exist within the forbidden bandgap.



Energy band diagram. *Vertical scale*: Electron energy *horizontal scale*: distance along the length of semiconductor

EHP generation

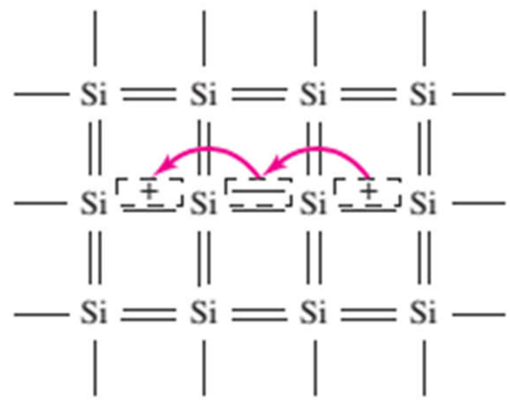
- EHP: Electron hole pair
- An electron in valence band if gains enough energy, moves to conduction band
- This results in creation of positively charged empty space called hole in valence band



Energy band diagram showing the generation process

Current in semiconductor

- In semiconductors two types of charged particles contribute to the current:
  - the negatively charged free **electron** and
  - the positively charged **hole**
- The magnitude of charge of **hole** is equal to the magnitude of the charge of electron (1.6×10^{-19} C)

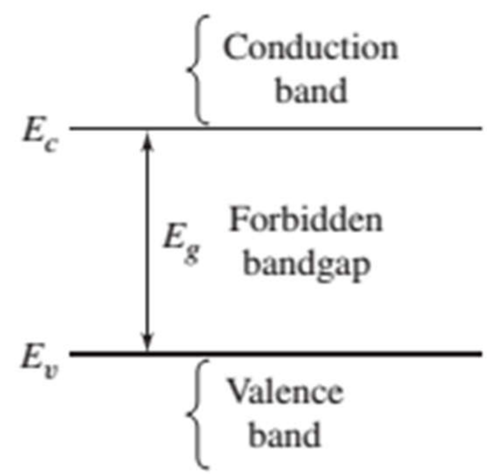


A two-dimensional representation of the silicon crystal showing the movement of hole

Bandgap energies of materials

- Insulators
  - Bandgap range 3-6 eV
  - No free electrons in conduction band at room temperature
- Semiconductors
  - Bandgap around 1 eV

Material	Eg (eV)
Silicon (Si)	1.1
Gallium arsenide (GaAs)	1.4
Germanium (Ge)	0.66



Intrinsic semiconductor

- A single-crystal semiconductor material with no other types of atoms within the crystal
- Pure semiconductor
- Intrinsic carrier concentration (n_i): In an intrinsic semiconductor, the concentrations of electrons and holes are equal
- Concentration: The number of carriers (electrons/holes) per cubic cm.
  - Example: 10^{15} /cm^3

Intrinsic carrier concentration (n_i)

$$n_i = BT^{3/2}e^{\left(\frac{-E_g}{2kT}\right)}$$

- where
  - B is a coefficient related to the specific semiconductor material,
  - Eg is the bandgap energy (eV),
  - T is the temperature (K),
  - k is Boltzmann's constant = 86×10^{-6} eV/K
- n_i depends on temperature
- The bandgap energy E_g and coefficient B are not strong functions of temperature

Material	Eg (eV)	B (cm^{-3} K$^{-3/2}$)
Silicon (Si)	1.1	5.23×10^{15}
Gallium arsenide (GaAs)	1.4	2.10×10^{14}
Germanium (Ge)	0.66	1.66×10^{15}

Problem

- Calculate the intrinsic carrier concentration of silicon at *T* = 300 K

Solution:

$$n_i = BT^{3/2}e^{\left(\frac{-E_g}{2kT}\right)} = 5.23\times10^{15}\times300^{3/2}\times e^{\left(\frac{-1.1}{2\times86\times10^{-6}\times300}\right)}$$

$$n_i = 5.23\times10^{15}\times300^{3/2}\times e^{\left(\frac{-1.1}{2\times86\times10^{-6}\times300}\right)}$$

$$n_i = 1.5\times10^{10}\ / cm^3$$

Note: The intrinsic carrier concentration of silicon appears large, but compared to concentration of silicon atoms (5×10^{22}), it is relatively less

Assignment A.1

- Calculate the intrinsic carrier concentration of silicon at $T = 313$ K.
- Calculate the intrinsic carrier concentration of gallium arsenide and germanium at $T = 300$ K.

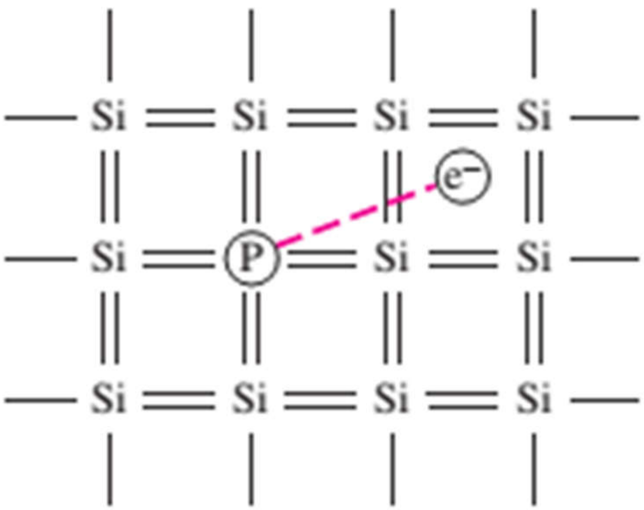
Extrinsic Semiconductors

- the electron and hole concentrations in an intrinsic semiconductor are relatively small
  - The resulting currents are small
- The carrier concentrations can be greatly increased by adding controlled amounts of certain impurities
  - To enhance currents
- Doping: The process of adding impurities
- Semiconductors added with impurity atoms are called **extrinsic semiconductors, or doped semiconductors**
- For silicon, the desirable substitutional impurities are from the group III and V elements of periodic table
- Group V: Phosphorous, Arsenic
- Group III: Boron

n-type semiconductor

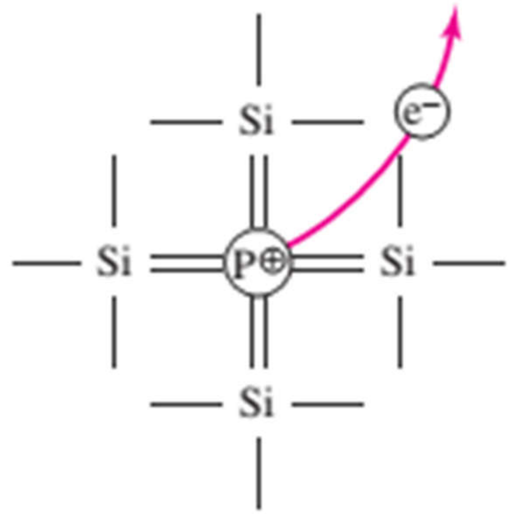
- Silicon doped with group V elements (P, As)
- Group V elements has 5 valence electrons
- Silicon doped with Phosphorous:
  - four valence electrons of the five in phosphorous forms covalent bond with four valence electrons of silicon, and one electron is free
  - Free electron contributes for electron current
  - a positively charged phosphorus ion is created
  - Phosphorous donates a free electron, therefore called as **donor impurity**
- **when a donor impurity is added to a semiconductor, free electrons are created without generating holes**

n-type semiconductor



Two-dimensional representation of a silicon lattice doped with a phosphorus atom and valence electron

e⁻ mobile carrier



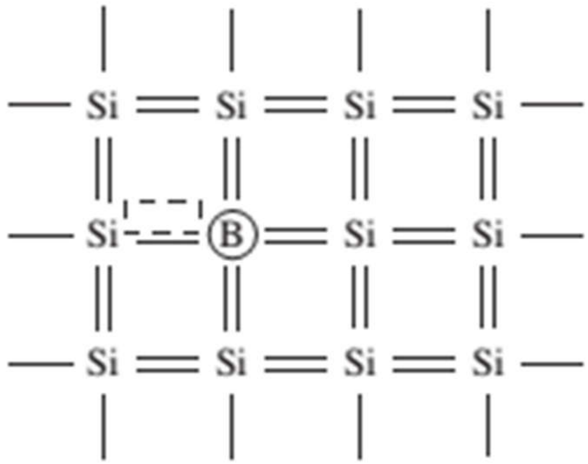
the resulting positively charged phosphorus ion after the fifth valence electron has moved into the conduction band

P^+ immobile ion

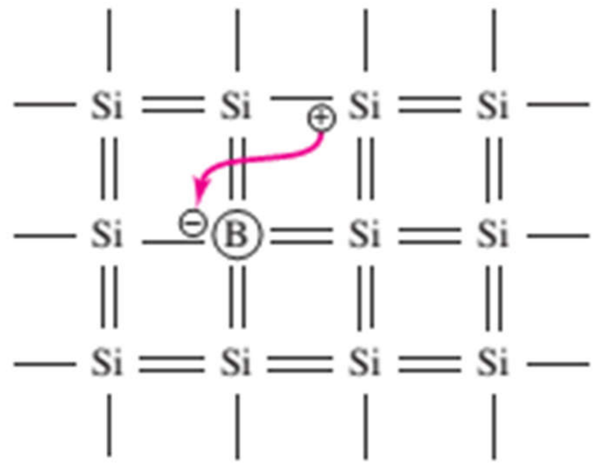
p-type semiconductor

- Silicon doped with group III element (Boron)
- Group III element has 3 valence electrons
- When silicon is doped with boron:
  - Three valence electrons of boron forms covalent bond with three valence electrons of silicon
  - One bond position is open
  - Adjacent electron with enough thermal energy can occupy the vacant position
  - Hole is created, contributes for hole current
  - Negatively charged boron ion is created
  - Boron has accepted an electron, hence called **acceptor impurity**
- **when an acceptor impurity is added to a semiconductor, free holes are created without generating electrons**

p-type semiconductor



Two-dimensional representation of a silicon lattice doped with a boron atom showing the vacant covalent bond position



the resulting negatively charged boron ion after it has accepted an electron from the valence band

B^- Immobile ion

⊕ Mobile carrier

Doping/diffusion/ion implantation

- Concentrations of electrons and holes can be controlled by the process of doping
- **Conductivity and current flow can be controlled**

Relationship between the electron and hole concentrations

- relationship between the electron and hole concentrations in a semiconductor *at thermal equilibrium* is given by

$$n_o p_o = n_i^2$$

where

- n_o is the thermal equilibrium concentration of free electrons
- p_o is the thermal equilibrium concentration of holes
- n_i is the intrinsic carrier concentration

Donor doped: Calculations of electron and hole concentrations

- Semiconductor doped with donor concentration N_d
- At room temperature (T = 300 K), If the donor concentration N_d is much larger than the intrinsic concentration, we can approximate $n_o \cong N_d$
- The hole concentration is

$$p_o = \frac{n_i^2}{N_d}$$

Acceptor doped: Calculations of electron and hole concentrations

- Semiconductor doped with acceptor concentration N_a
- At room temperature (T = 300 K), If the acceptor concentration N_a is much larger than the intrinsic concentration, we can approximate $p_o \cong N_a$
- The electron concentration is

$$n_o = \frac{n_i^2}{N_a}$$

To calculate the thermal equilibrium electron and hole concentrations

(a) Consider silicon at $T = 300$ K doped with phosphorus at a concentration of $N_d = 10^{16}$ cm^{-3}.

Solution: Since $N_d \gg n_i$, the electron concentration is

$$n_o \cong N_d = 10^{16} \text{ cm}^{-3}$$

and the hole concentration is

$$p_o = \frac{n_i^2}{N_d} = \frac{(1.5 \times 10^{10})^2}{10^{16}} = 2.25 \times 10^4 \text{ cm}^{-3}$$

To calculate the thermal equilibrium electron and hole concentrations

(b) Consider silicon at $T = 300\text{ K}$ doped with boron at a concentration of $N_a = 5 \times 10^{16}\text{ cm}^{-3}$.

Solution: Since $N_a \gg n_i$, the hole concentration is

$$p_o \cong N_a = 5 \times 10^{16}\text{ cm}^{-3}$$

and the electron concentration is

$$n_o = \frac{n_i^2}{N_a} = \frac{(1.5 \times 10^{10})^2}{5 \times 10^{16}} = 4.5 \times 10^3\text{ cm}^{-3}$$

Doping cm^{-3}	$\boldsymbol{n_o}$ cm^{-3}	$\boldsymbol{p_o}$ cm^{-3}
Donor $N_d = 10^{16}$	10^{16}	2.25×10^4
Acceptor Na = 5×10^{16}	4.5×10^3	5×10^{16}

Majority and minority carriers

- Semiconductor (silicon) doped with donor atoms/impurities (Phosphorous) has
  - Electrons as the majority carriers
  - Holes as the minority carriers
- Semiconductor (silicon) doped with acceptor atoms/impurities (Boron) has
  - Holes as the majority carriers
  - Electrons as the minority carriers

Assignment A.2

- Calculate the majority and minority carrier concentrations in (a) silicon and (b) GaAs at $T = 300$ K for (i) $N_d = 2 \times 10^{16}$ cm^{-3} and (ii) $N_a = 10^{15}$ cm^{-3}.
- Ans.
  - (a) (i) $n_o = 2 \times 10^{16}$ cm^{-3}, $p_o = 1.125 \times 10^{4}$ cm^{-3}

    (ii) $p_o = 10^{15}$ cm^{-3}, $n_o = 2.25 \times 10^{5}$ cm^{-3};
  - (b) (i) $n_o = 2 \times 10^{16}$ cm^{-3}, $p_o = 1.62 \times 10^{-4}$ cm^{-3};

    (ii) $p_o = 10^{15}$ cm^{-3}, $n_o = 3.24 \times 10^{-3}$ cm^{-3}

Drift and Diffusion Currents

- If charged particles (holes/electrons) move, a current is generated
- How to move charged particles?
- Two basic processes that cause electrons and holes to move in semiconductor
- Drift mechanism
  - Charged particles movement because of **electric fields**
- Diffusion mechanism
  - Charged particle movement because of **concentration gradient**

Current density (J)

- Current flowing through unit area (A/m^2)

Drift Current Density

- Drift = being carried away by some external force
- assume an electric field is applied across a semiconductor
- Electric field produces a **force** on the electrons and holes
- These electrons and holes experiences **velocity**, drift velocity and thereby net movement

Electric field applied across n-type semiconductor

- Consider an n-type semiconductor: Electrons are majority carriers
- Apply electric field *E*
- Electric field exerts a force on electrons in the ***opposite*** direction
- Electrons move in opposite direction to *E*, with a drift velocity of $v_{dn} = -\mu_n E$ (cm/s)
- -ve sign, drift velocity is opposite to *E*
- μ_n = constant, called electron mobility
- μ_n = 1350 cm^2/V-s for silicon
- Electron drift produces electron current density J_n (A/m^2)

$$J_n = -env_{dn} = -en(-\mu_n E) = en\mu_n E$$

Electric field applied across p-type semiconductor

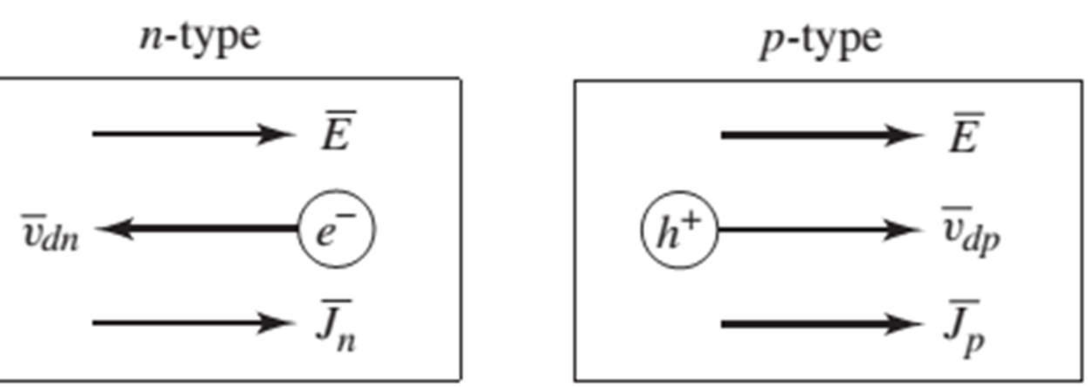
- Consider an p-type semiconductor: Holes are majority carriers
- Apply electric field E
- Electric field exerts a force on holes in the ***same*** direction
- <u>Holes move in same direction to E</u>, with a drift velocity of $v_{dp} = \mu_p E$ (cm/s)
- μ_p = constant, called hole mobility
- μ_p = 480 cm^2/V-s for silicon
- Hole drift produces hole current density J_p (A/m^2)

$$J_p = epv_{dp} = ep(\mu_p E) = ep\mu_p E$$

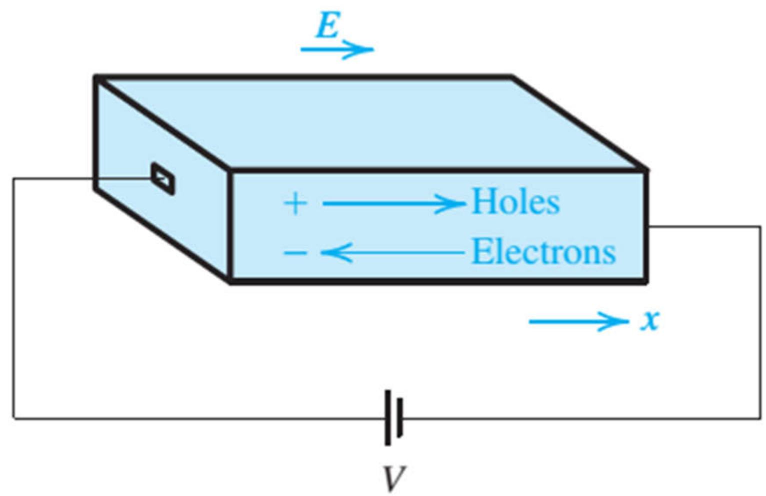
Mobility

- Indicates how an electron or hole moves in a material
- It is constant for a particular material

Directions of applied electric field and resulting carrier drift velocity and drift current density



Directions of applied electric field and resulting carrier drift velocity and drift current density



An electric field E established in a bar of silicon causes

- the holes to drift in the direction of E and
- the free electrons to drift in the opposite direction of E
- Both the hole and electron drift currents are in the direction of E

Total drift current density in a semiconductor

- A semiconductor has both electrons and holes
- Therefore total drift current is because of electrons and holes

$$J = en\mu_n E + ep\mu_p E = \sigma E = \frac{1}{\rho} E$$

$$where$$

$$\sigma = en\mu_n + ep\mu_p$$

$$\rho = \frac{E}{J}$$

Objective: to find the resistivity of intrinsic and extrinsic silicon

- Find the resistivity of (a) intrinsic silicon and (b) *p*-type silicon with $N_A = 10^{16}/\text{cm}^3$.
- Use $n_i = 1.5 \times 10^{10}/\text{cm}^3$, and
- assume that for intrinsic silicon $\mu_n = 1350\ \text{cm}^2/\text{V} \cdot \text{s}$ and $\mu_p = 480\ \text{cm}^2/\text{V} \cdot \text{s}$,
- and for the doped silicon $\mu_n = 1110\ \text{cm}^2/\text{V} \cdot \text{s}$ and $\mu_p = 400\ \text{cm}^2/\text{V} \cdot \text{s}$.

(Note that doping results in reduced carrier mobilities.)

Objective: to find the resistivity of intrinsic and extrinsic silicon

Solution:

(a) For intrinsic silicon $p = n = n_i = 1.5\times 10^{10}/cm^3$

$$\rho = \frac{1}{q(p\mu_p + n\mu_n)}$$

$$\rho = \frac{1}{1.6\times 10^{-19}(1.5\times 10^{10}\times 480 + 1.5\times 10^{10}\times 1350)}$$

$$= 2.28\times 10^{5}\ \Omega\cdot cm$$

Objective: to find the resistivity of intrinsic and extrinsic silicon

(b) For p-type silicon

$$p_p \simeq N_A = 10^{16}/\text{cm}^3$$

$$n_p \simeq \frac{n_i^2}{N_A} = \frac{(1.5 \times 10^{10})^2}{10^{16}} = 2.25 \times 10^4/\text{cm}^3$$

$$\rho = \frac{1}{q(p\mu_p + n\mu_n)}$$

$$= \frac{1}{1.6 \times 10^{-19}(10^{16} \times 400 + 2.25 \times 10^4 \times 1110)}$$

$$\simeq \frac{1}{1.6 \times 10^{-19} \times 10^{16} \times 400} = 1.56\ \Omega \cdot \text{cm}$$

Objective: to find the resistivity of intrinsic and extrinsic silicon

Observation:

Resistivity (ρ) of

(a) Intrinsic silicon $2.28\times 10^{5}\ \Omega\cdot$ cm

(b) For p-type silicon $1.56\ \Omega\cdot$ cm

Objective: Calculate the drift current density for a given semiconductor

- **Problem**: Consider silicon at $T = 300$ K doped with arsenic atoms at a concentration of $N_d = 8 \times 10^{15}$ cm^{-3}. Assume mobility values of $\mu_n = 1350$ cm^2/V–s and $\mu_p = 480$ cm^2/V–s. Assume the applied electric field is 100 V/cm.

Objective: Calculate the drift current density for a given semiconductor

- **Solution**: The electron and hole concentrations are

$$n \cong N_d = 8 \times 10^{15}\ \text{cm}^{-3}$$

and

$$p = \frac{n_i^2}{N_d} = \frac{(1.5 \times 10^{10})^2}{8 \times 10^{15}} = 2.81 \times 10^4\ \text{cm}^{-3}$$

the conductivity is given by

$$\sigma = e\mu_n n + e\mu_p p \cong e\mu_n n$$

$$\sigma = (1.6 \times 10^{-19})(1350)(8 \times 10^{15}) = 1.73(\Omega\text{–cm})^{-1}$$

The drift current density is then

$$J = \sigma E = (1.73)(100) = 173\ \text{A/cm}^2$$

Assignment A.3

- A uniform bar of *n*-type silicon of 2-µm length has a voltage of 1 V applied across it. If N_D = $10^{16}/cm^3$ and $\mu_n = 1350\ cm^2/V \cdot s$, find (a) the electron drift velocity, (b) the time it takes an electron to cross the 2-µm length, (c) the drift-current density, and (d) the drift current in the case that the silicon bar has a cross-sectional area of 0.25 μm^2.

Ans. 6.75×10^6 cm/s; 30 ps; $1.08\times 10^4\ A/cm^2$; 27 µA

Note: Drift velocity saturation

- the carrier drift velocities are linear functions of the applied electric field. This is true for relatively small electric fields.
- As the electric field increases, the carrier drift velocities will reach a maximum value of approximately 10^7 cm/s. Any further increase in electric field will not produce an increase in drift velocity. This phenomenon is called drift velocity saturation.

$$v_{dn} = -\mu_n E$$

Note: Conductivity, is not a linear function of impurity doping.

- The mobility values are actually functions of donor and/or acceptor impurity concentrations.
- As the impurity concentration increases, the mobility values will decrease.
- This effect then means that the conductivity, is not a linear function of impurity doping.

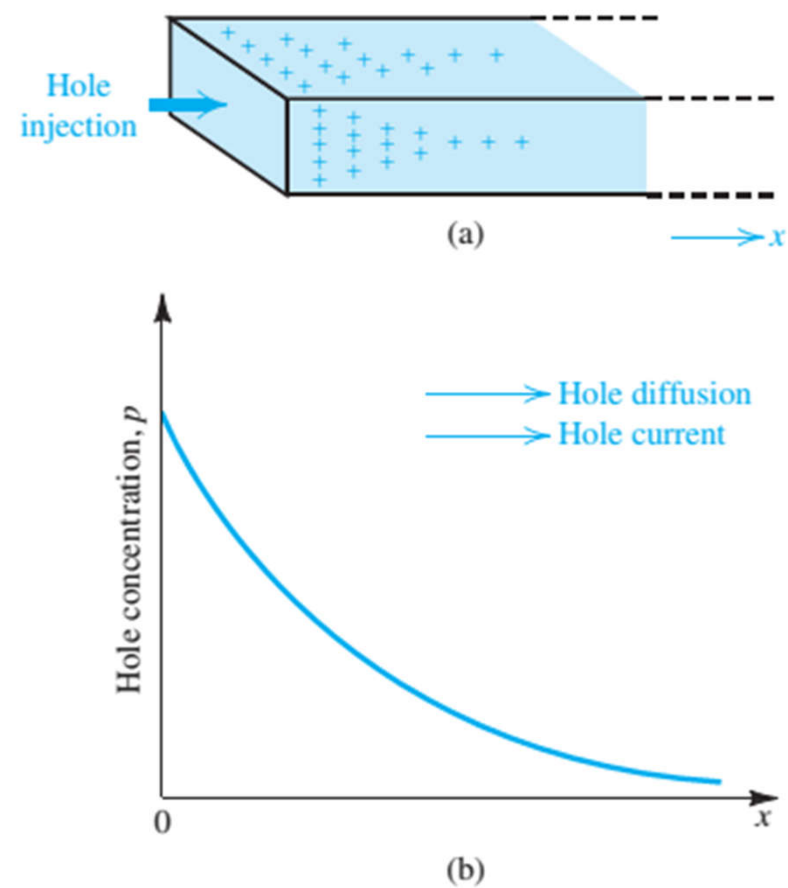
$$\sigma = en\mu_n + ep\mu_p$$

Diffusion Current

- Diffusion = spreading out something more widely
- Carrier diffusion occurs when the density of charge carriers in a piece of semiconductor is not uniform
- If the concentration of holes/electrons is made higher in one part of a piece of silicon than in another, then holes/electrons will diffuse from the region of high concentration to the region of low concentration
- The diffusion of charge carriers gives rise to a net flow of charge, or **diffusion current**.

Hole diffusion current

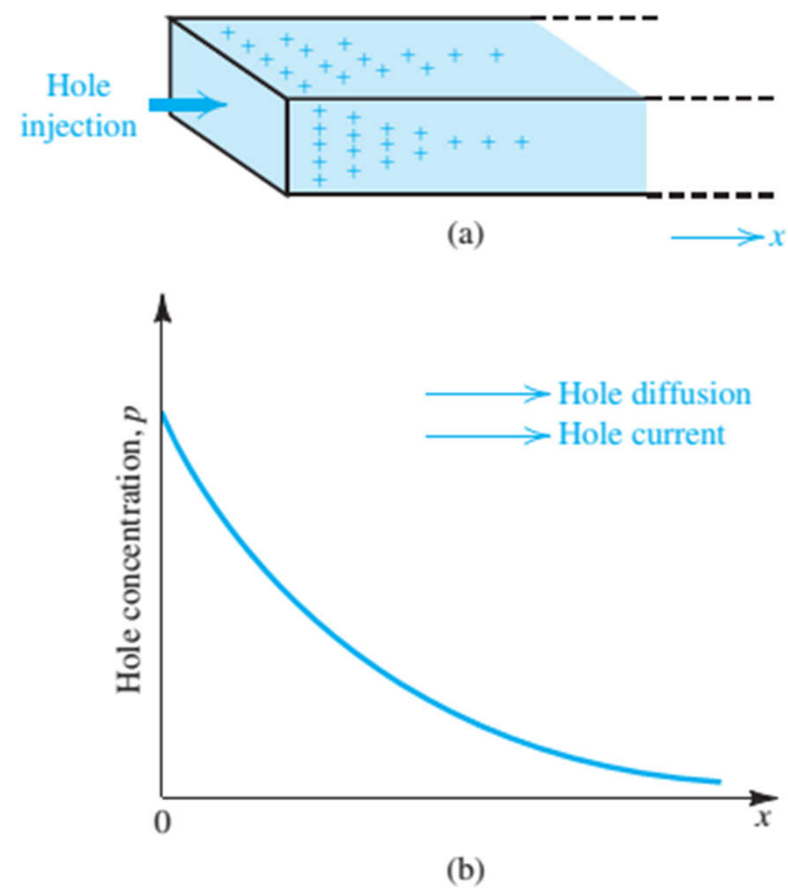
- Holes are arranged in the left side
- Hole concentration profile
- This profile results in diffusion of holes from left to right along the silicon bar
- Hole current in the +ve x-direction



Hole diffusion current

- The magnitude of the current at any point is proportional to the slope of the concentration profile, or the **concentration gradient**, at that point

$$J_p = -qD_p \frac{d}{dx}\left[p(x)\right]$$



(a)

(b)

Hole diffusion current

$$J_p = -qD_p \frac{d}{dx}[p(x)]$$

where

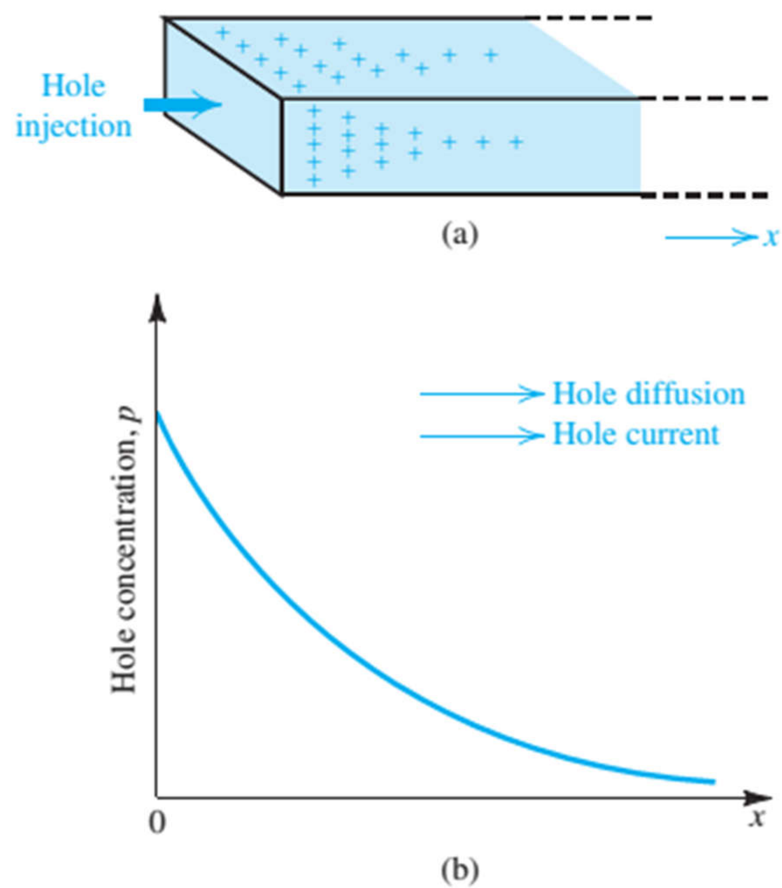
J_p is the hole-current density (A/cm^2)

q is the magnitude of electron charge

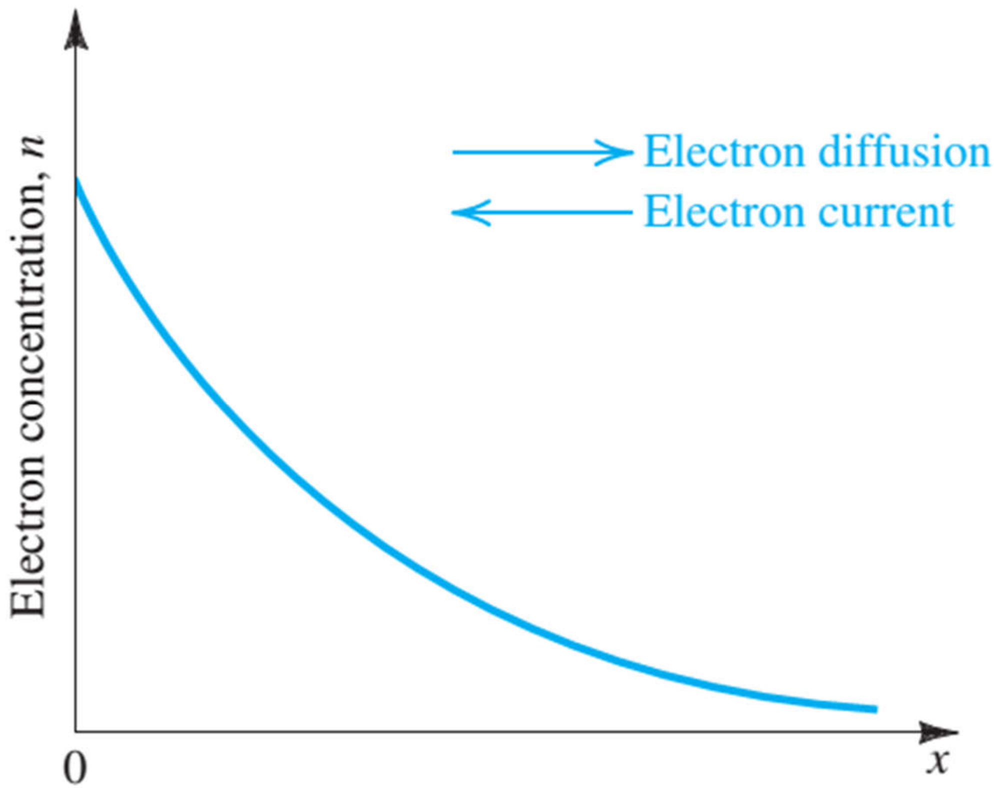
D_p is a constant called the **diffusion constant** or **diffusivity** holes

$p(x)$ is the hole concentration at point x

D_p = 12 cm^2/s for silicon



Electron diffusion current



- electron concentration profile in a bar of silicon
- electrons diffuse in the ***x* direction**
- electron diffusion current in the **negative-*x* direction**

$$J_n = qD_n \frac{d}{dx}\left[n(x)\right]$$

D_n = 35 cm^2/s for silicon

Problem: Diffusion current

- Consider a bar of silicon in which a hole concentration profile described by

$$p(x) = p_0 e^{\left(-x/L_p\right)}$$

is established. Find the hole-current density at $x = 0$. Let $p_0 = 10^{16}/\text{cm}^3$, $L_p = 1\ \mu\text{m}$, and $D_p = 12\ \text{cm}^2/\text{s}$. If the cross-sectional area of the bar is $100\ \mu\text{m}^2$, find the current I_p.

Problem: Diffusion current

$$J_p = -qD_p \frac{dp(x)}{dx}$$

$$= -qD_p \frac{d}{dx}\left[p_0 e^{-x/L_p}\right]$$

$$= q\frac{D_p}{L_p} p_0 e^{-x/L_p}$$

$$J_p(0) = q\frac{D_p}{L_p} p_0$$

$$= 1.6 \times 10^{-19} \times \frac{12}{1 \times 10^{-4}} \times 10^{16}$$

$$= 192 \text{ A/cm}^2$$

The current I_p can be found from

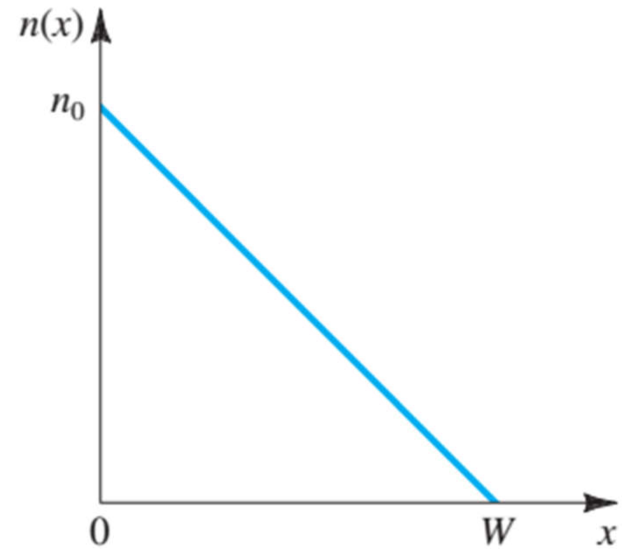
$$I_p = J_p \times A$$

$$= 192 \times 100 \times 10^{-8}$$

$$= 192\ \mu\text{A}$$

Assignment: Diffusion current A.4

- The linear electron-concentration profile shown in Fig. has been established in a piece of silicon. If $n_0 = 10^{17}/\text{cm}^3$ and $W = 1\ \mu\text{m}$, find the electron-current density in microamperes per micron squared ($\mu\text{A}/\mu\text{m}^2$). If a diffusion current of 1 mA is required, what must the cross sectional area (in a direction perpendicular to the page) be? Recall that $D_n = 35\ \text{cm}^2/\text{s}$.



Ans. 56 $\mu\text{A}/\mu\text{m}^2$; 18 μm^2

Einstein relationship

Relationship between D and μ

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

$$where$$

$$V_T = \frac{kT}{q} = 26\ \text{mV}$$

$$V_T = \text{Thermal voltage}$$

Assignment A.5

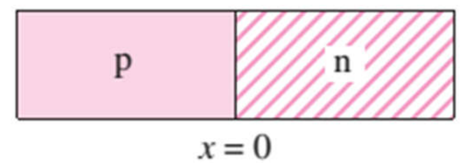
- Find D_n and D_p for intrinsic silicon using μ_n = 1350 $cm^2/V{\cdot}s$ and μ_p = 480 $cm^2/V{\cdot}s$.

Ans. 35 cm^2/s; 12.4 cm^2/s

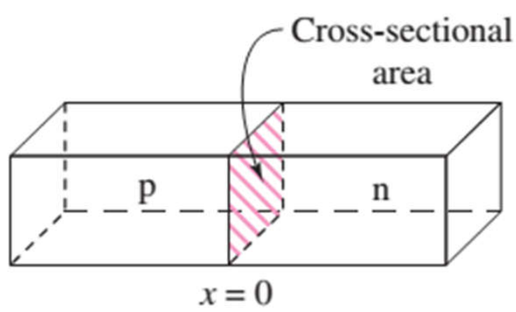
The pn Junction

Operation with Open-Circuit Terminals

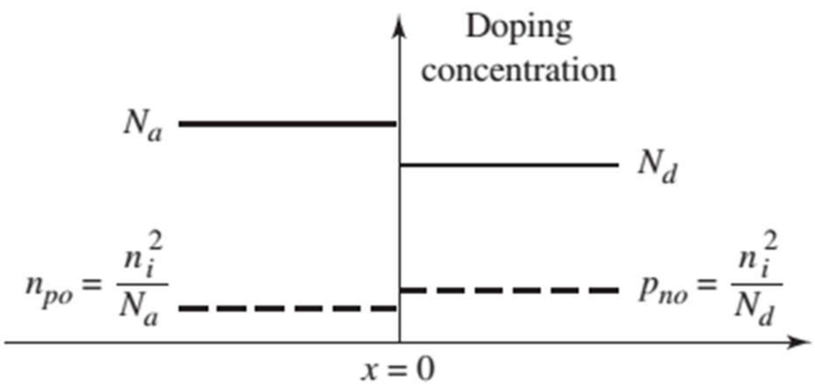
- The interface at $x = 0$ is called the **metallurgical junction**



simplified 1D geometry



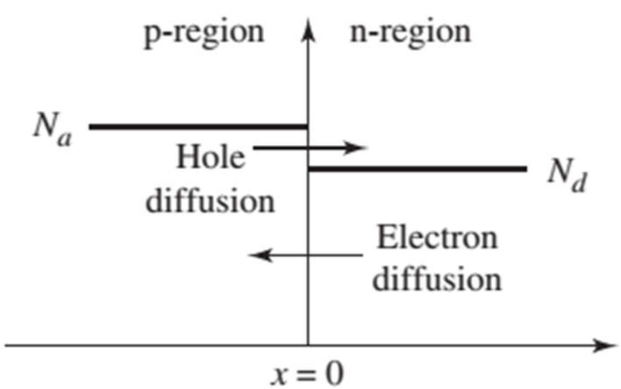
3D representation showing the cross-sectional area



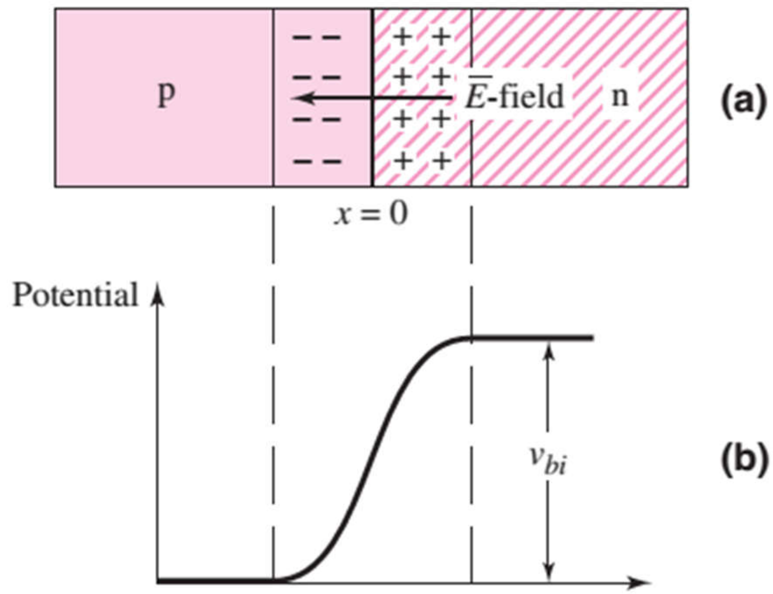
doping profile

The pn Junction

Operation with Open-Circuit Terminals



Initial diffusion of holes and electrons



The pn junction in thermal equilibrium.

(a) The space charge region with negatively charged acceptor ions in the p-region and positively charged donor ions in the n-region; the resulting electric field from the n- to the p-region.

(b) The potential through the junction and the built-in potential barrier V_{bi} across the junction.

The pn Junction

Operation with Open-Circuit Terminals

- Diffusion of holes from the p-region into the n-region, and a diffusion of electrons from the n-region into the p-region
- The flow of holes from the p-region results in negatively charged acceptor ions
- The flow of electrons from the n-region results in positively charged donor ions
- Diffusion results in charge separation, which sets up electric field
- The positively charged region and the negatively charged region comprise the **space-charge** region, or **depletion region**
  - no mobile electrons or holes
- Because of the electric field in the space charge region, there is a potential difference across that region
- This potential difference is called the **built-in potential barrier,** or built-in voltage

$$V_{bi} = \frac{kT}{e} \ln\left(\frac{N_a N_d}{n_i^2}\right) = V_T \ln\left(\frac{N_a N_d}{n_i^2}\right)$$

Objective: To calculate the built-in potential barrier of a pn junction

Problem: Consider a silicon pn junction at $T = 300$ K, doped at $N_a = 10^{16}$ cm^{-3} in the p-region and $N_d = 10^{17}$ cm^{-3} in the n-region.

Solution:

$n_i = 1.5 \times 10^{10}$cm^{-3} for silicon at room temperature

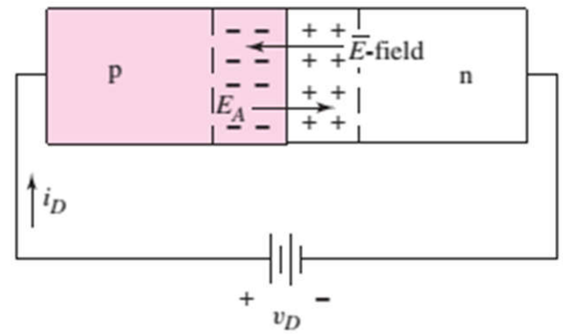
$$V_{bi} = V_T \ln\left[\frac{N_a N_d}{n_i^2}\right] = 0.026 \ln\left[\frac{10^{16} \times 10^{17}}{\left(1.5 \times 10^{10}\right)^2}\right] = 0.757\,\mathrm{V}$$

Assignment A.6

- Calculate V_{bi} for (a) GaAs pn junction and (b) Germanium pn junction at T = 300 K for $N_a = 10^{16}$ cm^{-3} and $N_d = 10^{17}$ cm^{-3}

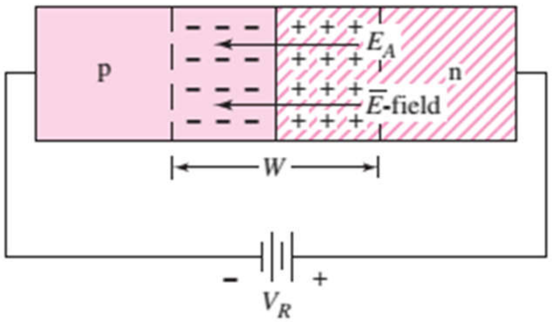
Ans: (a) V_{bi} = 1.23 V, (GaAs) (b) V_{bi} = 0.374 V. (Ge)

Forward-Biased pn Junction



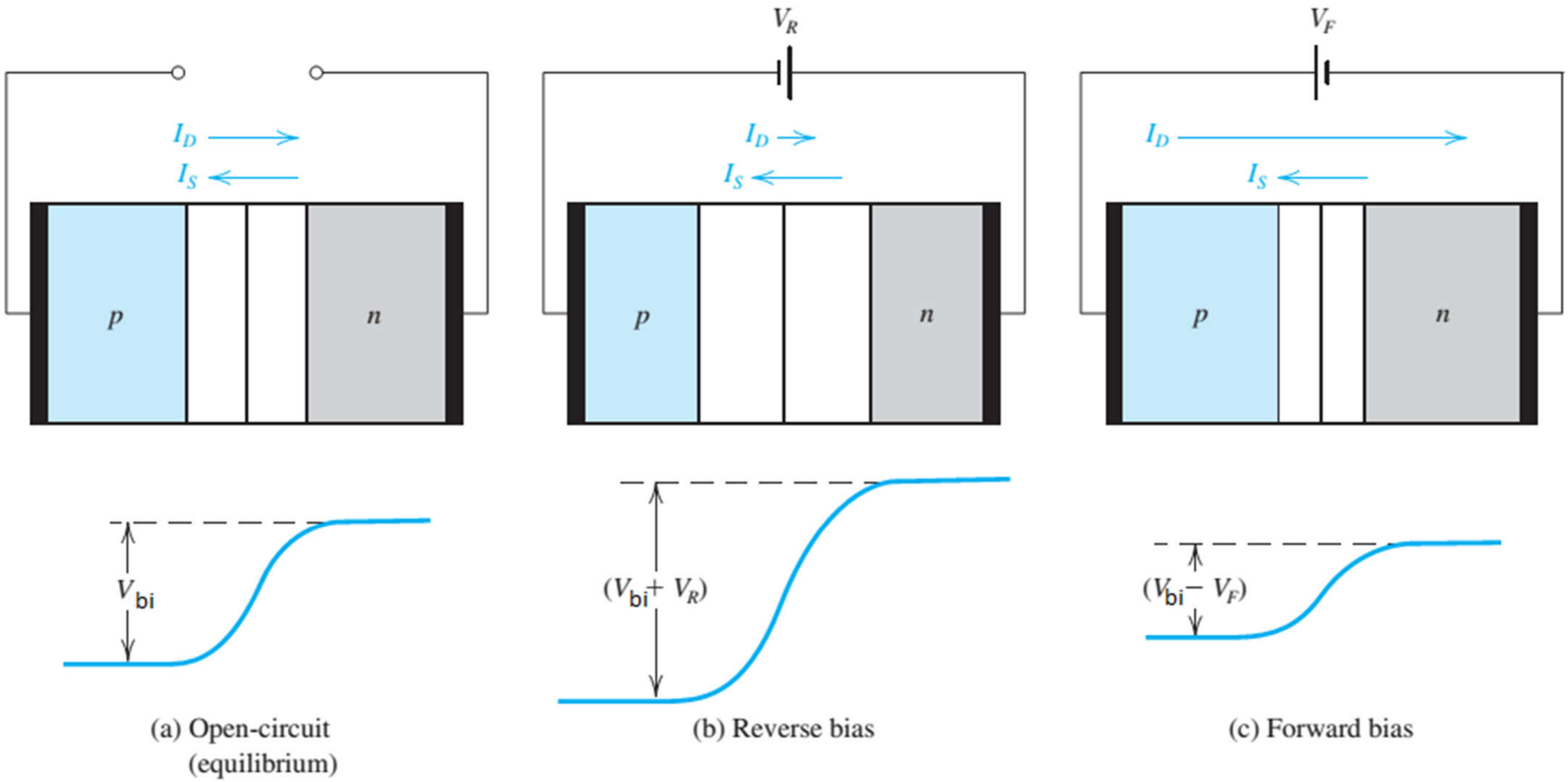
- If a positive voltage v_D is applied to the p-region and negative voltage to n-region then the diode is forward biased
- The electric fields in the space-charge region
  - very large compared to those in the remainder of the p- and n regions
  - The applied electric field, E_A, (induced by the applied voltage) is in the opposite direction from that of the thermal equilibrium space-charge *E*-field
- The net result is that the electric field in the space-charge region is lower than the equilibrium value
- Majority carrier electrons from the n-region diffuse into the p-region, and majority carrier holes from the p-region diffuse into the n-region
- Width of the space charge region decreases compared to equilibrium width of the space charge region

Reverse-Biased pn Junction



- When a positive voltage is applied to the n-region and negative voltage is applied to the p-region of a pn junction, then the diode is said to be reverse biased
- The electric fields in the space-charge region
  - very large compared to those in the remainder of the p- and n regions
  - The applied electric field, E_A, (induced by the applied voltage) is in the same direction from that of the thermal equilibrium space-charge *E*-field
- The net result is that the electric field in the space-charge region is higher than the equilibrium value
- This increased electric field holds back the holes in the p-region and the electrons in the n-region, so there is essentially no current across the pn junction.
- Width of the space charge region increases compared to equilibrium width of the space charge region

pn junction summary



The *pn* junction in: **(a)** equilibrium; **(b)** reverse bias; **(c)** forward bias

Junction capacitance of the RB pn junction diode

- a capacitance is associated with the pn junction when a reverse-bias voltage is applied
- **Junction capacitance,** or depletion layer capacitance

$$C_j = C_{jo}\left(1 + \frac{V_R}{V_{bi}}\right)^{-1/2}$$

where C_{jo} is the junction capacitance at zero applied voltage

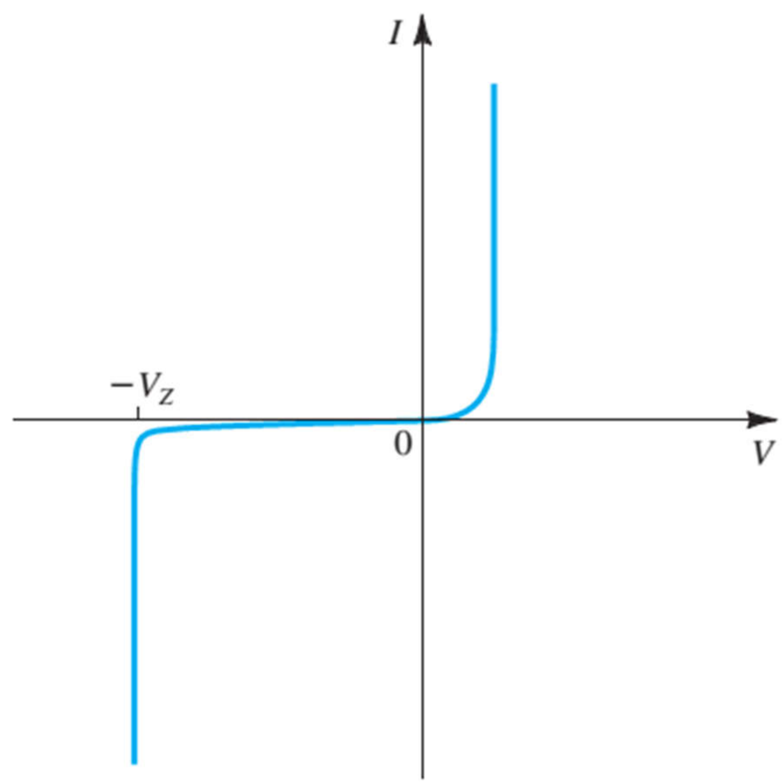
Useful for electrically tunable resonant circuits

Ideal Current–Voltage Relationship of diode

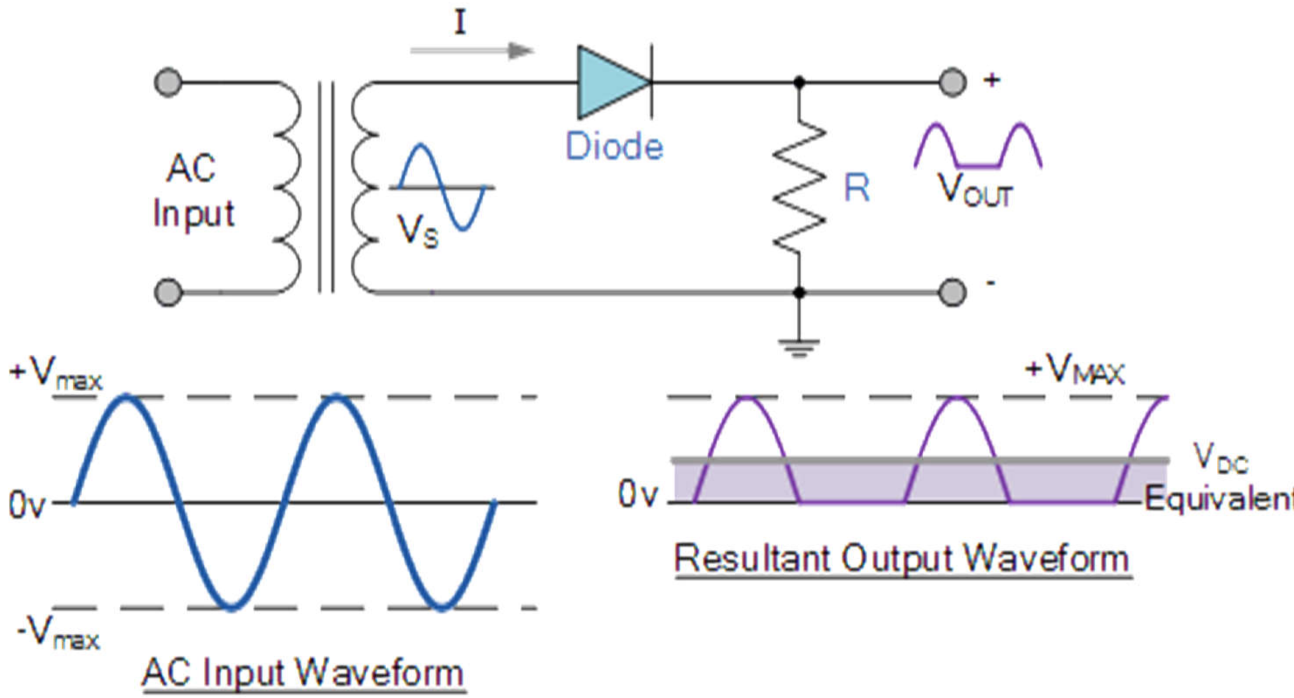
$$i_D = I_S\left(e^{\frac{v_D}{V_T}} - 1\right) \cong I_S e^{\frac{v_D}{V_T}}$$

- I_S is the **reverse-bias saturation current.** For silicon pn junctions, typical values of I_S are in the range of 10^{-18} to 10^{-12} A
- The parameter V_T is the thermal voltage
- Nonlinear rectifying current characteristics

I-V characteristics of diode



half-wave rectifier



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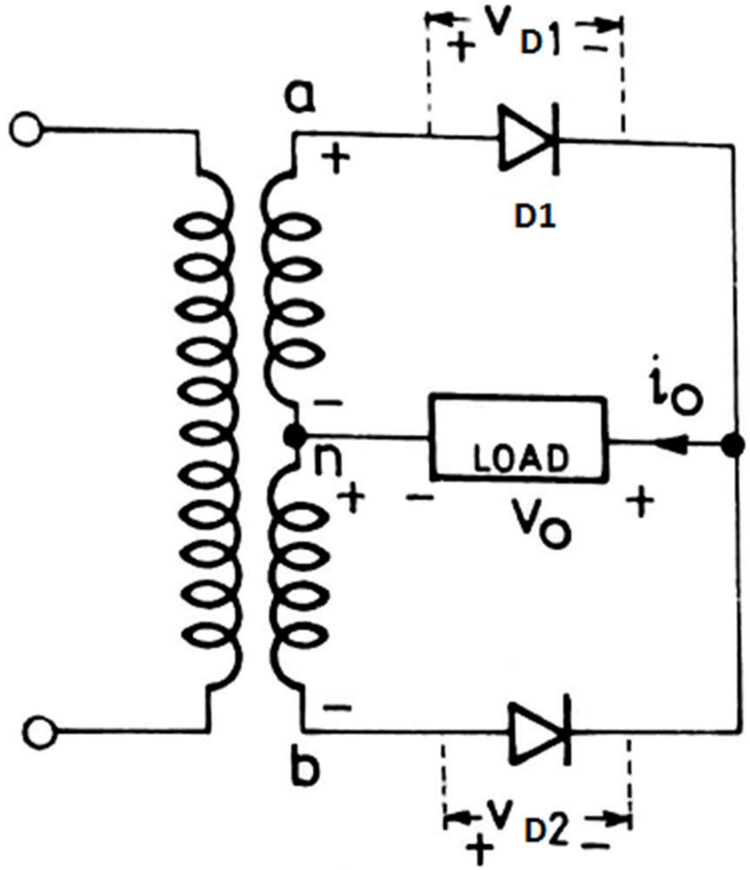
Full-wave rectifier



Full-wave rectifier

- RMS value of voltage at the output resistance

$$V_{rms} = \sqrt{\frac{1}{\pi}\left[\int_0^{\pi} v^2 d(\omega t)\right]} = \sqrt{\frac{1}{\pi}\left[\int_0^{\pi} \left(V_m \sin \omega t\right)^2 d(\omega t)\right]}$$

$$\sin^2 \theta = \frac{1 - \cos 2\theta}{2}$$

$$V_{rms} = \frac{V_m}{\sqrt{2}}$$

Full-wave rectifier

- Average value of voltage at the output resistance

$$V_{dc} = \frac{1}{\pi}\left[\int_{0}^{\pi} v d(\omega t)\right] = \frac{1}{\pi}\left[\int_{0}^{\pi} \left(V_m \sin \omega t\right) d(\omega t)\right]$$

$$V_{dc} = \frac{2V_m}{\pi}$$

Full-wave rectifier

- Ripple factor: indicates how close the rectifier output voltage to its DC value

$$\gamma = \sqrt{\left(\frac{V_{rms}}{V_{dc}}\right)^2 - 1} = 0.482$$

Full-wave rectifier

- Efficiency, η is the ratio of output power (dc) to input power (ac)

$$\eta = \frac{Output\ power\,(DC)}{Input\ power\,(AC)} = \frac{\dfrac{V_{dc}^2}{R_L}}{\dfrac{V_{rms}^2}{R_L}} = 81.2\%$$

Full-wave rectifier

- Form factor: ratio of the rms value of the output voltage to the average value of the output voltage

$$\text{Form factor} = \frac{\text{RMS value of output voltage}}{\text{Average value of output voltage}}$$

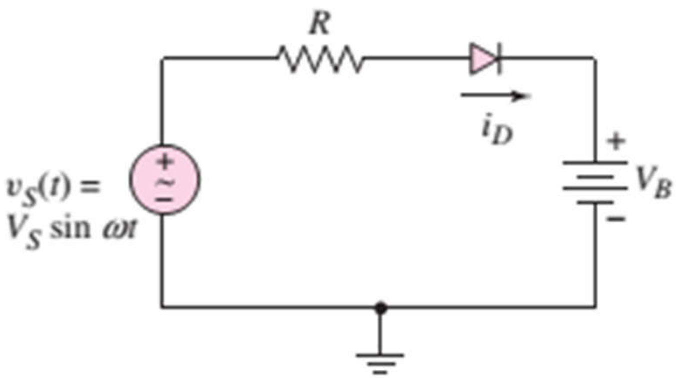
$$\text{Form factor} = \frac{\dfrac{V_m}{\sqrt{2}}}{\dfrac{2V_m}{\pi}} = 1.11$$

Full-wave rectifier

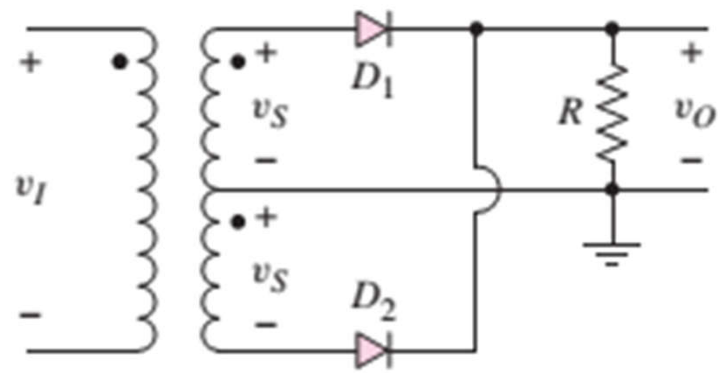
- Peak factor: the ratio of the peak value of the output voltage to the rms value of the output voltage

$$V_{pf} = \frac{\text{Peak value of output voltage}}{\text{RMS value of output voltage}} = \frac{V_m}{V_{rms}} = \sqrt{2}$$

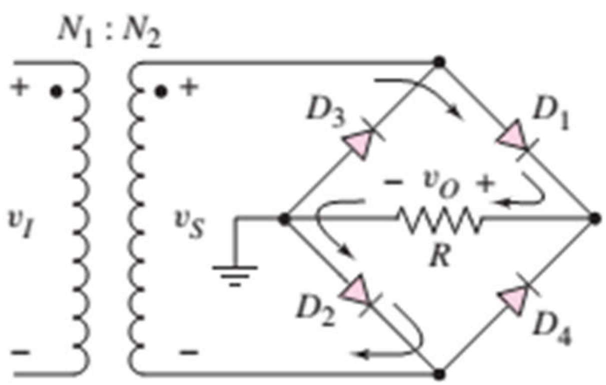
Diode rectifier circuits

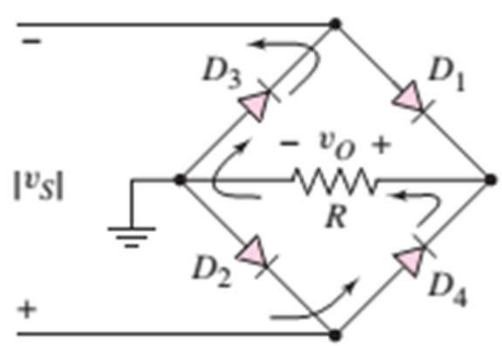


Half wave rectifier



Full wave rectifier,
centre tapped transformer





Full wave bridge rectifier

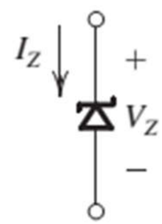
Passive filters

- To smoothen the ripple
  - Inductor filter
  - Capacitor filter
  - LC filter
  - CLC or pi filter

Shunt capacitor filter

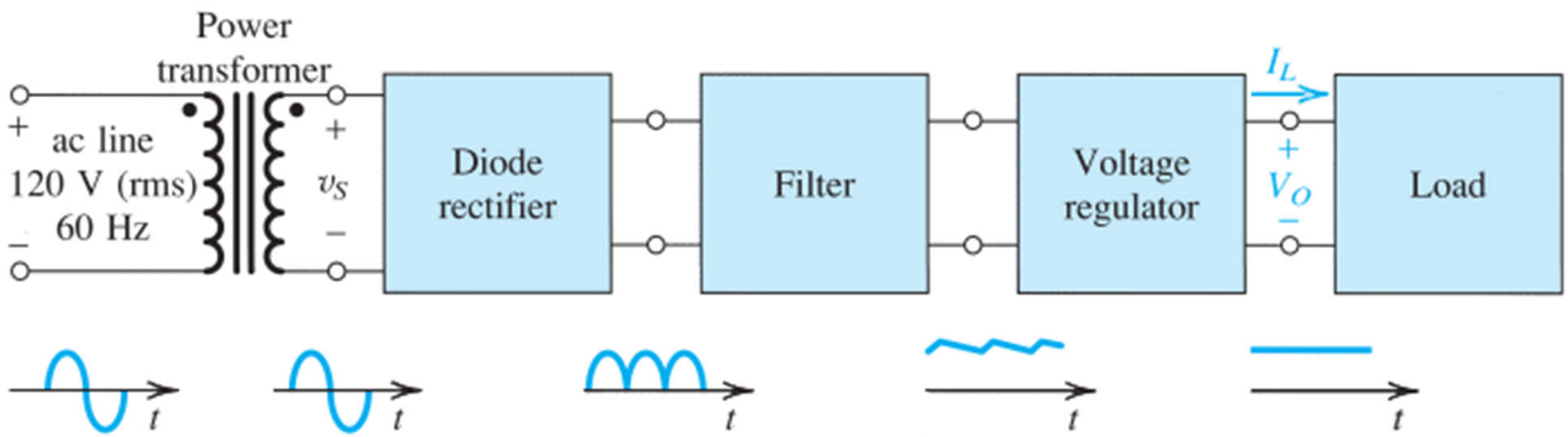
Voltage regulator

- Provides constant DC voltage to the circuit
- Zener diode is a voltage regulator



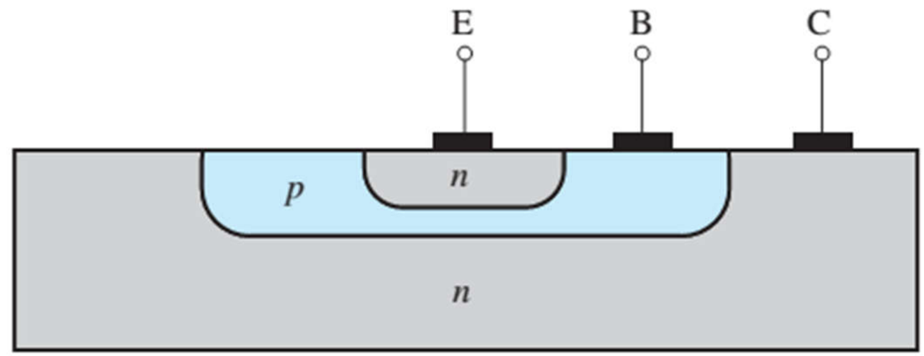
- The first integrated voltage regulator (μA723, National LM100)

Regulated D-C power supply

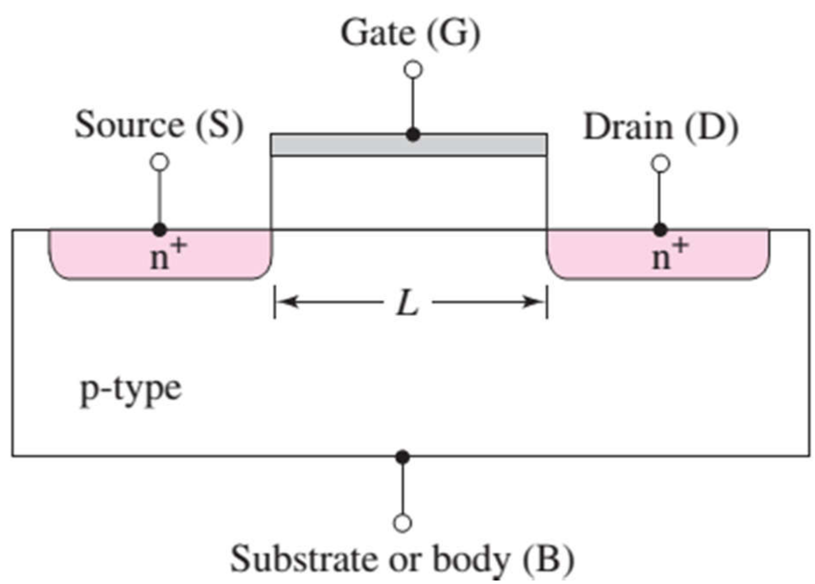


Transistors

- *Transistor*
  - *Transfers resistance*
- Transistor types
  - BJT (bipolar)
  - FET (Unipolar)



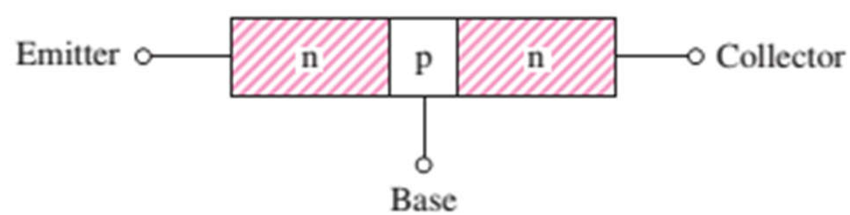
BJT



MOSFET

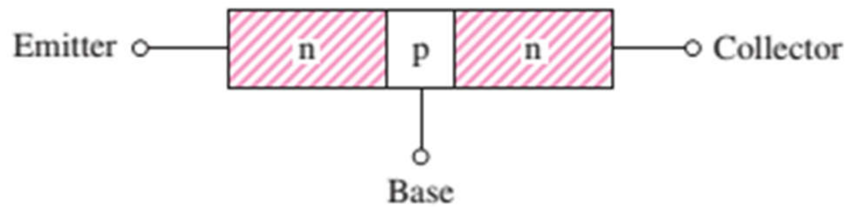
Bipolar junction transistor

- Transistor principle:
  the voltage between two terminals controls the current through the third terminal
- Current in the transistor is because of both holes and electrons, hence the name “*Bipolar*”
- Applications
  - Amplifier
  - Switch
- MOSFET
  - Amplifier
  - Switch
- Differences between BJT and MOSFET

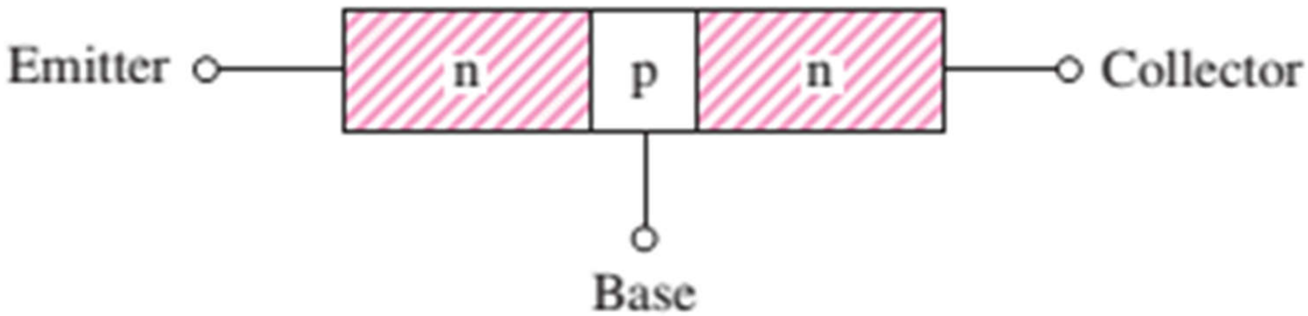


Bipolar junction transistor (BJT)

- Three doped regions
- Three terminals
- Two pn junctions
- Single pn junction has two modes
  - FB
  - RB
- BJT has two junctions
  - Four modes of operation

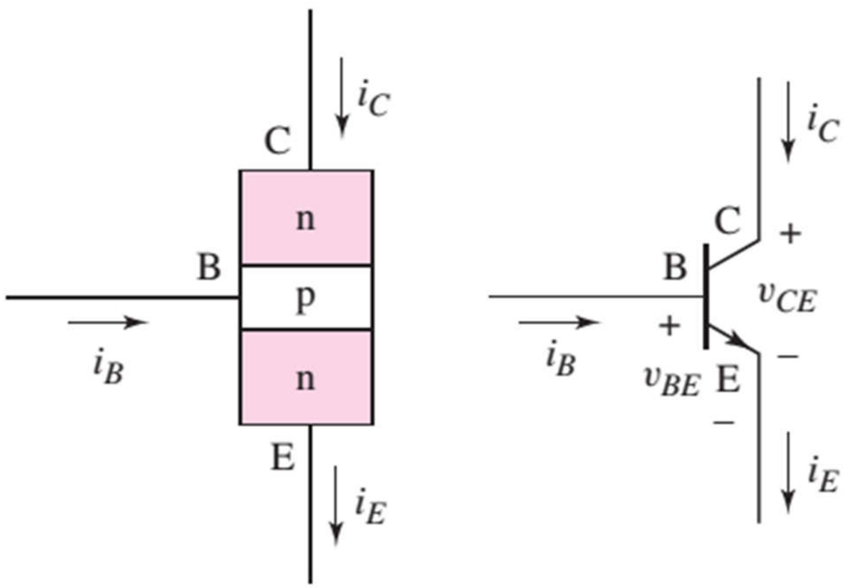


Modes of operation

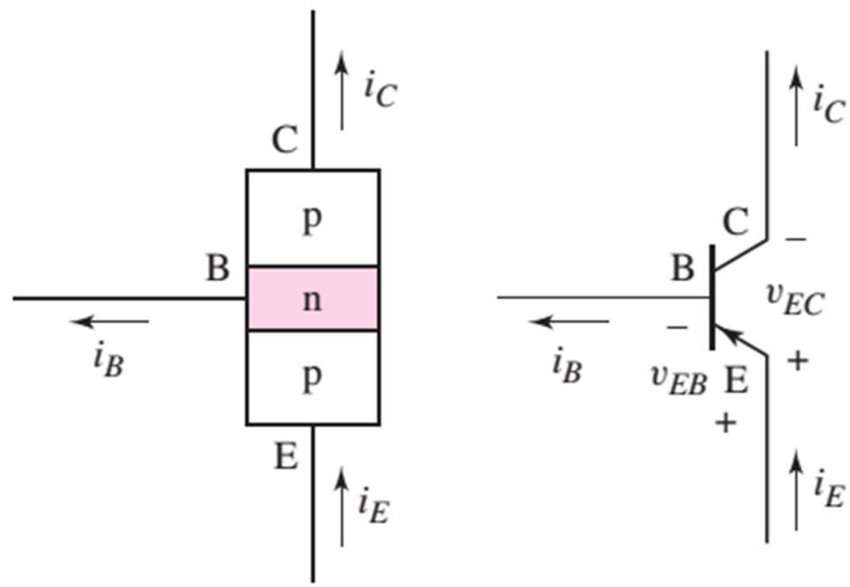


EB	CB	Mode
FB	RB	Active
FB	FB	Saturation
RB	RB	Cut-off
RB	FB	Reverse active

Block diagrams and circuit symbols for BJT

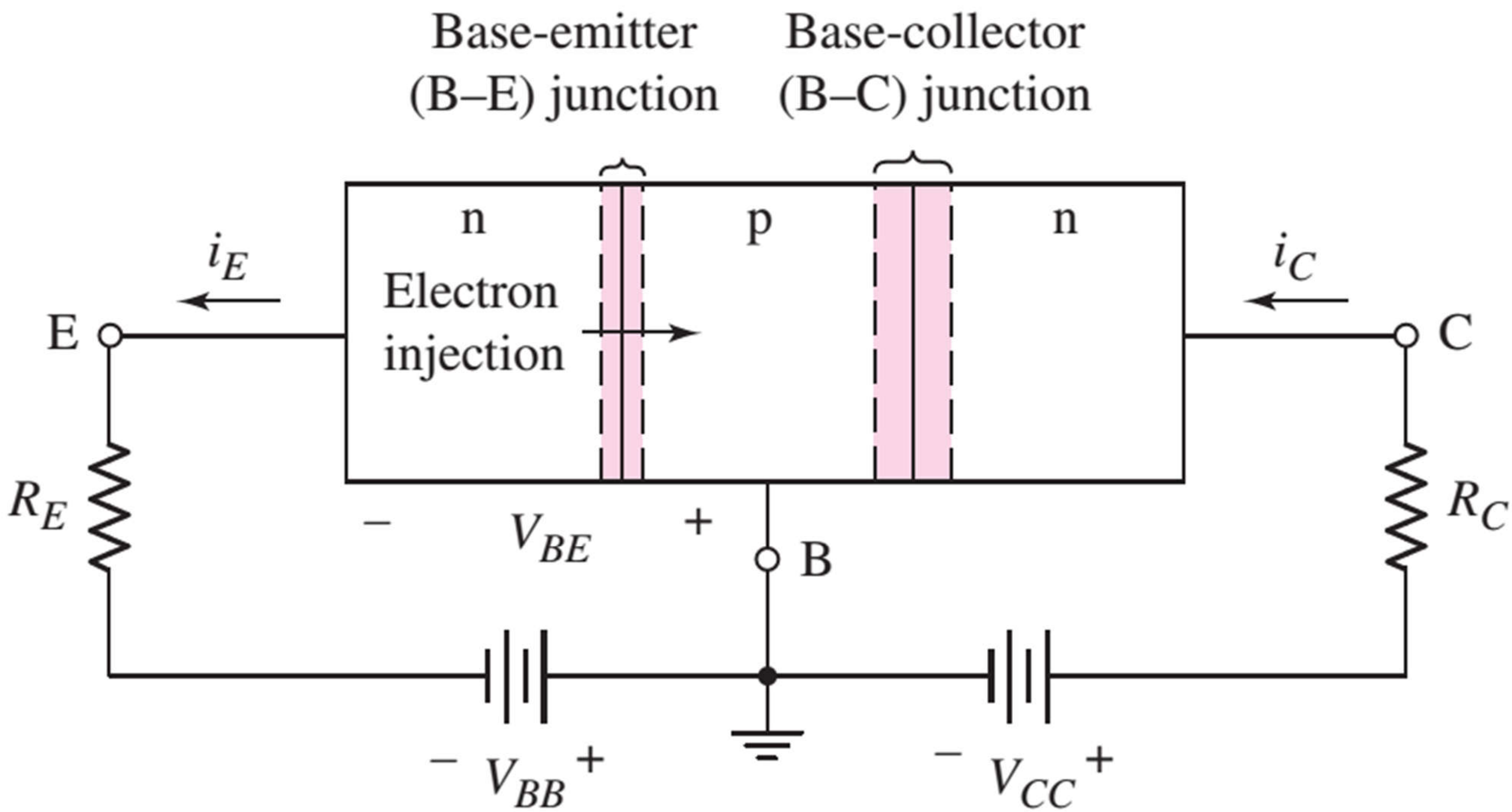


NPN transistor



PNP transistor

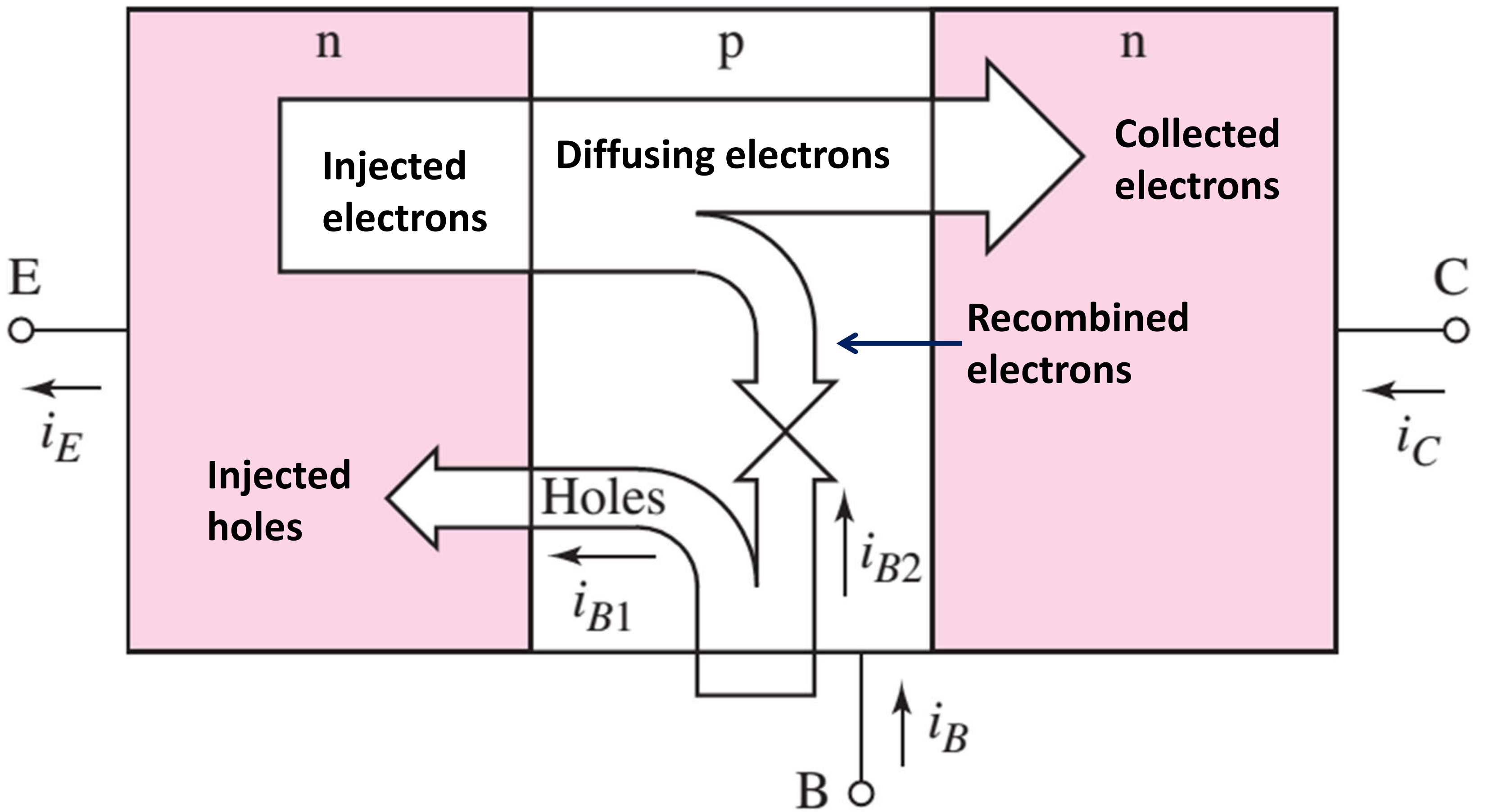
Transistor as an amplifier



Current flow in a *npn* transistor biased to operate in the active mode

Currents in npn BJT

Doping levels: Emitter high, colletor low and base moderate



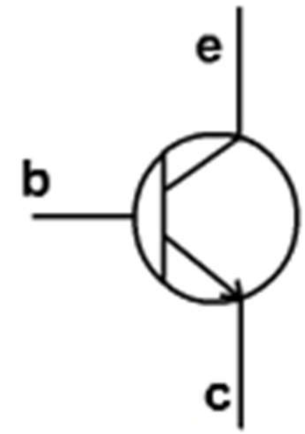
Electron and hole currents in a npn **bipolar transistor biased in the forward-active mode**

Currents in BJT

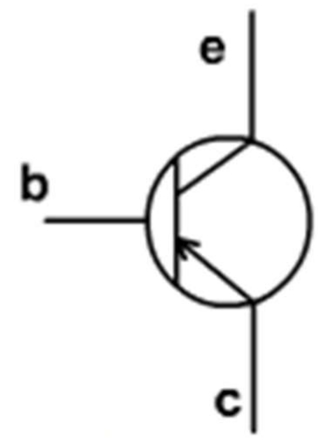
- The total current flowing into the transistor must be equal to the total current flowing out of it
- the emitter current I_E is equal to the sum of the collector (I_C) and base current (I_B)
- $I_E = I_C + I_B$
- $I_C = \alpha I_E$
- $I_C = \beta I_B$
- α = Common base current gain
- β = Common emitter current gain

$$I_C = I_S e^{V_{BE}/V_T}$$

$$\beta = \frac{\alpha}{1-\alpha}$$



npn



pnp

Problem

Objective: Calculate the collector and emitter currents, given the base current and current gain.

Assume a common-emitter current gain of $\beta = 150$ and a base current of $i_B = 15\ \mu A$. Also assume that the transistor is biased in the forward-active mode.

Solution: The relation between collector and base currents gives

$$i_C = \beta i_B = (150)(15\,\mu A) \Rightarrow 2.25\,\text{mA}$$

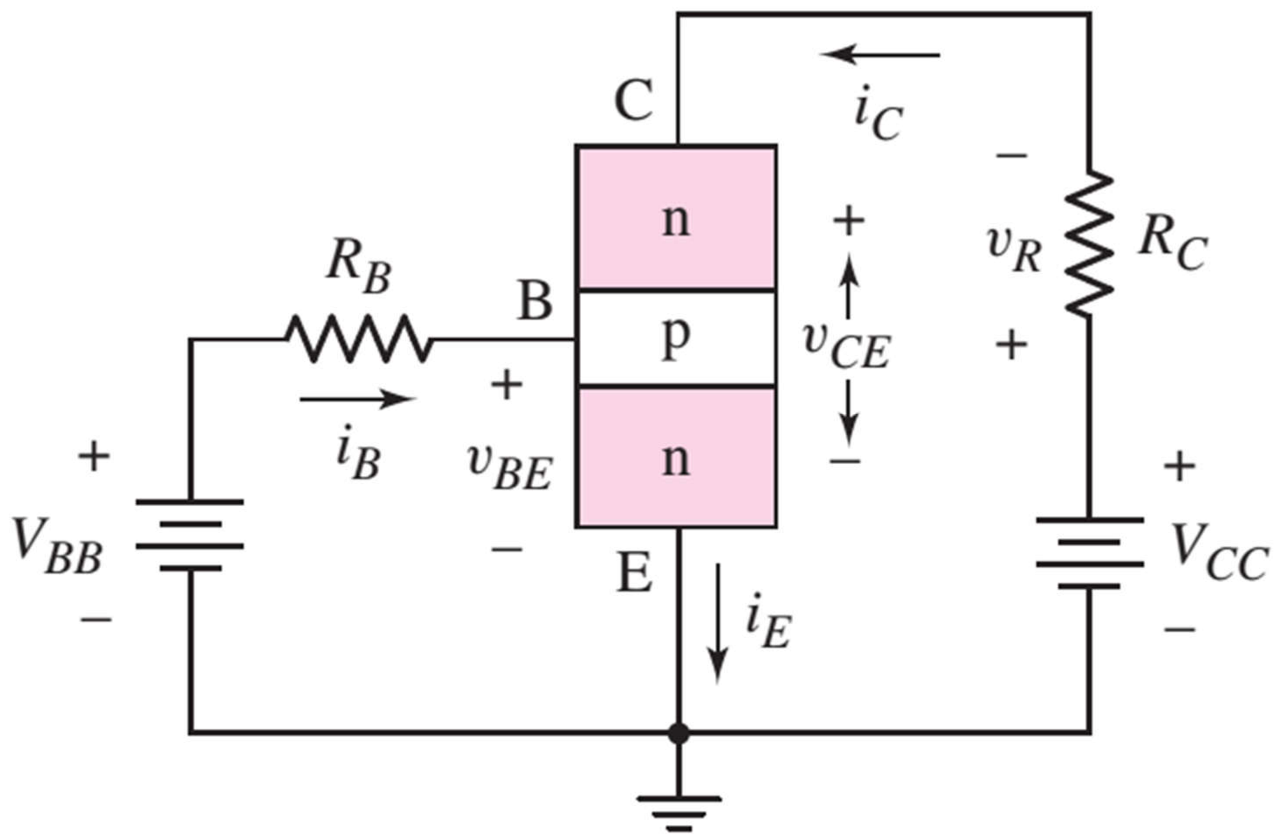
and the relation between emitter and base currents yields

$$i_E = (1+\beta)i_B = (151)(15\,\mu A) \Rightarrow 2.27\,\text{mA}$$

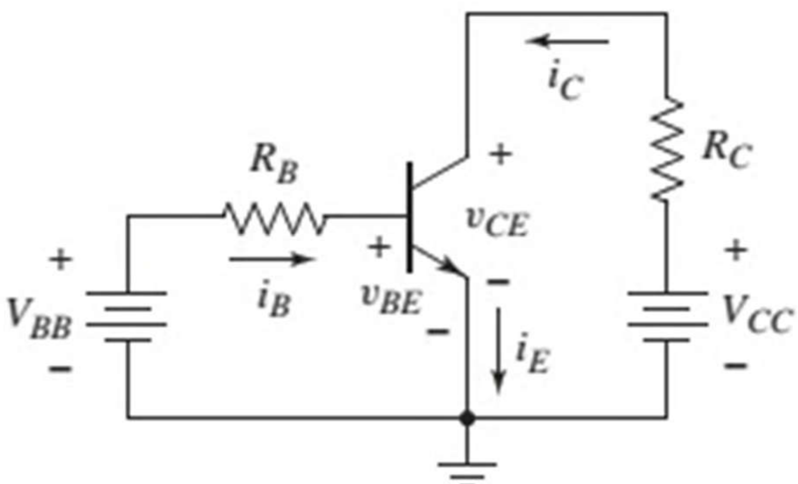
the common-base current gain is

$$\alpha = \frac{\beta}{1+\beta} = \frac{150}{151} = 0.9934$$

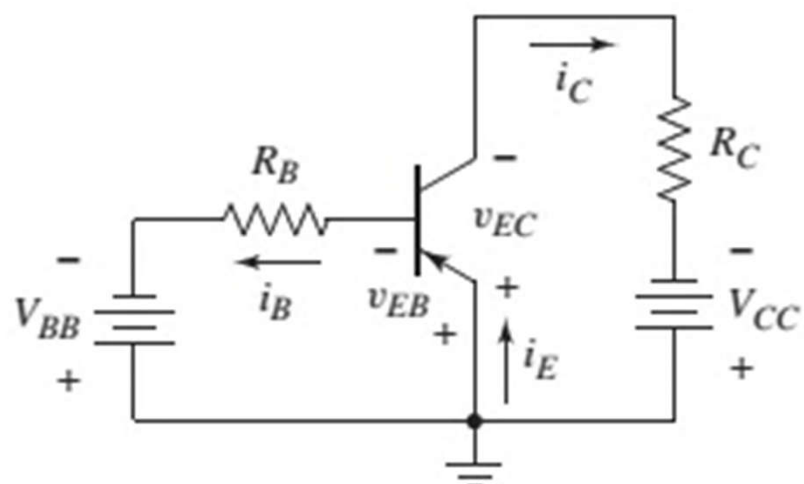
Common emitter amplifier circuit



Common emitter circuits

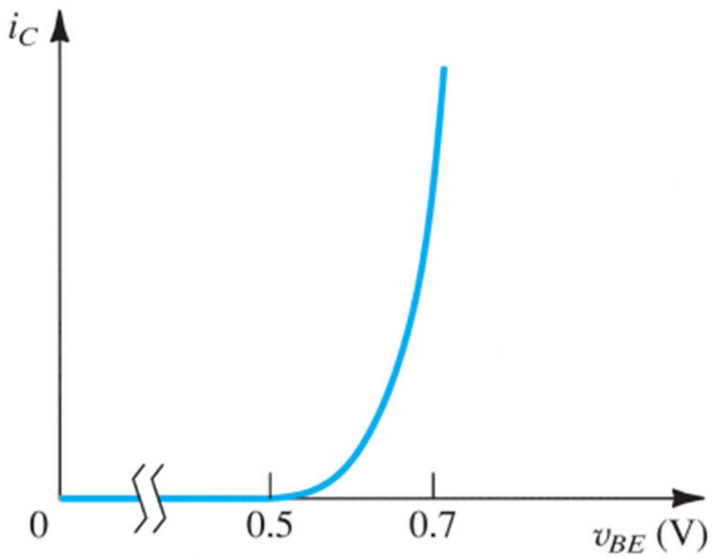


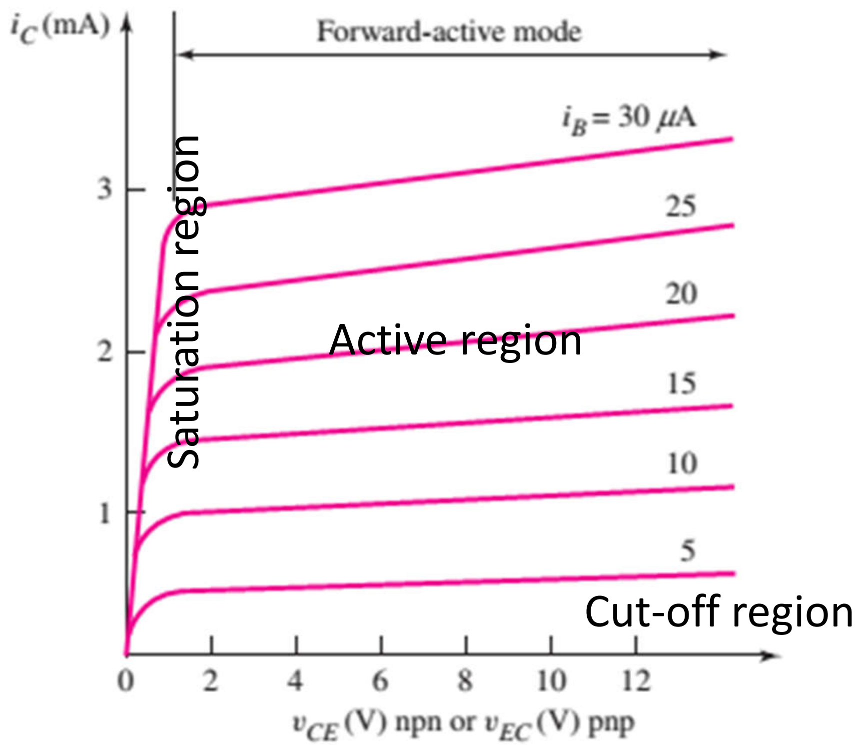
NPN transistor



PNP transistor

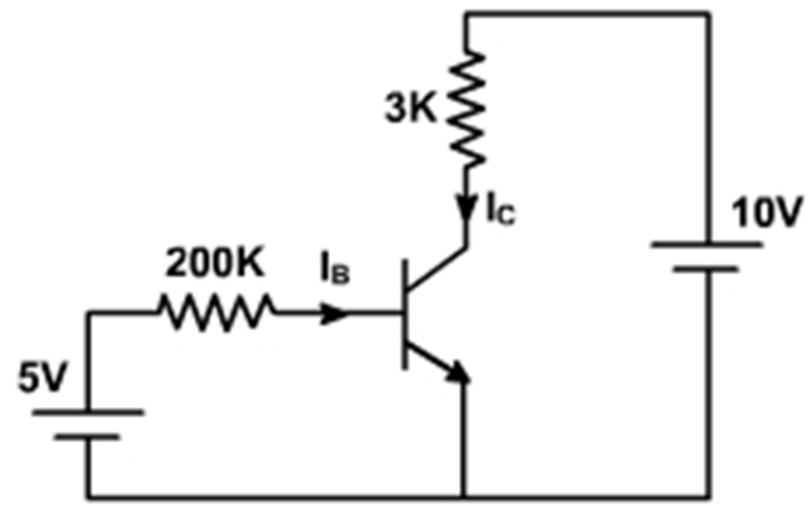
Input and output characteristics of BJT





Find the transistor currents in the circuit shown in fig. if I_{CO}= 20nA, β =100

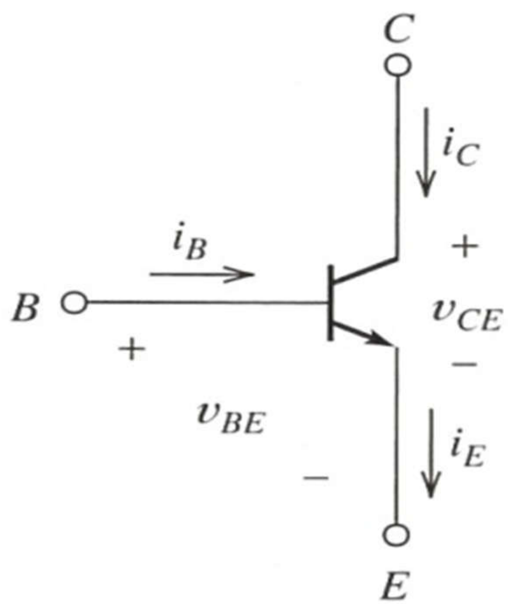
- For the base circuit, 5 = 200 x I_B + 0.7
- Therefore, $I_B = \frac{5-0.7}{200k} = 0.0215\,\text{mA}$
- Since $I_{CO} << I_B$, therefore, $I_C = \beta\, I_B$ = 2.15 mA
- From the collector circuit, V_{CE} = 10 - 3 x 2.15 = 3.55 V
- Since, $V_{CE} = V_{CB} + V_{BE}$
- Thus, V_{CB} = 3.55 - 0.7 = 2.85 V



Problem

Suppose that a certain *npn* transistor has V_{BE} = 0.7 V for I_E =10 mA. Compute V_{BE} for I_E = 1 mA.

Repeat for I_E = 1 µA. Assume that V_T = 26 mV.



$$I_E = I_{ES}\left(\exp\left(\frac{V_{BE}}{V_T}\right)\text{-}1\right) \approx I_{ES}\exp\left(\frac{V_{BE}}{V_T}\right)$$

$$10\,\text{mA}{=}I_{ES}\exp\left(\frac{0.7}{0.026}\right) \quad \textit{and} \quad 1\,\text{mA}{=}I_{ES}\exp\left(\frac{V_{BE}}{0.026}\right)$$

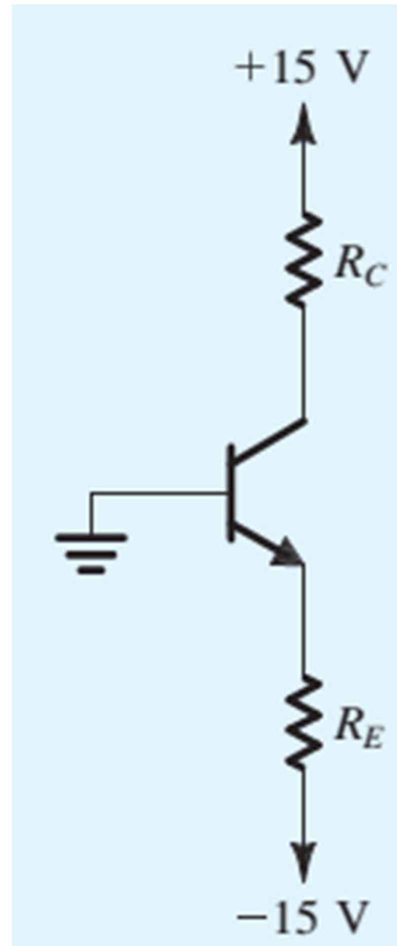
$$\textit{divide the above} \;\Rightarrow\; 10 = \exp\left(\frac{0.7\text{ - }V_{BE}}{0.026}\right)$$

$$\Rightarrow \quad 0.026\times\ln 10 = 0.7 - V_{BE}$$

$$\therefore V_{BE} = 0.7 - 0.026\times\ln 10 = 0.64\,\text{V}$$

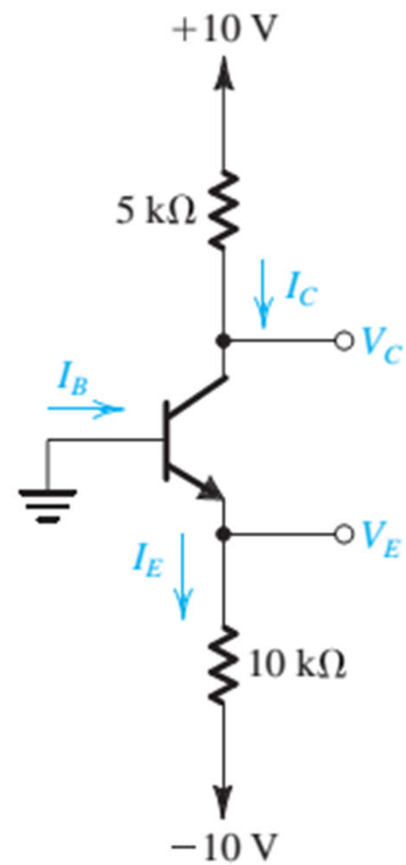
Assignment A.7

- The transistor in the circuit of Fig. has β = 100 and exhibits a v_{BE} of 0.7 V at i_C = 1 mA. Design the circuit so that a current of 2 mA flows through the collector and a voltage of +5 V appears at the collector.



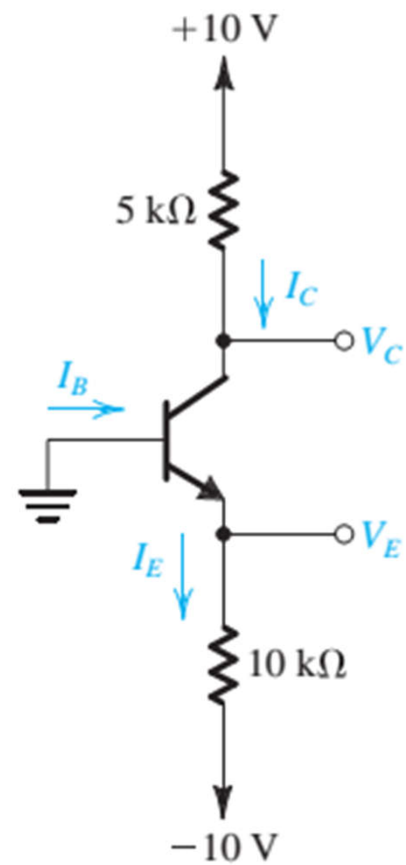
Assignment A.8

- In the circuit shown in Fig., the voltage at the emitter was measured and found to be –0.7 V. If β = 50, find I_E, I_B, I_C, and V_C.



Assignment A.9

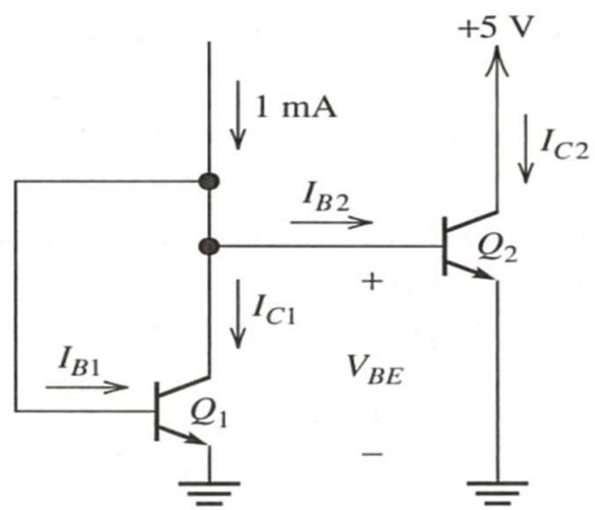
- In the circuit shown in Fig., measurement indicates V_B to be +1.0 V and V_E to be +1.7 V. What are α and β for this transistor? What voltage V_C do you expect at the collector?



Problem

Consider the circuit shown in Figure. Transistors Q_1 and Q_2 are identical, both having $I_{ES} = 10^{-14}A$ and $\beta = 100$. Calculate V_{BE} and I_{C2}. Assume that $V_T = 26mV$ for both transistors.

Hint: Both transistors are operating in the active region.
Because the transistors are identical and have identical values of V_{BE}, their collector currents are equal.



$$I_{B1} + I_{B2} + I_C = 1mA \quad \& \quad I_C = \beta I_B$$

$$\Rightarrow \quad I_C\left(\frac{2}{\beta}+1\right) = 1mA \quad \Rightarrow \quad I_C = \frac{1mA}{1.02} = 0.98\,mA$$

$$I_E = \left(1+\frac{1}{\beta}\right) I_C = 0.99\,mA$$

$$\text{since} \quad I_E \approx I_{ES}\exp\left(\frac{V_{BE}}{V_T}\right) \quad \textit{we have}$$

$$\therefore V_{BE} = V_T \ln\frac{I_E}{I_{ES}} = 0.026 \times \ln\left(0.99\times10^{11}\right) = 0.658\,V$$

Assignment A.10

- Draw circuit diagrams for CC and CB configurations

Transistor Configuration Comparison Chart

AMPLIFIER TYPE	COMMON BASE	COMMON EMITTER	COMMON COLLECTOR
INPUT/OUTPUT PHASE RELATIONSHIP	0°	180°	0°
VOLTAGE GAIN	HIGH	MEDIUM	LOW
CURRENT GAIN	LOW(a)	MEDIUM(b)	HIGH(g)
POWER GAIN	LOW	HIGH	MEDIUM
INPUT RESISTANCE	LOW	MEDIUM	HIGH
OUTPUT RESISTANCE	HIGH	MEDIUM	LOW

List of Semiconductor devices

- Voltage regulator: the voltage across the diode remains fixed
- VARACTOR: VARiable reACTOR, depletion width of the reverse biased pn junction varies with (reverse) voltage, hence depletion capacitance varies. This property is used in tuning radio/TV receivers.
- Tunnel diode: Also called as Esaki diode. Applications are for oscillation, amplification, switching etc.
- Solar cells: Converts optical energy into electrical energy
- Photo diode: Also called as photo detector, detects the presence of light
- Light emitting diode (LED): Emits light when subjected to electrical signal. LEDs emit more directional light.
- LASER: Emits light when subjected to electrical signal. Lasers emit coherent light in much narrower wavelength bands.

Acknowledgments

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