Chapter 16: Semiconductor Devices

EXERCISES [PAGES 363 - 364]

Exercises | Q 1.1 | Page 363

Choose the correct option:
In a BJT, the largest current flow occurs

1. **in the emitter**
2. in the collector
3. in the base
4. through CB junction

SOLUTION

In the emitter

Exercises | Q 1.2 | Page 363

Choose the correct option:
A Series resistance is connected in the Zener diode circuit to

1. **Properly reverse bias the Zener**
2. Protect the Zener
3. properly forward bias the Zener
4. Protect the load resistance

SOLUTION

Properly reverse bias the Zener

Exercises | Q 1.3 | Page 363

Choose the correct option:
A LED emits visible light when its

1. junction is reverse biased
2. depletion region widens
3. **holes and electrons recombine**
4. junction becomes hot

SOLUTION

holes and electrons recombine

Exercises | Q 1.4 | Page 363

Choose the correct option.
Solar cell operates on the principle of:

1. diffusion
2. recombination
3. **photovoltaic action**
4. carrier flow

SOLUTION

Photovoltaic action

Exercises | Q 1.5 | Page 363
Choose the correct option:
A logic gate is an electronic circuit which:

1. **makes logical decisions**
2. allows electron flow only in one direction
3. works using binary algebra
4. alternates between 0 and 1 value

SOLUTION

Makes logical decisions

Exercises | Q 2.1 | Page 363
Answer in brief.
Why is the base of a transistor made thin and is lightly doped?

SOLUTION

The base of a transistor is lightly doped than the emitter and is made narrow so that virtually all the electrons injected from the emitter (in an npn transistor) diffuse right across the base to the collector junction without recombining with holes. That is, the base width is kept less than the recombination distance. Also, the emitter is much heavily doped than the base to improve emitter efficiency and common-base current gain α.

Exercises | Q 2.2 | Page 364
Answer in brief.
How is a Zener diode different than an ordinary diode?

SOLUTION

A Zener diode is heavily doped - the doping concentrations for both p- and n-regions is greater than 10^{18} cm^{-3} while those of an ordinary diode are about 10^{17} cm^{-3} or less. Due to this, the peak inverse voltage (PIV) of an ordinary diode is higher than a Zener diode and the breakdown occurs by impact ionization (avalanche process). Their I-V characteristics are otherwise similar.

Exercises | Q 2.3 | Page 364
Answer in brief.
On which factors does the wavelength of light emitted by a LED depend?

SOLUTION

The intensity of the emitted light is directly proportional to the recombination rate and hence to the diode forward current. The colour of the light emitted by an LED depends on the compound semiconductor material used and its composition (and doping levels) as given below:

Typical semiconductor materials and emitted colours of LEDs

Material	Emitted colour(s)
Gallium arsenide (GaAs), Indium gallium arsenide phosphide (InGaAsP)	Infrared
Aluminum gallium arsenide (AlGaAs)	Deep red, also IR laser
Indium gallium phosphide (InGaP)	Red
Gallium arsenide phosphide (GaAsP), aluminum indium gallium phosphide (AlInGaP)	Orange, red or yellow
Gallium phosphide (GaP)	Green or yellow
Aluminium gallium phosphide (AlGaP), zinc selenide (ZnSe), zinc selenide telluride (ZnSeTe), nitrogen impregnated gallium phosphide (GaP:N)	Green
Indium gallium nitride (InGaN), gallium nitride (GaN), sine sulphide (ZnS)	Blue and violet Longer wave lengths (green and yellow) are obtained by increasing the indium (In) content. Phosphor encapsulation produces white light.
Aluminium gallium nitride (AlGaN)	Ultraviolet

Exercises | Q 2.4 | Page 364

Answer in brief.
Why should a photodiode be operated in reverse biased mode?

SOLUTION

A photodiode is operated in a reverse-biased mode because as a photodetector or photosensor, it must conduct only when radiation is incident on it. In the reverse biased mode, the dark current for zero illumination is negligibly small-of the order of few picoamperes to nanoamperes. But when illuminated, the photocurrent is several orders of magnitude greater.

Exercises | Q 2.5 | Page 364

Answer in brief.
State the principle of solar cells.

SOLUTION

A solar cell is an unbiased pn-junction that converts the energy of sunlight directly into electricity with a high conversion efficiency.

Principle: A solar cell works on the photovoltaic effect in which an emf is produced between the two layers of a pn-junction as a result of irradiation.

Exercises | Q 2.6 | Page 364
Answer in brief.
State the uses of the solar cell.

SOLUTION

Uses of solar cells:

1. A solar cell array consisting of a set of solar cells is used during daylight hours to power electrical equipment as well as to recharge batteries which can then be used during the night.

2. Solar cell arrays provide electrical power to equipment on a satellite as well as at remote places on the Earth where electric power lines are absent.

3. Large-scale solar power generation systems linked with the commercial power grid.

4. Independent power supply systems for radar detectors, monitoring systems, radio relay stations, road lights, and roadsigns.

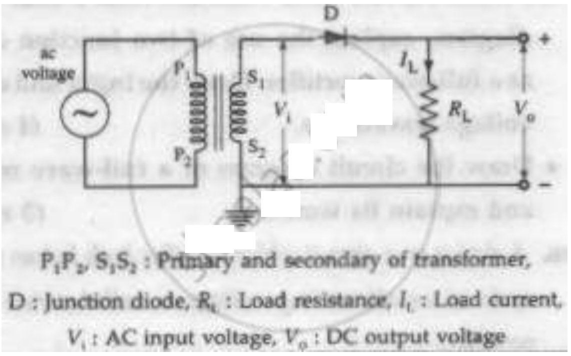
5. Indoor uses include consumer products like, calculators, clocks, digital thermometers, etc. (They use very low levels of power and work under low brightness long-wavelength light from incandescent lamps, etc.)

Exercises | Q 3 | Page 364
Draw the circuit diagram of a half-wave rectifier. Explain its working. What is the frequency of ripple in its output?

SOLUTION

A device or a circuit which rectifies only one-half of each cycle of an alternating voltage is called a half-wave rectifier.

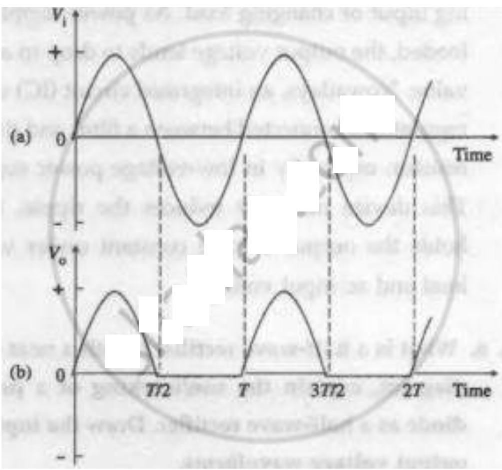
Electric circuit: The alternating voltage to be rectified is applied across the primary coil (P_1P_2) of a transformer. The secondary coil (S_1S_2) of the transformer is connected in series with the junction diode and a load resistance R_L, as shown in the following figure. The alternating voltage across the secondary coil is the ac input voltage V_i. The de voltage across the load resistance is called the output voltage V_0.



Half-wave rectifier circuit

Working: Due to the alternating voltage Vi, the p-region of the diode becomes alternatively positive and negative with respect to the n-region.

During the half-cycle when the p-region is positive, the diode is forward biased and conducts. A current I_L passes through the load resistance R_L in the direction shown.



Voltage waveforms for a half-wave rectifier (a) input (b) output

During the next half-cycle, when the p-region is negative, the diode is reverse biased and the forward current drops to zero.

Thus, the diode conducts only during one-half of the input cycle and thus acts as a half-wave rectifier. The intermittent output voltage V_0 has a fixed polarity but changes periodically with time between zero and a maximum value. I_L is unidirectional. The above figure shows the input and output voltage waveforms. The pulsating de output voltage of a half-wave rectifier has the same frequency as the input

Exercises | Q 4 | Page 364
Why do we need filters in a power supply?

SOLUTION

A rectifier-half-wave or full-wave-outputs a pulsating de which is not directly usable in most electronic circuits. These circuits require something closer to pure de as produced by batteries. Unlike the pure de waveform of a battery, a rectifier output has an ac ripple riding on a de waveform.

The circuit used in a de power supply to remove the ripple is called a filter. A filter circuit can produce a very smooth waveform that approximates the waveform produced by a battery. The most common technique used for filtering is a capacitor connected across the output of a rectifier.

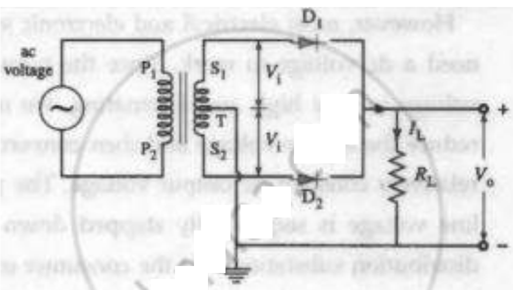
Exercises | Q 5 | Page 364

Draw a neat diagram of a full-wave rectifier and explain it’s working.

SOLUTION

A device or a circuit which rectifies both halves of each cycle of an alternating voltage is called a full-wave rectifier.

Electric circuit: The alternating voltage to be rectified is applied across the primary coil (P_1P_2) of a transformer with a center-tapped secondary coil (S_1S_2). The terminals S_1 and S_2 of the secondary are connected to the two p-regions of two junction diodes D_1 and D_2, respectively. The center-tap Tis connected to the ground. The load resistance RL is connected across the common n-regions and the ground.



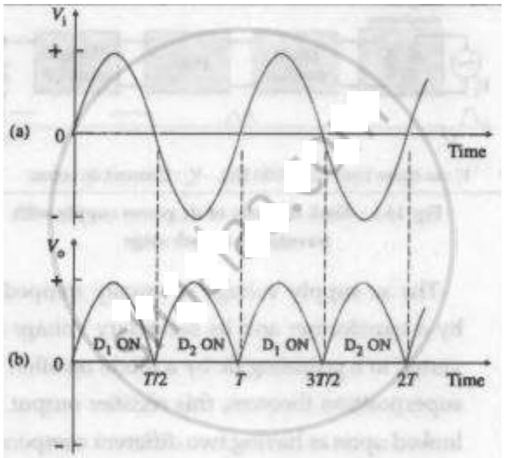
P_1P_2, S_1S_2 : Primary and secondary of transformer, T : Centre-tap on secondary; D_1, D_2 : Junction diodes, R_L : Load resistance, I_L : Load current, V_i : AC input voltage, V_o : DC output voltage

Full-wave rectifier circuit

Working: During the one-half cycle of the input, terminal S_1 of the secondary is positive while S_2 is negative with respect to the ground (the centre-tap T).

During this half cycle, diode D_1 is forward biased and conducts, while diode D_2 is reverse biased and does not conduct.

The direction of current I_L through R_L is in the sense shown.



Voltage waveforms for a full-wave rectifier

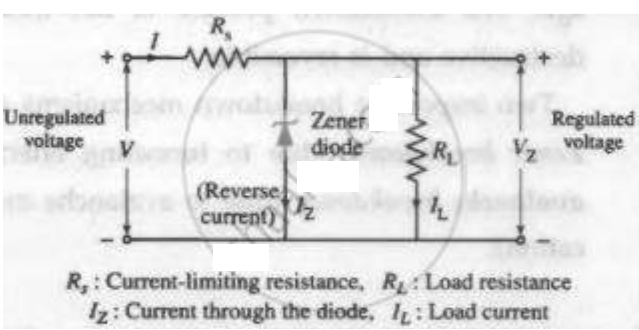
(a) input (b) output

During the next half-cycle of the input voltage, S_2 becomes positive while S, is negative with respect to T. Diode D_2 now conducts sending a current I_L through R_L in the same sense as before. D_1 now does not conduct. Thus, the current through R_L flows in the same direction, i.e., it is unidirectional, for both halves or the full-wave of the input. This is called full-wave rectification. The output voltage has a fixed polarity but varies periodically with the time between zero and a maximum value. The above figure shows the input and output voltage waveforms. The pulsating de output voltage of a full-wave rectifier has twice the frequency of the input.

Exercises | Q 6 | Page 364
Explain how a Zener diode maintains a constant voltage across a load.

SOLUTION

Principle: In the breakdown region of a Zener diode, for widely changing Zener current, the voltage across the Zener diode remains almost constant.



Zener diode as a voltage regulator

Electric circuit: The circuit for regulating or stabilizing the voltage across a load resistance RL against change in load current and supply voltage is shown in the above figure. The Zener diode is connected parallel to load R_L such that the current through the Zener diode is from the n to p region. The series resistance R_s limits the current through the diode below the maximum rated value.

From the circuit, $I = I_z + I_L$

and $V = IR_s + V_z$

$= (I_Z + I_L)R_s + V_Z$

Working: When the input unregulated de voltage V across the Zener diode is greater than the Zener voltage V_z in magnitude, the diode works in the Zener breakdown region. The voltage across the diode and load R_L is then V_z. The corresponding current in the diode is I_z.

As the load current (I) or supply voltage (V) changes, the diode current (I_z) adjusts itself at constant V_z· The excess voltage V- V_z appears across the series resistance · For constant supply voltage, the supply current I and the voltage drop across R_S remain constant. If the diode is within its regulating range, an increase in load current is accompanied by a decrease in I_z at constant V_z.

Since the voltage across R_L remains constant at V_z, the Zener diode acts as a voltage stabilizer or voltage regulator.

Exercises | Q 7 | Page 364

Explain the forward and the reverse characteristic of a Zener diode.

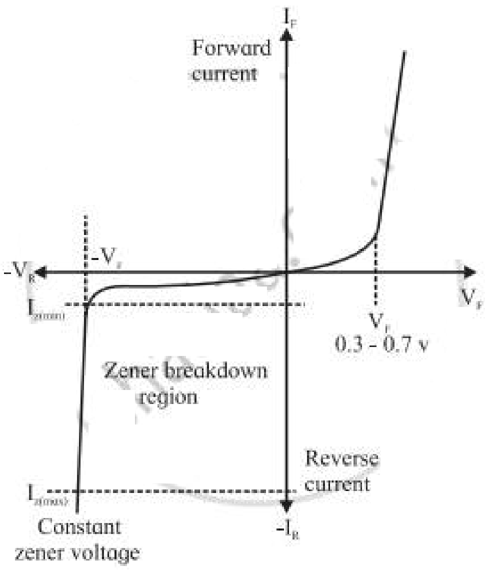
SOLUTION

The forward bias region of a Zener diode is identical to that of a regular diode. There is a forward current only after the barrier potential of the pnjunction is overcome. Beyond this threshold or cut-in voltage, there is an exponential upward swing.
The typical forward voltage at room temperature with a current of around 1 mA is around 0.6 V.

In the reverse bias condition, the Zener diode is an open circuit and only a small reverse saturation current flows as shown with a change of scale. At the reverse breakdown voltage, there is an abrupt rapid increase in the current- the knee is very sharp, followed by an almost vertical increase in current.

The voltage across the Zener diode in the breakdown region is very nearly constant with only a small increase in voltage with increasing current. There is a minimum Zener current, I_z (min), that places the operating point in the desired breakdown region.

At some high current level, I_{ZM}, the power dissipation of the diode becomes excessive beyond which the diode can be damaged.



Zener diode characteristics

The I-V characteristics of a Zener diode is not totally vertical in the breakdown region. This means that for slight changes in current, there will be a small change in the voltage across the diode. The voltage change for a given change in current is the resistance R_Z of the Zener diode.

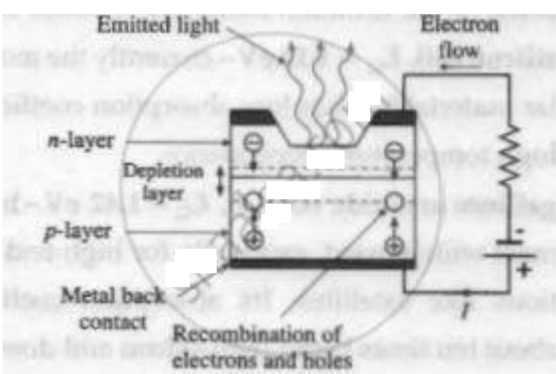
Exercises | Q 8 | Page 364

Explain the working of a LED.

SOLUTION

Working: An LED is forward-biased with about 1.2 V to 3.6 V at 12 mA to 20 mA. Majority carriers electrons from n type layer and holes from the p-type layer are injected into the active layer. Electrons cross the junction into the player.

In the active player, some of these excess minority carriers, electrons, recombine radiatively with majority carriers, holes, thereby emitting photons. The resulting photon has energy approximately equal to the bandgap of the active layer material. Modifying the bandgap of the active layer creates photons of different energies.



Working of an LED

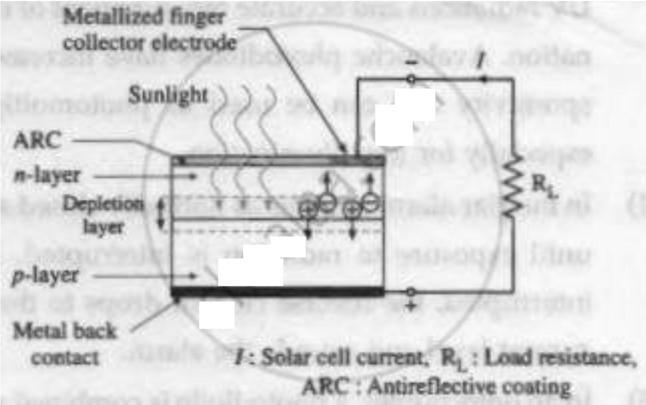
In the energy band diagram, this recombination is equivalent to a transition of the electron from a higher energy state in the conduction band to a lower energy state in the valence band. The energy difference is emitted as a photon of energy hv.

Exercises | Q 9 | Page 364

Explain the construction and working of the solar cell.

SOLUTION

Construction: A simple pn-junction solar cell consists of a p-type semiconductor substrate backed with a metal electrode back contact. A thin n-layer (less than 2.5 μm, for silicon) is grown over the p-type substrate by doping with suitable donor impurity. Metal finger electrodes are prepared on top of the n-layer so that there is enough space between the fingers for sunlight to reach the n-layer and, subsequently, the underlying pn-junction.



Sectional view of a solar cell

Working: When exposed to sunlight, the absorption of incident radiation (in the range near-UV to infrared) creates electron-hole pairs in and near the depletion layer.

Consider light of frequency v incident on the pn-junction such that the incident photon energy hv is greater than the band gap energy E_G of the semiconductor. The photons excite electrons from the valence band to the conduction band, leaving vacancies or holes in the valence band, thus generating electron-hole pairs.

The photogenerated electrons and holes move towards the n side and p side, respectively. If no external load is connected, these photogenerated charges get collected at the two sides of the junction and give rise to a forward photovoltage. In a closed circuit, a current I passes through the external load as long as the solar cell is exposed to sunlight.

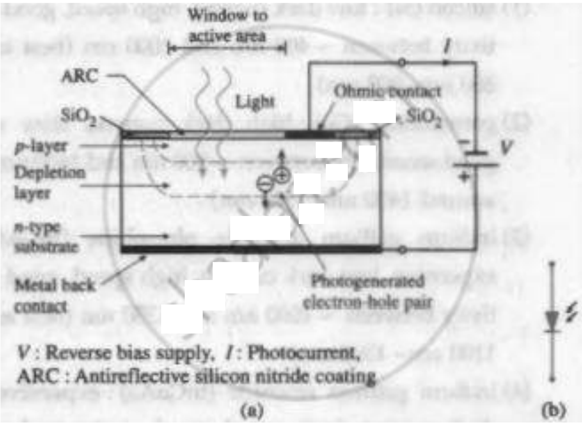
A solar cell module consists of several solar cells connected in series for higher voltage output. For outdoor use with higher power output, these modules are connected in different series and parallel combinations to form a solar cell array.

Exercises | Q 10 | Page 364
Explain the principle of operation of a photodiode.

SOLUTION

Construction: A photodiode consists of an n-type silicon substrate with a metal electrode back contact. A thin p-type layer is grown over the n-type substrate by diffusing a suitable acceptor dopant.

The area of the player defines the photodiode active area. An ohmic contact pad is deposited on the active area. The rest of the active area is left open with a protective anti-reflective coating of silicon nitride to minimize the loss of photons. The nonactive area is covered with an insulating opaque SiO_2 coating.



Depending on the required spectral sensitivity, i.e., the operating wavelength range, typical photodiode materials are silicon, germanium, indium gallium arsenide phosphide (InGaAsP), and indium gallium arsenide (InGaAs), of which silicon is the cheapest while the last two are expensive.

Working: The band gap energy of silicon is E_G = 1.12 eV at room temperature. Thus, photons or particles with energies greater than or equal to 1.12 eV, which corresponds to λ ≤ 10 nm, can transfer electrons from the valence band into the conduction band.

A photodiode is operated in the reverse bias mode which results in a wider depletion region. When operated in the dark (zero illumination), there is a reverse saturation current due solely to the thermally generated minority charge carriers. This is called the dark current. Depending on the minority carrier concentrations, the dark current in an Si photodiode may range from 5 pA to 10 nA.

When exposed to radiation of energy hν ≥ E_G (in the range near-UV to near-IR), electron-hole pairs are created in the depletion region. The electric field in the depletion layer accelerates these photogenerated electrons and holes towards the n side and p side, respectively, constituting a photocurrent I in the external circuit from the p side to the n side. Due to the photogeneration, more charge carriers are available for conduction and the reverse current is increased. The photocurrent is directly proportional to the intensity of the incident light. It is independent of the reverse bias voltage.

1. **silicon (Si):** low dark current, high speed, good sensitivity between ~ 400 nm and 1000 nm (best around 800 nm-900 nm)

2. **germanium (Ge):** high dark current, slow speed, good sensitivity between ~ 900 nm and 1600 nm (best around 1400 nm-1500 nm)

3. **indium gallium arsenide phosphide (In GaAsP):** expensive, low dark current, high speed, good sensitivity between ~1000 nm and 1350 nm (best around 1100 run- 1300 nm)

4. **indium gallium arsenide (In GaAs):** expensive, low dark current, high speed, good sensitivity between ~900 nm and 1700 nm (best around 1300 nm-1600 nm].

Exercises | Q 11.1 | Page 364

What is a logic gate?

SOLUTION

A logic gate is a basic switching circuit used in digital circuits that determines when an input pulse can pass through to the output. It generates a single output from one or more inputs.

Exercises | Q 11.2 | Page 364

What do you mean by a truth table?

SOLUTION

Boolean expression:

An equation expressing a logical compound statement in Boolean algebra is called a Boolean expression. A Boolean expression for a logic gate expresses the relation between input(s) and output of a logic gate.

Exercises | Q 11.3 | Page 364

What do you mean by a Boolean expression?

SOLUTION

The table which shows the truth values of a Boolean expression for a logic gate for all possible combinations of its inputs is called the truth table of the logic gate.

The truth table contains one row for each input combination. Since a logical variable can assume only two possible values, 0 and l, there are 2N combinations of N inputs so that the table has 2N rows.

Exercises | Q 12.1 | Page 364

What is a logic gate?

SOLUTION

A logic gate is a basic switching circuit used in digital circuits that determines when an input pulse can pass through to the output. It generates a single output from one or more inputs.

Exercises | Q 12.2 | Page 364

Write the truth table and Boolean expression for an AND gate.

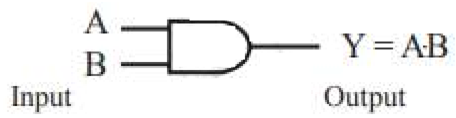
SOLUTION

The AND gate: It is a circuit with two or more inputs and one output in which the output signal is HIGH if and only if all the inputs are HIGH simultaneously.

The AND operation represents a logical multiplication.

The following figure shows the 2-input AND gate logic symbol and the Boolean expression and the truth table for the AND function.

Logic symbol:



Boolean expression: Y = A*B

Truth table:

Inputs		Output Y
A	**B**	
0	0	0
1	0	0
0	1	0
1	1	1

Exercises | Q 13.1 | Page 364

What are the uses of logic gates?

SOLUTION

Explanation/Uses:

Any digital computation process consists of performing a sequence of arithmetical operations on the data of the problem. At each stage in the computation, the nature of the operation to be performed is decided partly by the pre-determined program and partly by the outcome of earlier stages in the process. We therefore need switches with multiple inputs to perform logical operations, i.e., the outputs of these switches are determined in specified ways by the condition (binary state) of their inputs. These arrangements are known as logic gates, and mostly they are an extension of a simple transistor switch.

Exercises | Q 13.2 | Page 364

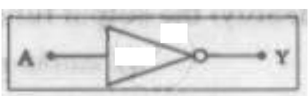
Why is a NOT gate known as an inverter?

SOLUTION

The not gate or Inverter: It is a circuit with one input whose output is high if the input is low and vice versa. The not operation outputs an inverted version of the input. Hence, a not gate is also known as an inverter.

The small invert bubble on the output side of the inverter logic symbol, the following figure, and the over bar ($\overline{}$) in the Boolean expression represent the invert function.

Logic symbol:



Boolean expression: $Y = \overline{A}$

Truth table:

Input A	Output Y
0	1
1	0

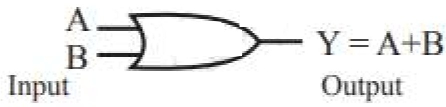
Exercises | Q 14.1 | Page 364

Write the Boolean expressions for an OR gate.

SOLUTION

It is a circuit with two or more inputs and one output in which the output signal is high if any one or more of the inputs is high. The or operation represents a logical addition. The figure shows the 2-input or gale logic symbol, and the Boolean expression, and the truth table for the or function.

Logic symbol:



Boolean expression: Y = A + B

Truth table:

Inputs		Output Y
A	**B**	
0	0	0
1	0	1
0	1	1
1	1	1

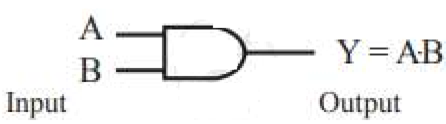
Exercises | Q 14.2 | Page 364

Write the truth table and Boolean expression for an AND gate.

SOLUTION

The AND gate: It is a circuit with two or more inputs and one output in which the output signal is HIGH if and only if all the inputs are HIGH simultaneously.
The AND operation represents a logical multiplication.
The following figure shows the 2-input AND gate logic symbol and the Boolean expression and the truth table for the AND function.

Logic symbol:



Boolean expression: Y = A*B

Truth table:

Inputs		Output Y
A	**B**	
0	0	0
1	0	0
0	1	0
1	1	1

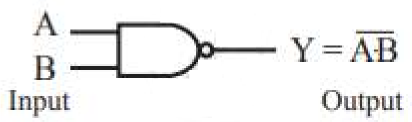
Exercises | Q 14.3 | Page 364

Write the Boolean expressions for a NAND gate.

SOLUTION

It is a circuit with two or more inputs and one output, whose output is high if any one or more of the inputs is low; the output is low if all the inputs are high.

Logic symbol:



Boolean expression: Y = A·B‾

Truth table:

Inputs		Output Y
A	**B**	
0	0	1
1	0	1
0	1	1
1	1	0

The NAND gate is a combination of an AND gate followed by a NOT gate so that the truth table of the NANO function is obtained by inverting the outputs of the AND gate.

Exercises | Q 15 | Page 364
Why are the emitter, the base, and the collector of a BJT doped differently?

SOLUTION

A BJT being a bipolar device, both electrons and holes participate in the conduction process. Under the forward-biased condition, the majority carriers injected from the emitter into the base constitute the largest current component in a BJT. For these carriers to diffuse across the base region with negligible recombination and reach the collector junction, these must overwhelm the majority carriers of the opposite charge in the base.

The total emitter current has two components, that due to majority carriers in the emitter and that due to minority carriers diffused from the base into the emitter. The ratio of the current component due to the injected majority carriers from the emitter to the total emitter current is a measure of the emitter efficiency. To improve the emitter efficiency and the common-base current gain (a), it can be shown that the emitter should be much heavily doped than the base.

Also, the base width is a function of the base-collector voltage. A low doping level of the collector increases the size of the depletion region. This increases the maximum collector-base voltage and reduces the base width. Further, the large depletion region at the collector-base junction-extending mainly into the collector-corresponds to a smaller electric field and avoids avalanche breakdown of the reverse-biased collector-base junction.

[Note: Effective dopant concentrations of (a) npn transistor (b) pnp transistor are shown below.]

The base doping is less than the emitter doping but greater than the collector doping.

Exercises | Q 16 | Page 364

Which method of biasing is used for operating a transistor as an amplifier?

SOLUTION

For use as an amplifier, the transistor should be inactive mode. Therefore, the emitter-base junction is forward biased and the collector-base junction is reverse biased. Also, an amplifier uses an emitter bias rather than a base bias.

Exercises | Q 17 | Page 364

Define α and β. Derive the relation between then.

SOLUTION

The de common-base current ratio or current gain (α_{dc}) is defined as the ratio of the collector current to emitter current.

$$\alpha_{dc} = \frac{I_C}{I_E}$$

The de common-emitter current ratio or current gain (β_{dc}) is defined as the ratio of the collector current to base current.

$$\beta_{dc} = \frac{I_C}{I_B}$$

Since the emitter current $I_E = I_B + I_C$,

$$\frac{I_E}{I_C} = \frac{I_B}{I_C} + 1$$

$$\therefore \frac{1}{\alpha_{dc}} = \frac{1}{\beta_{dc}} + 1$$

Therefore, the common-base current gain in terms of the common-emitter current gain is

$$\alpha dc = \frac{\beta_{dc}}{1 + \beta_{dc}}$$

and the common-emitter current gain in terms of the common-base current gain is

$$\beta_{dc} = \frac{\alpha_{dc}}{1 - \alpha_{dc}}$$

For a transistor, α_{dc} is dose to but always less than 1 (about 0.92 to 0.98) and β_{dc} ranges from 20 to 200 for most general purpose transistors.

Exercises | Q 18 | Page 364

The common-base DC current gain of a transistor is 0.967. If the emitter current is 10mA. What is the value of base current?

SOLUTION

Given:

Current gain (α) = 0.967

Emitter current = 10mA

To Find:

The value of base current of the transistor =?

Solution:

- The common gain DC current us is given by

  $\alpha = 0.967 = \frac{I_C}{I_E} = \frac{I_C}{10}$

  $I_C = 0.967 \times 10$

  $I_C = 9.67mA$

- The base current of the transistor is given by the formula

  $I_E = I_B + I_C$

  $10 = I_B + 9.67$

  $I_B = 0.33mA$

The value of base current of the transistor is 0.33mA

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In a common-base connection, a certain transistor has an emitter current of 10mA and a collector current of 9.8 mA. Calculate the value of the base current.

SOLUTION

Data: I_E = 10 mA, I_C = 9.8 mA

$I_E = I_B + I_C$

Therefore, the base current,

$I_B = I_E + I_C$ = 10 - 9.8 = 0.2 mA

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In a common-base connection, the emitter current is 6.28mA and the collector current is 6.20 mA. Determine the common-base DC current gain.

SOLUTION

Data : I_E = 6.28 mA, I_C = 6.20 mA

$$\alpha_{dc} = \frac{I_C}{I_E} \text{ and } \beta_{dc} = \frac{I_C}{I_B} = \frac{\alpha_{dc}}{1 - \alpha_{dc}}$$

Common-emitter current gain, $\alpha_{dc} = \frac{6.20}{6.28} = 0.9873$

Therefore, common-base current gain,

$$\beta_{dc} = \frac{0.9873}{1 - 0.9873} = \frac{0.9873}{0.0127} = 77.74$$

OR

$I_E = I_B + I_C$

$\therefore I_B = I_E + I_C$ = 6.28 - 6.20 = 0.08 mA

$$\therefore \beta_{dc} = \frac{6.20}{0.08} = 77.5$$