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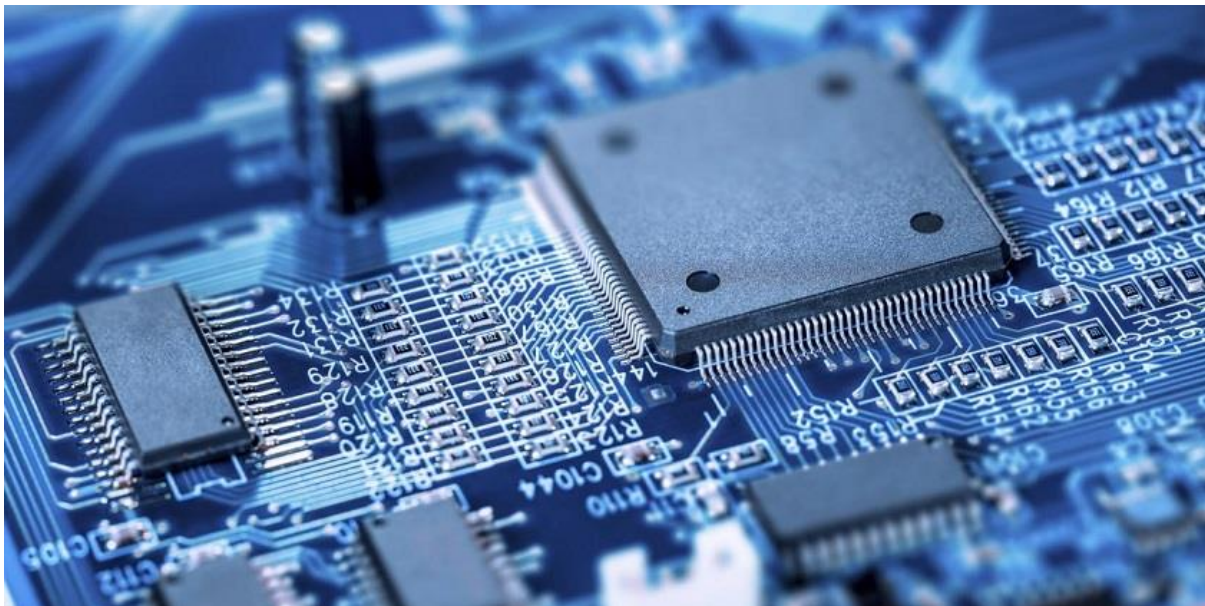
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SENIOR FIVE TERM 3

TOPIC 6/6: DIGITAL ELECTRONICS

Competency: The learner models capacitors for use in electronic devices.

Digital electronics



Digital electronics is a branch of electronics that deals with systems and devices that process and control digital signals, which are represented by discrete values, typically binary (0s and 1s), unlike analog electronics that use continuously varying signals.

This field forms the foundation of modern electronic devices and systems like computers, smartphones, and communication systems, utilizing logic gates and other components to perform calculations and process information.

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Components of digital electronic and their uses

1. Potential divider

A potential divider is any circuit arrangement used to reduce voltage by certain fraction to suit a certain part of the circuit.

For instance, in the circuit Fig. 1 below

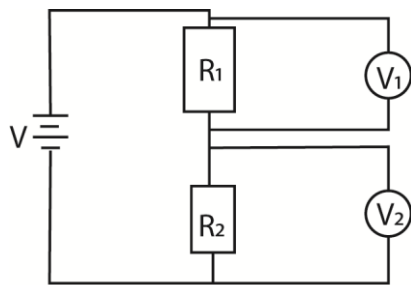


Fig.1

The current through the resistors is the same, therefore the voltage is divided as follows

$$V = \frac{R_1}{R_1 + R_2} V \text{ and } V_2 = \frac{R_2}{R_1 + R_2} V$$

$$\Rightarrow \frac{V_1}{V_2} = \frac{R_1}{R_2}$$

Hence, potential dividers are used to provide specific voltages to certain parts of the circuit in devices from the main voltage. They are used in smartphones, televisions, etc

Example 1.

Find the value of the variable resistor if the bulb is designed to operate at 9V in the Fig 2

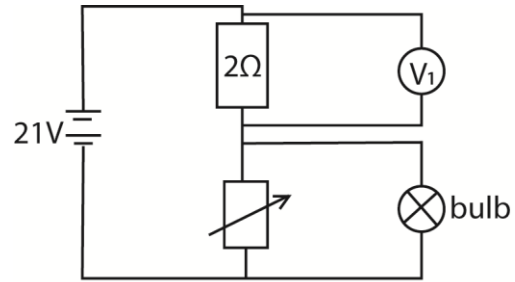


Fig.2

Solution

Let the resistance of the bulb be R

Resultant resistance of the bulb and the variable resistor = $\frac{4R}{R+4}$

Total resistance in the circuit = $\left(\frac{4R}{R+4} + 3\right) \Omega$

Since the variable resistor and the bulb are in parallel each must be at 9V

$$9V = \frac{\frac{4R}{R+4}}{\frac{4R}{R+4} + 2} \times 21$$

$$21 \left(\frac{4R}{R+4}\right) = 9 \left(\frac{4R}{R+4} + 2\right)$$

$$12 \left(\frac{4R}{R+4}\right) = 18$$

$$48R = 18R + 72$$

$$30R = 72$$

$$R = 2.4\Omega$$

Trial 1

Compute the missing value in the following circuits, Fig. 3

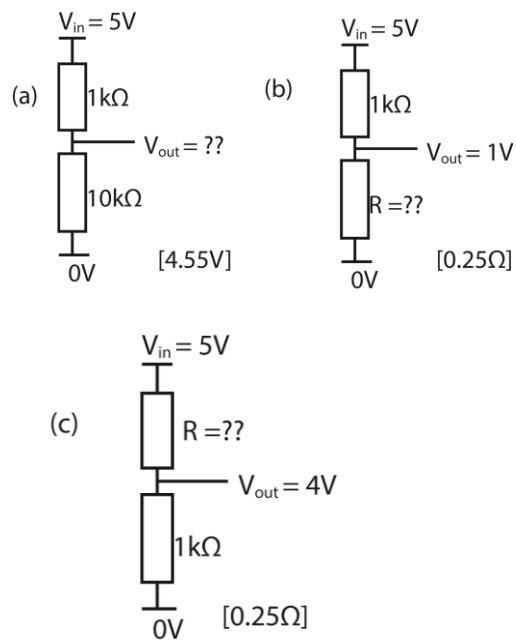


Fig. 3

Applications of potential dividers in electronic devices

- Volume Controls in Audio Devices:** Turning a volume knob usually adjusts a potential divider circuit, changing the voltage sent to an amplifier and controlling sound output smoothly.
- LED Brightness Control:** In some basic circuits, varying the input to an LED through a potential divider can adjust its brightness.
- Sensor Readouts:** Many sensors (like temperature or light sensors) change their resistance. Combined with a fixed resistor, they form a divider that outputs a voltage representing the sensor's reading.
- Biasing Transistors:** In amplifiers and other circuits, potential dividers set the correct base voltage for transistors, ensuring they operate in the right region for amplification.

- Reference Voltages for Comparators:** Comparators compare an input voltage with a reference. That reference is often set using a potential divider to establish precise threshold levels.
- Battery Monitoring:** To safely measure high battery voltages with a microcontroller, a potential divider scales the voltage down to within safe limits for the device's analog inputs.

Binary System

It is the system that uses **1** to represent a true value/ on/high or conducting state and **0** to represent false value/off/low/cut off state in a circuit.

It is used in electronic to formulate and stored data, and in component such as switches and transistors can easily represent these two distinct states (on/off, conducting/cut off) or voltage levels (high/low)..

Logic gates

Logic gates *are* electronic switches. They take one or more input signals, **(0s and 1s)**, and process them **to produce a single binary output** based on specific rules of logic. Logic gates can be represented by symbols or algebraic equations called Boolean algebra.

Logic gates are like the decision-makers of the digital world, flipping switches to make sense of 1s and 0s.

Function of logic gates

1. **Perform Logical Decisions:** They take input values (0s and 1s) and decide the output based on logic rules—just like "if this, then that."
2. **Enable Arithmetic Operations:** By combining a bunch of them it is possible to get adders, subtractors, and even complex arithmetic units inside processors.
3. **Store and Transfer Data:** Using flip-flops (built from gates), they can *store bits* of data—essential for memory, registers, and timing.
4. **Control Signal Flow:** In circuits, they help route signals, acting like intelligent traffic cops directing digital signals to the right destinations.
5. **Build Complex Systems** Everything from microcontrollers to CPUs is constructed using layers and layers of logic gates working together.

Types of logic gates

They are three types of basic logic gates

- An **AND gate** only gives a 1 if *both* inputs are 1.
- An **OR gate** gives a 1 if *at least one* input is 1.
- A **NOT gate** flips the input—turns 1 into 0, and 0 into 1.

Boolean algebra, Symbols and Truth tables of logic gates

Note:

- A truth table represents all possible combinations of inputs in a logic circuit together with their possible outcomes.

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- If n is the number of inputs into a logic circuit, the total possible number of combination of inputs is given by 2^n .

(i) The AND gate

Boolean algebra: The AND gate is also known as the multiplication operation and is represented by dot (.) sign in Boolean algebra of digital logic gates. The logic operation A AND B can be written as $A \cdot B = AB$. Note that $A \cdot B = 1$ if and only if both A and B have value 1.

Circuit symbol of AND gate



Truth table of the AND gate with two inputs

A	B	A.B
1	1	1
1	0	0
0	1	0
0	0	0

Truth table of the AND gate with three inputs

A	B	C	A.B.C
1	1	1	1
1	1	0	0
1	0	1	0
1	0	0	0
0	1	1	0
0	1	0	0
0	0	1	0
0	0	0	0

A	B	C	A.B.C
1	1	1	1
1	1	0	1
1	0	1	1
1	0	0	1
0	1	1	1
0	1	0	1
0	0	1	1
0	0	0	0

(ii) The OR gate

Boolean algebra: The OR gate is also known as the Addition operation and is represented by the plus (+) sign in Boolean Algebra of digital logic gates. The logic operation A OR B is written as $A + B = B + A$. Note that $A + B = 1$ if and only if both A and B each has a value of 1

Circuit symbol of OR gate



Truth table of the OR gate with two inputs

A	B	A+B
1	1	1
1	0	1
0	1	1
0	0	0

Truth table of the OR gate with three inputs

(iii) A NOT gate

Boolean algebra: The logic operation for NOT A is represented as A' or \bar{A} and the circuit diagram is



Other gates

(iv) NAND gate

The Boolean algebra for a NAND gate expresses its logical function, which is the inverse of an AND gate, meaning it outputs a logical "0" only when all inputs are logical "1". For a two-input NAND gate with inputs A and B, the Boolean expression is $Q = \overline{A \cdot B}$ or $(A \cdot B)'$ or $Q = \sim(A * B)$, where the over line or apostrophe denotes the logical negation (NOT) of the AND operation.

Symbol for NAND gate



Truth table of the NAND gate with two inputs

A	B	$(A \cdot B)'$
1	1	0
1	0	1
0	1	1
0	0	1

(v) **NOR gate**

The Boolean expression for a NOR gate represents the logical NOT of the OR operation of its inputs, meaning the output is true (1) only when all inputs are false (0), otherwise the output is false (0). For a 2-input NOR gate with inputs A and B, the Boolean expression is commonly written as $Q = \overline{A + B}$ or $(A + B)'$ or $\sim(A+B)$ where the over line or apostrophe denotes the logical negation (NOT) of the OR operation.

Symbol for NOR gate



Truth table of the NOR gate with two inputs

A	B	$(A+B)'$
1	1	0
1	0	0
0	1	0
0	0	1

Logic circuits

Logic circuits are the **building blocks of digital electronics**. They process binary signals—just 1s and 0s—to perform specific logical operations like AND, OR, and NOT. They are decision-making tools because depending on the input, they produce a certain output.

There are two main types:

1. **Combinational Logic Circuits** These provide outputs based *only* on the current inputs. Examples: adders, multiplexers, encoders, and decoders.
2. **Sequential Logic Circuits** These depend on both current inputs and past inputs (they have memory). Examples: flip-flops, counters, and registers.

Memory circuits in electronics

Memory circuits are the **storage units** of electronic systems—they hold data either temporarily or permanently, depending on their type. For example

1. **RAM (Random Access Memory)**
 - o **Volatile memory**, meaning it loses data when power is off.
 - o Used for temporary storage while a device is running (like keeping apps open on your phone).
2. **ROM (Read-Only Memory)**

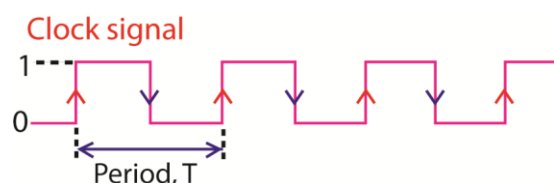
- **Non-volatile**, retaining data even without power.
 - Stores permanent instructions for a device (like firmware that boots your computer).
3. **Flash Memory**
- A kind of non-volatile memory that can be rewritten electronically.
 - Found in USB drives, SSDs, and memory cards.
4. **Registers and Caches**
- Extremely fast, small memory inside CPUs for quick data access.
 - Help speed up processing by minimizing delays.
5. **Flip-Flops and Latches**
- Fundamental building blocks of memory circuits in digital logic.
 - Each stores one bit of data and can be combined into larger structures.

Clock signal

In sequential circuits there are many processes going on; the output of one circuit is the input of other(s). For orderly operations, the inputs and outputs have to be timed. This is done using clock signals

Definition

A **clock signal** is a periodic electric signal that oscillates between high and low states



Clock signals are heartbeats of digital circuits. They synchronize digital circuits,

ensuring that data is processed and transferred at the right time.

Functions of the clock

A clock controls **when** data is moved, stored, or processed in devices like microcontrollers, processors, and memory. Each pulse tells the system, “Now is the time to act!”

Components where timing is required in electronic devices

- **Microprocessors** (keeping all tasks in sync)
- **Flip-flops and counters** (updated on clock edges)
- **Communication circuits** (timing data transmission)
- **Digital watches and timers** (literally counting the seconds)

Clock signal characteristics

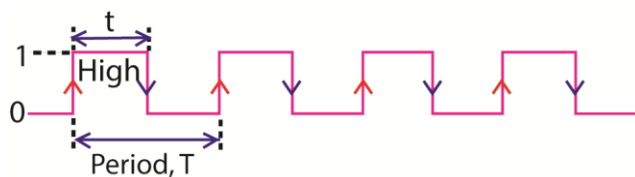
- Clock Signal:** is a repetitive square wave (alternating HIGH and LOW states) used to control the timing of operations in circuits.
- Clock source:** It is where clock signal originates. It can be a port of design or a pin of cell inside the design. It is usually generated by crystal oscillator, phase-locked loop (PLLs) or external clock in some systems
- Clock Pulse:** A single cycle of the clock signal—used to trigger or advance operations in sequential logic like flip-flops or counters.
- Clock Frequency:** The number of clock cycles per second, measured in **Hertz (Hz)**. Higher frequency means faster operations. It determines how often a

clock signal switches between high and low states.

- (v) **Clock Period:** The time it takes for one full clock cycle. It indicates time after which the clock repeats its behaviors. It's the inverse of the frequency (Period = 1/Frequency).
- (vi) **Rising Edge / Falling Edge** Refers to transitions in the clock signal:

- **Rising edge:** LOW → HIGH
- **Falling edge:** HIGH → LOW Many circuits are edge-triggered, meaning they respond only when a specific edge occurs.

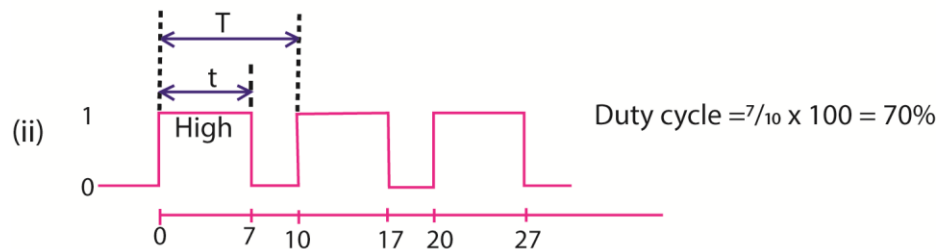
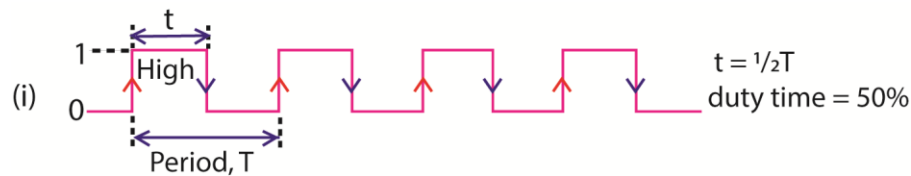
- (vii) **Duty Cycle** The percentage of time the clock signal stays HIGH during each cycle.



In the diagram above duty cycle = $\frac{t}{T} \times 100\%$

Example 2

Calculate the duty time in clock pulses below:



- (viii) **Asynchronous / Synchronous**

Most complex designs require more than one clock. When there are multiple clocks in a design, they would need to interact or share a

relationship. This relationship can be synchronous or asynchronous.

- **Synchronous clock** share a fixed phase relationship, as they are

often derived from the same source.

- **Asynchronous clocks do not share a fixed phase relationship.**

- (ix) **Clock Skew** A small delay difference in clock signals reaching different parts of a circuit. Too much skew can cause timing errors.
- (x) **Clock Divider** A circuit that reduces a high-frequency clock signal into a slower one—used when different parts of a system need different speeds.

Vital clock

Vital clocks are clocks that don't physically exist in the specific block but represent an external trigger that impacts the timing of the clock.

Types of clock pulse

(1) Single Pulse (One-Shot Pulse)

- A solitary high signal generated in response to a trigger.
- Useful for initiating a single action, like flipping a flip-flop once.

(2) Continuous Pulse (Free-Running Clock)

- A regular stream of pulses at a fixed frequency—typical in microprocessors and timers.
- Generated by oscillators, crystals, or clock generator ICs.

(3) Gated Clock

- A clock pulse that can be turned on/off by an enable signal.

- Helps conserve power or coordinate multiple subsystems.

(4) Edge-Triggered Pulse

- Devices respond on either the **rising edge** (LOW to HIGH) or the **falling edge** (HIGH to LOW) of the clock pulse.
- Common in flip-flops and counters.

(5) Duty-Cycled Clock

- The pulse has a specific high/low ratio (e.g. 50% duty cycle for even on/off times).
- Affects timing and energy consumption in circuits.

(6) Variable Frequency Clock

- The frequency of the pulses can change during operation.
- Seen in adaptive systems like dynamic CPU scaling.

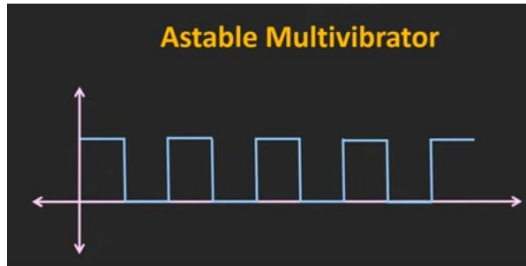
Multivibrators circuits

Multivibrator is circuit in electronics used to generate and manipulate signals. It is like the rhythm section in a band—providing beats or holding a state until the next cue.

There are three main types, each with a unique personality:

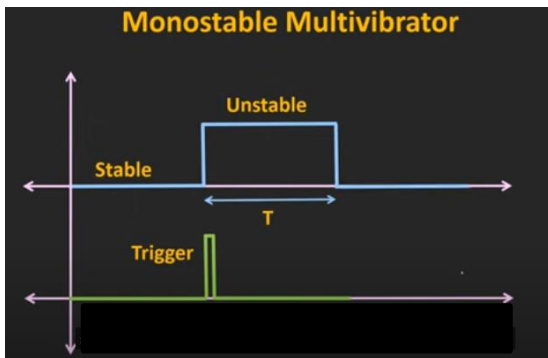
1. **Astable multivibrator** is a free-running multivibrator that has NO stable state but switches continuously between two states; this action produces a train of square pulses at a fixed known frequency. The time for which the output remains in a particular state can be decided by

passive components like a resistor and a capacitor. It is like a blinking light that never stops—it's always on the move.



Used for: generating square waves, LED flashers, clock signals.

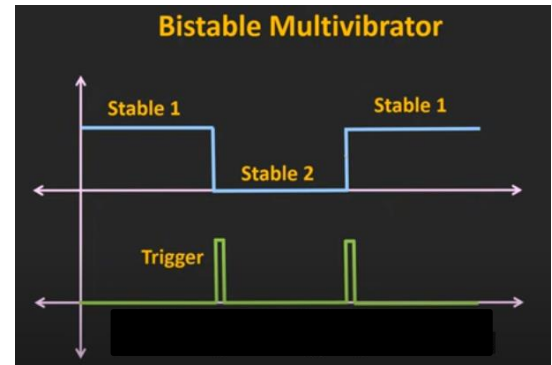
2. **Monostable Multivibrator** is a one shot multivibrator that has only ONE stable state and one temporary state. Once externally triggered it returns to its first stable state



Used for: timers, pulse stretching, delay circuits. For instance, a camera flash: press the button (trigger) → bright flash (temporary state) → back to normal.

3. Bistable Multivibrator

Bistable multivibrator has two stable states; it toggles between them when triggered.



Used for: memory storage, flip-flops, switch debouncing. This is the basis for storing binary data—just a fancy way of saying ON or OFF.

Classification of substances as conductors, insulators and semi-conductors in terms of energy band gaps

An energy band gap (or bandgap) is a forbidden energy range in a solid where no electron states exist, separating the filled **valence band** (where electrons are bound) from the empty **conduction band** (where electrons can move freely). It's the minimum energy an electron needs to jump from the valence band to the conduction band, determining if a material is a conductor (no gap), semiconductor (small gap), or insulator (large gap)

- **Conductors (Metals):** Have no band gap; the valence and conduction bands overlap, allowing electrons to move freely.
- **Semiconductors (e.g., Silicon):** Have a small, finite band gap, meaning electrons can jump to the conduction band with some energy (heat, light).

- **Insulators (e.g., Glass):** Have a very large band gap, making it extremely difficult for electrons to jump to the conduction band, hence poor conductivity.

How semiconductors conduct electricity.

Silicon and germanium for example are tetravalent. They have four electrons in their outermost shell, called valence electrons. One valence electron is shared with each of four surrounding atoms in a tetrahedral arrangement, forming 'covalent bonds' which maintain the crystalline solid structure. Fig. 4 is a two-dimensional representation of the silicon structure.

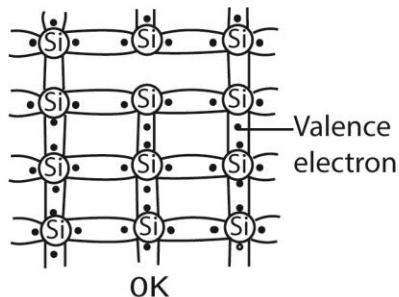


Fig. 4: Two dimensional structure of silicon

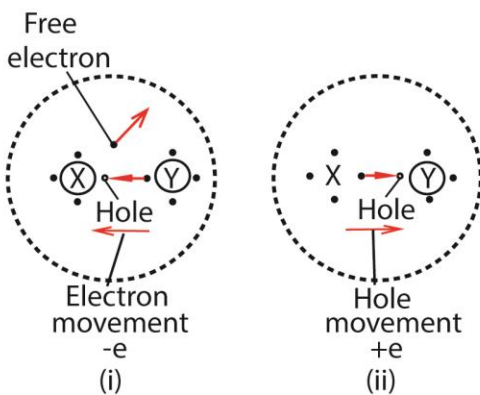


Fig. 5 Semiconductor: Electron (-) and hole (+) movement

At 0 K, all the valence electrons are firmly bound to the nucleus of their particular atom. At room temperature, however, the thermal energy of a valence electron may become greater than the energy binding it to its nucleus. The covalent bond is then broken. The electron leaves the atom, X say, and becomes a free electron. This leaves X with a vacancy or hole. Fig. 5 (i). Since X now has a net positive charge, an electron in a neighboring atom may then be attracted. Thus the hole appears to move to Y.

The hole movement through a semiconductor is random. But if a battery is connected, the valence electrons are urged to move in one direction and to fill the holes. The holes then drift in the direction of the field. Thus the holes move as if they were carriers with a positive charge $+e$, where e is the numerical value of the charge on an electron. Fig. 5 (ii). The current in the semiconductor is also carried by the free electrons present. These are equal in number to the holes in a pure semiconductor and drift in the opposite directions since they are negative charges. The mobility of an electron, its average velocity per unit electric field intensity, is usually much greater than that of a hole.

It should be noted that, in a pure semiconductor, there are equal numbers of electrons and holes. Electron-hole pairs are said to be produced by the movement of an electron from bound state in an atom to a

higher energy level, where it becomes a free electron.

Effect of temperature on resistance of conductors and semiconductors

For conductors; increase in temperature increases the resistance because it increases the vibrations of atoms that impede movement of electrons.

For nonconductors, increase in temperature decreases the resistance because it breaks the covalent bonds to produce more electron-hole pairs that act as carriers of current.

Doping of semiconductors

It is an intentional introduction of impurity atoms (dopants) into pure (intrinsic) semiconductors (silicon or germanium) in order to increase and control their conductivity.

Doping Method

It is done via thermal diffusion in a furnace, by introducing dopant gases like Boron tribromide or Phosphoryl chloride.

N-Type Semiconductor Formation (Negative)

Dopant Type: Pentavalent impurities (Group 15 elements like Phosphorus (P), Arsenic (As), Antimony (Sb))

Mechanism: A pentavalent atom replaces a silicon atom, forming four bonds with neighbors, but has one extra valence electron.

Result: This extra electron is loosely bound and easily moves into the conduction band, becoming a free charge carrier.

Majority Carriers: Electrons (negative).

N-type semiconductors offer advantages like **higher conductivity** due to abundant free electrons, enabling faster current flow, making them great for digital electronics like transistors and diodes.

P-Type Semiconductor Formation (Positive)

Dopant Type: Trivalent impurities (Group 13 elements like Boron (B), Aluminum (Al), Gallium (Ga)).

Mechanism: A trivalent atom replaces a silicon atom, forming only three bonds, leaving a missing electron in the fourth bond, known as a "hole".

Result: Nearby electrons jump into this hole, effectively making the hole move, behaving like a positive charge carrier.

Majority Carriers: Holes (positive).

P-N Junction

It is made by fusing p- and n-semiconductors to form a boundary or junction between them.

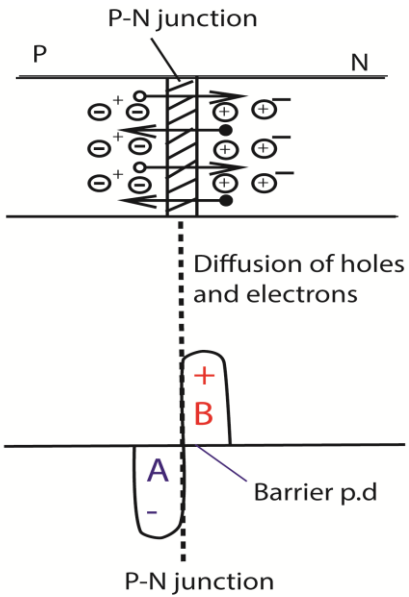


Fig. 6. P – N junction and barrier p.d

During the process of junction formation, the high concentration of holes (positive charges) on one side of a p-n junction, and the high concentration of electrons on the other side, causes the two carriers to diffuse respectively to the other side of the junction, as shown in Fig. 6

The electrons which move to the p-semiconductor side recombine with holes there. These holes therefore disappear, and an excess negative charge A appears on this side as shown in figure (ii).

In a similar way, an excess positive charge B builds up in the n- semiconductor when holes diffuse across the junction.

Together with the negative charge A on the p-side, an e.m.f. or p.d. is produced which opposes the diffusion of charges across the junction. This is called a barrier p.d. and when the flow ceases it has a magnitude of a few tenths of a volt.

Junction Diode

When a battery B, with an e.m.f greater than the barrier p.d., is joined with its positive pole to the p-semiconductor, P, and its negative pole to the n-semiconductor, N, p-charges (holes) are urged across the p-n junction from P to N and n-charges (electrons) from N to P. Fig. 7 (i) below. Thus an appreciable current is obtained. The p-n junction is now said to be forward-biased, and when the applied p.d. is increased, the current increases.

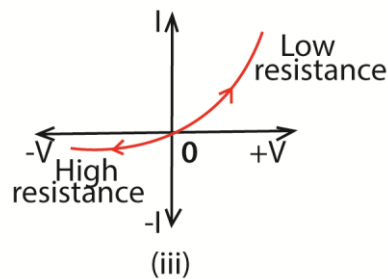
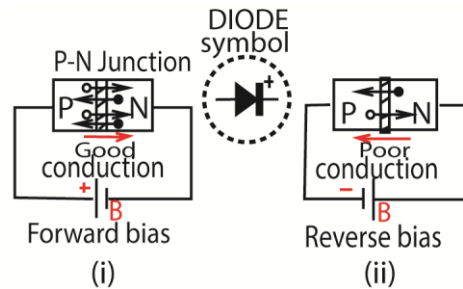


Fig. 7. Junction diode characteristic

When the poles of the battery are reversed only a very small current flows as shown in Fig. 7. (ii) above. In this case the p-n junction is said to be reverse-biased. This time only the minority carriers, negative charges in the p-semiconductor and positive charges in the n-semiconductor, are urged across the p-n junction by the battery. Since the minority carriers are thermally-generated, the magnitude of the reverse current depends only on the temperature of the semiconductors.

It can now be seen that the p-n junction acts as a **rectifier**. It has a low resistance for one direction of p.d. and a high resistance for the opposite direction, as shown by the characteristic curve in Fig. 7(iii).

It is therefore called a junction diode.

Advantages of Junction diode over diode valve

- (i) It low voltage battery B to function.
- (ii) It does not need time to warm up
- (iii) It less bulky
- (iv) Cheaper to manufactures

On this account, the junction diode has replaced the diode valve in receivers.

Characteristics of Junction diodes

- (i) **Unidirectional Current**
Flow: Conducts current primarily in one direction (Anode to Cathode) and blocks it in the opposite.
- (ii) **Anode & Cathode:** Two terminals; the arrow in the symbol points from the positive anode to the negative cathode.
- (iii) **Forward Bias:** When positive voltage is applied to the anode, current flows easily (low resistance) after overcoming a small threshold voltage (e.g., ~0.7V for silicon).
- (iv) **Reverse Bias:** When negative voltage is applied to the anode, the diode acts as an insulator (high resistance), blocking current.
- (v) **Forward Voltage Drop (V_f):** The small, relatively constant voltage drop across the diode when conducting forward current (e.g., 0.7V for silicon, 0.3V for germanium).

- (vi) **Reverse Breakdown:** If reverse voltage exceeds a specific limit (Peak Inverse Voltage - PIV), the diode breaks down, allowing large reverse current, potentially damaging it.
- (vii) **I-V Curve:** A graph showing current (y-axis) vs. voltage (x-axis), illustrating the sharp turn-on in forward bias and the blocking/breakdown in reverse bias.

Zener Diode

In Zener diodes both forward and reverse biases cause an increase in conduction across a p-n junction as shown in the Fig. 8 (i) below.

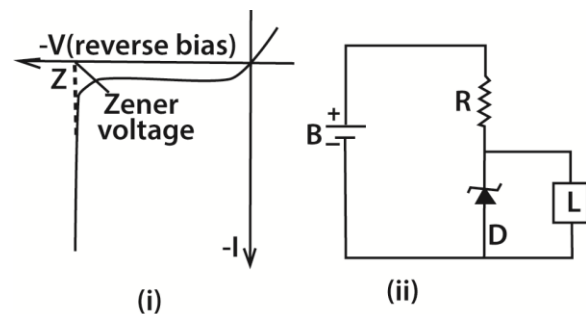


Fig. 8. Zener diode and voltage regulation

The increase in conduction of reverse bias (Zener effect, after the discoverer) is partly due to the high electric field which exists across the narrow p-n junction at the breakdown or Zener voltage Z , which drags more electrons from their atoms and thus increases considerably the number of electron-hole pairs. Ionization by collision also contributes to the increase in carriers.

Zener diodes are used as voltage regulators or stabilizers in circuits. In Fig. 8. (ii), a suitable diode D is placed across a circuit L . Although the battery supply B may fluctuate, and produce changes of current in L and D , if R is suitably chosen, the

voltage across D remains practically constant over a reverse current range of tens of milliamperes at the Zener voltage. The voltage across L thus remains stable.

Applications by Diode Type

- (i) **Rectifier Diodes:** Convert alternating current (AC) to direct current (DC) in power supplies, battery chargers, and automotive alternators.
- (ii) **Zener Diodes:** Maintain a constant voltage, protecting circuits from overvoltage and providing stable reference voltages.
- (iii) **Light-Emitting Diodes (LEDs):** Produce light for indicators, displays, and general illumination; also used in laser diodes for pointers, scanners, and optical communication.
- (iv) **Photodiodes:** Detect light, used in light sensors, solar cells, and optical receivers.
- (v) **Switching Diodes:** Enable rapid switching in digital circuits, logic gates (AND, OR, NOT), and high-frequency applications.
- (vi) **Varactor/Variable Capacitance Diodes:** Used in voltage-controlled tuning circuits, like in radios.

General Functions of diodes

- (i) **Power Conversion:** Rectifying AC to DC for electronics.
- (ii) **Protection:** Preventing current from flowing the wrong way (reverse polarity).
- (iii) **Signal Processing:** Demodulating radio signals to extract audio/data.
- (iv) **Sensing:** Detecting light, temperature, or other physical changes.

The Transistor

The transistor is a current amplifier. A transistor is made from three layers of p- and n-semiconductors. They are called respectively the emitter (E), base (B) and collector (C). Fig. 9. (i) illustrates a p-n-p transistor, with electrodes connected to the respective three layers.

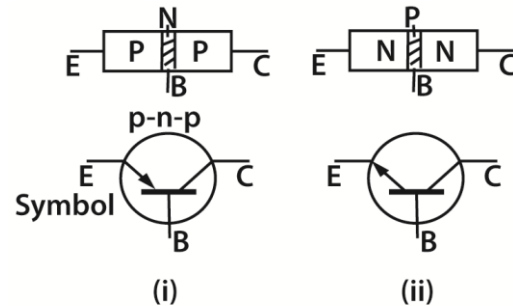


Fig. 9. Transistor symbols

In n-p-n transistor, the emitter is n-type, the base is p-type and the collector is n-type. Fig. 9. (ii). The base is deliberately made very thin in manufacture.

The transistor, like the triode valve, is thus a three-terminal device. Fig. 9.(i) and (ii) shows the circuit symbols for p-n-p and n-p-n transistors respectively. In an actual transistor, the collector terminal is displaced more than the others for recognition or has a dot near it.

Common-Base. (C-B) Arrangement

The transistor may be regarded as two p-n junctions back-to-back. Fig. 41.24 (i) shows batteries correctly connected to a p-n-p transistor. The emitter-base is forward-biased; the collector-base is reverse-biased; and the base is common. This is called the common-base (C-B) mode of using a transistor. Note carefully the polarities of the two batteries. The positive pole of the supply voltage X is joined to the emitter E but the negative pole of the supply voltage Y is joined to the collector C.

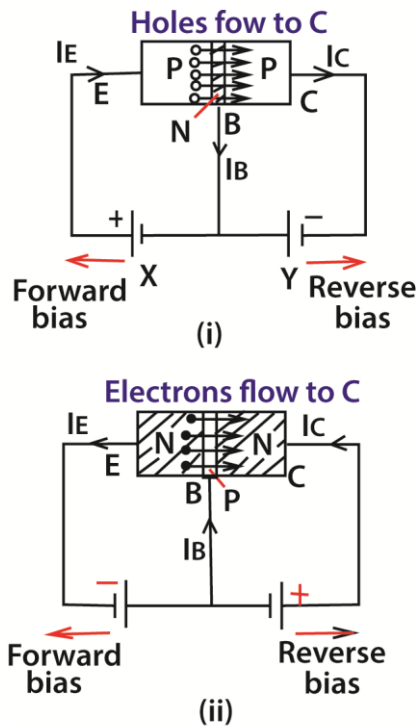


Fig. 10. Transistor in action

If batteries are connected the wrong way round to a transistor the latter may be seriously damaged. In the case of a n-p-n transistor, therefore, the negative pole of one battery is joined to the emitter and the positive pole of the other is joined to the collector. Fig. 10. (ii).

Consider Fig. 10. (i). Here the emitter-base is forward biased by X, so that positive charges or holes flow across the junction from E to the base B. The base is so thin, however, that the great majority of the holes are urged across the base to the collector by the battery Y. Thus a current I_C flows in the collector circuit. The remainder of the holes flow in the base circuit, so that a small current I_B is obtained here. From Kirchhoff's first law, it follows that, if I_E is the emitter current,

$$I_E = I_C + I_B$$

Typical values for a.f. amplifier transistors are:

$$I_E = 1.0 \text{ mA}, I_C = 0.98 \text{ mA}, I_B = 0.02 \text{ mA}.$$

Although the action of n-p-n transistors is similar in principle to p-n-p transistors, the carriers of the current in the former case are mainly electrons and in the latter case holes. Electrons are more speedy carriers than holes. Thus n-p-n transistors are used in high-frequency circuits, where the carriers are required to respond very quickly to signals.

Common-Base Characteristics

The behaviour of a particular transistor in the common-base arrangement can be obtained from its characteristic curves. Fig. 11 shows a circuit for determining the curves. V_{CC} represents the supply voltage, for example 9 V; A_1, A_2 are current measuring instruments; V are voltmeters; and the two potentiometers of 1 megohm and 50 kilohm are used to vary the input or emitter current, I_E .

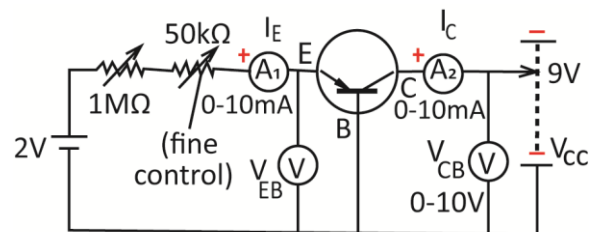


Fig. 11. Common base characteristic investigation

The more important curves are:

- (i) Output characteristics (I_C v. V_{CB} , with I_E constant),
- (ii) input characteristics (I_E v. V_{EB} , with V_{CB} constant),
- (iii) transfer characteristics (I_C v. I_E , with V_{CB} constant). Are shown below

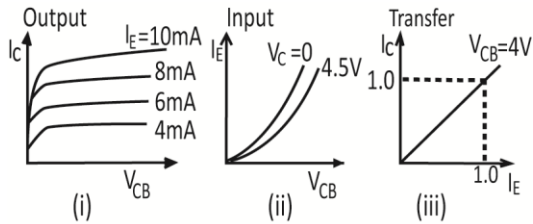


Fig. 12. C-B characteristic

Typical results are shown in Fig. 12. (i), (ii), (iii).

- The flat output characteristics in Fig. 12 (i) show that the output resistance, $\Delta V_{CB} / \Delta I_E$ is high.
- The input resistance, $\Delta V_{EB} / \Delta I_E$, varies with the slope of the curve in 12. (ii) and is generally low.
- From the straight line graph of the transfer characteristic in Fig. 12(iii), it follows that a linear relation exists between I_C and I_E .

Common-Emitter (C-E) Arrangement

The slope of the transfer characteristic in Fig. 12 (iii) provides the current gain of the transistor, $\Delta I_C / \Delta I_E$. It is practically 1, showing that the common-base arrangement is unsuitable for current amplification. Now in a typical transistor, as already seen, $I_C = 0.98$ mA and $I_B = 0.02$ mA. Thus I_C is 49 times as large as I_B and a similar order of magnitude for current gain occurs with changes in I_B . On this account the common-emitter (or grounded-emitter) arrangement is widely used in a.f. amplifiers. Fig. 13 shows a circuit for determining the output characteristics, input characteristics and transfer characteristic in the common-emitter (C-E) arrangement.

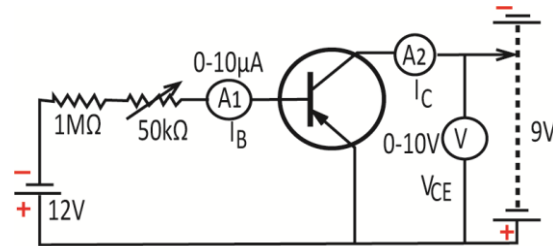


Fig.13. Common-emitter characteristic investigation

The results are shown in Fig. 14 (i), (ii), (iii).

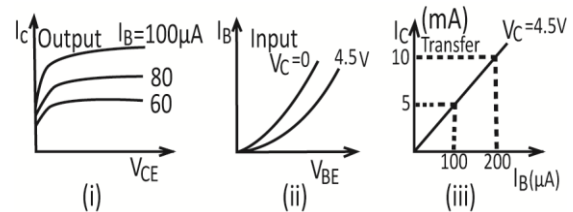


Fig. 14. C-E characteristics

Output characteristic: Since the knee of the curve occurs at a low voltage of the order of 1 V, only low battery supply voltages are needed to operate a transistor in the linear region beyond the knee. This is an advantage of the transistor compared with the valve. Further, the small slope of the straight line shows that the output resistance is high. Thus although the load in the collector circuit may vary, the collector current is constant for a given alternating input or base current. Hence the transistor can be considered as a constant current generator in circuitry, whereas the triode valve is treated as a constant voltage generator with a given input

Transfer characteristic: The output current I_C varies fairly linearly with the input current I_B . The current gain, denoted by β , is the ratio $\Delta I_C / \Delta I_B$, V_C constant. From Fig. 14 (iii), $\beta = (10-5) \text{ mA} / (200-100) \mu\text{A} = 50$. The reader should note that 'current amplification' usually refers to variations in current in amplifier circuit analysis. The

ratio I_C/I_B provides the d.c. current amplification.

Input characteristic: The input resistance, r_i , is the ratio $\Delta V_{BE}/\Delta I_B$ with V_C constant. It varies at different points of the curve and has a medium value such as 10000 or 1 k Ω .

Relation between Current Gain in C-E and C-B Arrangements

In the C-B arrangement, the current gain is denoted by α and is the ratio $\Delta I_C/\Delta I_E$. In the C-E arrangement, the current gain is denoted by β and is the ratio $\Delta I_C/\Delta I_B$.

Since, $I_E = I_C + I_B$, hence $\Delta I_E = \Delta I_C + \Delta I_B$. Using $\Delta I_C/\Delta I_B = \beta$, then $\Delta I_B = \Delta I_C/\beta$. Thus, by substitution for $\Delta I_E = \Delta I_C + \Delta I_B$,

$$\Delta I_E = \Delta I_C + \frac{\Delta I_C}{\beta}$$

$$\therefore \frac{\Delta I_E}{\Delta I_C} = \frac{1}{\alpha} = 1 + \frac{1}{\beta}$$

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

$$\beta = \frac{\alpha}{1-\alpha} \dots\dots\dots(i)$$

If $\alpha = 0.98$, then $\beta = \frac{0.98}{0.02} = 49$ from (i)

Leakage Current

When the base current I_B is zero, some current still flows in the collector circuit in the common-emitter arrangement. This is due to the minority carriers present in the collector-base part of the transistor, which is reverse-biased. The collector current when I_B is zero is denoted by I_{CEO} and is called the **leakage current**.

In the common-base arrangement, the leakage current obtained when I_E is zero is denoted by I_{CBO} . This is also due to minority

carriers in the collector-base, which is reverse-biased. Thus the leakage current flows when a transistor is in the C-E or C-B arrangement.

Since the current gain in the C-E arrangement is the ratio $\Delta I_C/\Delta I_B$, with the usual notation, it follows that, generally,

$$I_C = \beta I_B + I_{CEO} \dots\dots\dots(i)$$

Similarly

$$I_C = \alpha I_E + I_{CBO} \dots\dots\dots(ii)$$

Now any change in I_{CEO} or minority carriers is magnified β times in the C-E arrangement, since I_{CEO} also flows in the base-emitter circuit when the transistor is operating. A temperature change from 25°C to 45°C, which would increase the current I_{CEO} by 10 μA say, would thus be amplified to about 49 x 10 μA or 490 μA , if β is 49. This increase in current, nearly 0.5 mA, would have a considerable effect on the output in the collector circuit, and it would lead to a distorted output, for example.

On the other hand, $\alpha = 0.98$ for the same transistor. Thus in the C-B arrangement, a similar temperature rise and current increase of 10 μA would produce a change in 0.98 x 10 μA , or nearly 10 μA , in the output or collector circuit. This is only a very small change compared to the C-E case. On this account the C-E arrangement, which is very sensitive to temperature change, must be stabilized for excessive temperature rise. Silicon transistors are much less sensitive to temperature change than germanium transistors and are hence becoming used more widely.

Simple C-E Amplifier Circuit

Fig. 15 shows a p-n-p transistor in a simple or basic C-E arrangement. It uses one battery supply, V_{CC} . A load, R_L , is placed in the collector or output circuit. A resistor R provides the necessary bias, V_{BE} , for the base-emitter circuit.

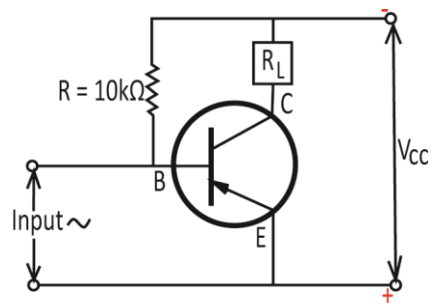


Fig. 15. Simple amplifier

The base-emitter is then forward-biased but the collector-base is reverse-biased, that is, the potential of B is negative relative to E but positive relative to C.

Suppose a small signal is applied, so that the base current changes by an amount ΔI_B . Then I_C changes by $\beta \Delta I_B$.

$$\therefore \text{voltage gain} = \frac{\text{output voltage}}{\text{input voltage}} = \frac{\beta \Delta I_B \cdot R_L}{V_i}$$

$$= \frac{\beta \Delta I_B \cdot R_L}{\Delta I_B \cdot r_i} \text{ where } r_i \text{ is input}$$

resistance or resistance to a.c between base-emitter.

$$= \frac{\beta \cdot R_L}{r_i}$$

If $\beta = 49$, $R_L = 4700 \Omega$, $r_i = 1000 \Omega$, the voltage gain = $49 \times 4.7 = 230$ (approx.).

C-E Amplifier Circuit

In practice, Fig. 15 is unsuitable as an amplifier circuit since there is no arrangement for temperature stabilization. A more reliable C-E a.f amplifier circuit is shown in Fig. 16. Its principal features are:

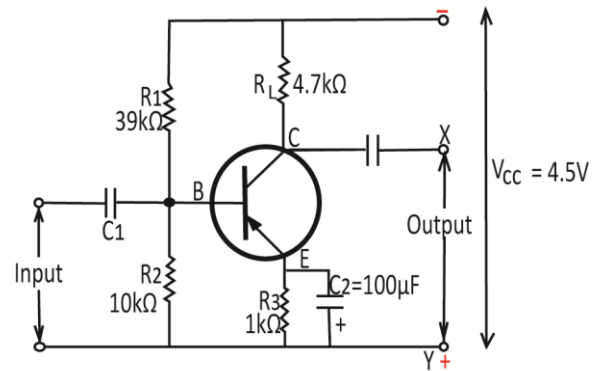


Fig. 16. Simple amplifier

- (i) $V_{CC} = 4.5V$ a potential divider arrangement, R_1 , R_2 , which provides the necessary base-bias;
- (ii) a load R_L which produces the output across X, Y;
- (iii) a capacitor C_1 which isolates the d.c. component in the input signal from the circuit ;
- (iv) a large capacitor C_2 across a resistor R_3 , which prevents undesirable feedback of the amplified signal to the base-emitter circuit;
- (v) an emitter resistance R_3 , which stabilizes the circuit for excessive temperature rise. Thus if the collector current rises, the current through R_3 increases. This lowers the p.d. between E and B, so that the collector current is automatically lowered.

Transistor Oscillator Circuit

Like the triode valve, a transistor can be arranged to provide 'positive feedback' to an oscillatory (L-C) circuit. Oscillations in the L-C circuit can thus be maintained.

Fig. 17 shows one form of transistor oscillator circuit.

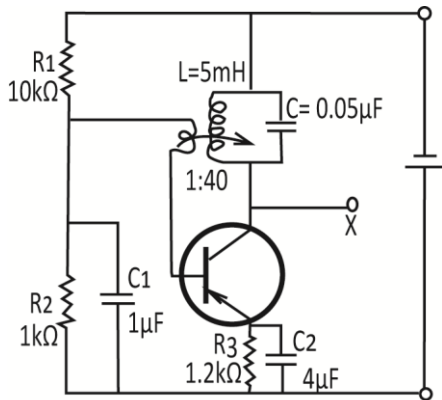


Fig. 17. Transistor Oscillator

Its main features are:

- (i) a coil-capacitor, L-C, load in the collector circuit;
- (ii) positive feedback through the coil L_1 to maintain the oscillations in the L-C circuit;
- (iii) a potential divider arrangement, R_1 , R_2 , to provide the necessary base bias;
- (iv) an emitter resistor R_3 to stabilize the circuit for excessive temperature rise ;
- (v) large capacitors C_1 and C_2 across R_2 and R_3 respectively, which prevent undesirable feedback to the base circuit.

Approximately, the frequency of oscillation is given by $f = \frac{1}{2\sqrt{LC}}$, in this case an audio-frequency. Other frequencies may be obtained by changing the magnitude of C.

Thermistor

A thermistor is a heat-sensitive resistor usually made from semiconductor materials which have a high negative temperature coefficient of resistance. Its resistance thus decreases appreciably with temperature rise.

One use of a thermistor is to safeguard against current surges in circuits where this

could be harmful, for example, in a circuit where the heaters of radio valves are in series.

A thermistor, T, is included in the circuit, as shown (Fig. 18). When the supply voltage is switched on, the thermistor has a high resistance at first because it is cold. It thus limits the current to a moderate value. As it warms up, the thermistor resistance drops appreciably and an increased current then flows through the heaters. Thermistors are also used in transistor receiver circuits to compensate for excessive rise in collector current.

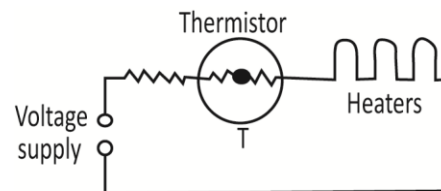


Fig. 18. Use of thermistor

Phototransistor

A photodiode is a junction diode sensitive to light. When the diode is reverse-biased, minority carriers flow in the circuit and constitute a so-called 'dark' current. If the junction of the diode is now illuminated, the light energy produces more electron-hole pairs, which are then swept across the junction. The increased current which flows is the 'light' current.

A phototransistor is a transistor sensitive to light in which the base is usually left disconnected. When light falls on the emitter side, more electron-hole pairs are produced in the base. This is amplified by transistor action, and a larger collector current is obtained. In principle the phototransistor is a photodiode plus amplifier.

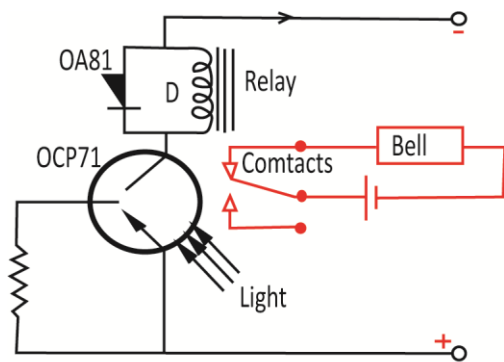


Fig. 19 Phototransistor operating relay

Fig. 19 shows a circuit in which a Mullard phototransistor OCP71 is connected in series with a relay coil D and a d.c. supply voltage .

When the photo- transistor is illuminated, the increase in collector current closes the contacts of a magnetic relay. Current then flows in a circuit connected to the relay, and a bell, for example, may then ring. Fig. 19. When the light is switched off, the falling current in the relay coil produces an induced voltage in the same direction as the battery supply. This would raise the collector voltage and prevent the switch-off at the contacts. The diode OA81 across the coil acts as a safeguard. As soon as the rising induced voltage becomes equal to the battery voltage the diode conducts, and prevents any further rise in collector voltage.

Common Applications of transistors

- **Computing:** Billions of transistors make up microprocessors (CPUs) and memory chips (RAM).
- **Communication:** Amplifying signals in cell phones, radios, and Wi-Fi devices.

- **Power Control:** Regulating power in power supplies, managing motors, and converting energy in solar systems (inverters, charge controllers).
- **Signal Generation:** Creating precise frequencies for clocks and oscillators in digital devices.
- **Automotive:** Used in engine control, power windows, and electronic systems in modern vehicles.
- **Healthcare:** Powering wearable health monitors and pacemakers.

Revision exercise

1. Explain, with reference to the carriers, the effect of temperature rise on the resistance of a pure metal and on the resistance of a pure semiconductor.
2. Explain what is meant by
 - (i) a p- and a n-semiconductor.
 - (ii) a p-n junction.
3. Draw a sketch of the characteristic of a p-n junction diode. Explain, in terms of the movement of carriers, why the resistance of the diode is low in one direction and high in the reverse direction.
4. Draw a sketch of a p-n-p transistor used in
 - (i) a common-base (CB) and
 - (ii) a common-emitter (CE) arrangement, showing clearly the polarities of the batteries. Explain why the common-emitter arrangement is

- preferred in an a.f. amplifier circuit.
5. Draw a circuit showing how the collector current-collector voltage and the emitter current-emitter voltage

characteristics of a transistor can be found for the common-emitter (CE) arrangement. Sketch the characteristics obtained. Draw a sketch of a simple CE a.f. amplifier.

Thank you
Dr. Bbosa Science