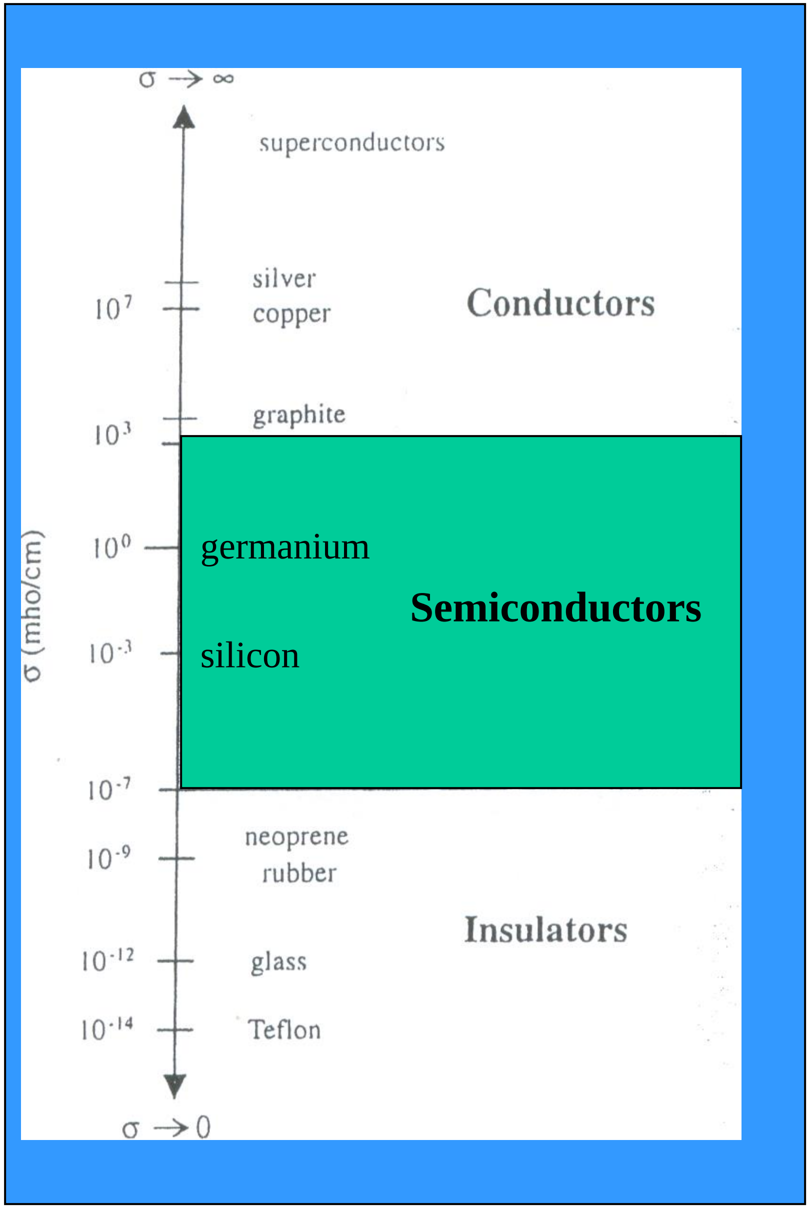
Mechatronics

Topic #5

Basic Electronics

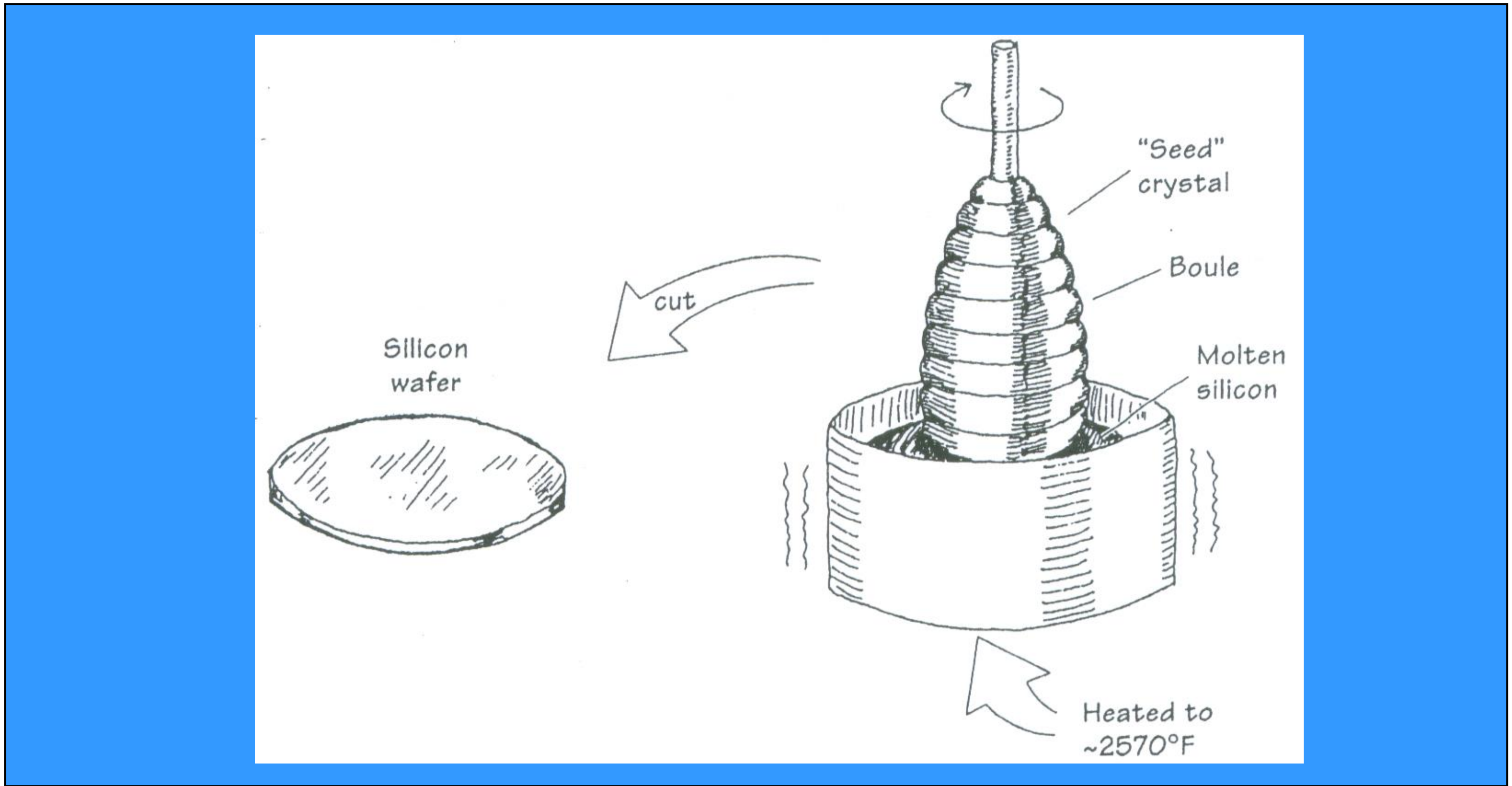
Semiconductor —I

- Materials that permit flow of electrons are called conductors (e.g., gold, silver, copper, etc.).
- Materials that block flow of electrons are called insulators (e.g., rubber, glass, Teflon, mica, etc.).
- Materials whose conductivity falls between those of conductors and insulators are called semiconductors.
- Semiconductors are “part-time” conductors whose conductivity can be controlled.



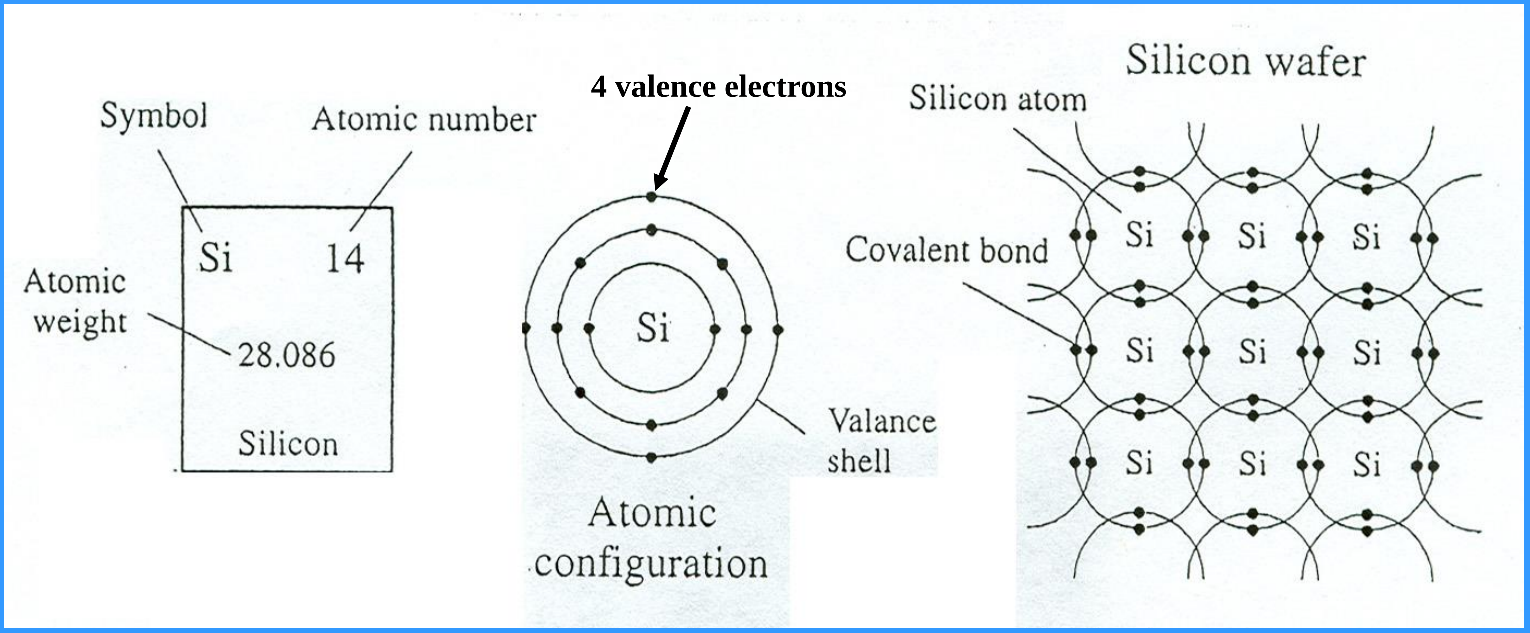
Semiconductor —II

- Silicon is the most common material used to build semiconductor devices.
- Si is the main ingredient of sand and it is estimated that a cubic mile of seawater contains 15,000 tons of Si.
- Si is spun and grown into a crystalline structure and cut into wafers to make electronic devices.



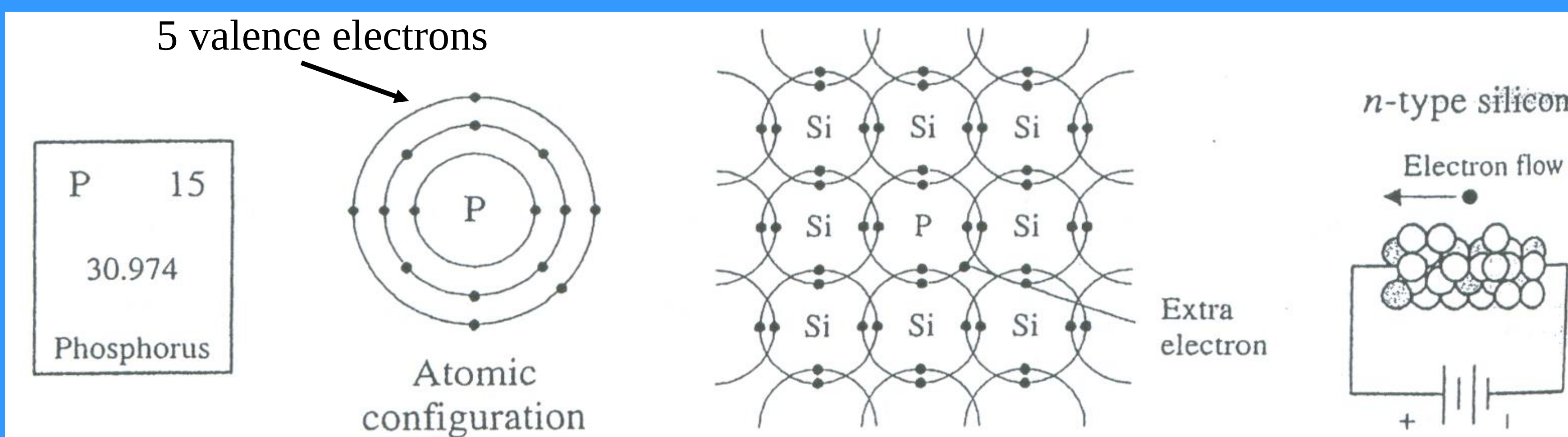
Semiconductor —III

- Atoms in a pure silicon wafer contain four electrons in outer orbit (called valence electrons).
  - Germanium is another semiconductor material with four valence electrons.
- In the crystalline lattice structure of Si, the valence electrons of every Si atom are locked up in covalent bonds with the valence electrons of four neighboring Si atoms.
  - In pure form, Si wafer does not contain any free charge carriers.
  - An applied voltage across pure Si wafer does not yield electron flow through the wafer.
  - A pure Si wafer is said to act as an insulator.
- In order to make useful semiconductor devices, materials such as phosphorus (P) and boron (B) are added to Si to change Si's conductivity.



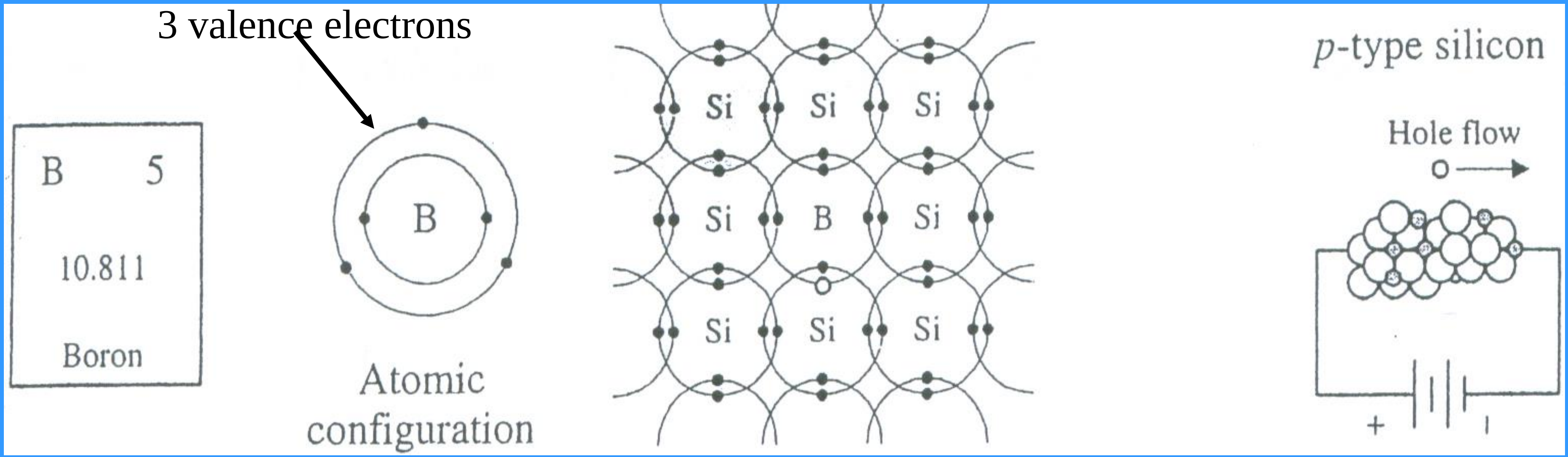
N-Type Silicon

- Pentavalent impurities such as phosphorus, arsenic, antimony, and bismuth have 5 valence electrons.
- When phosphorus impurity is added to Si, every phosphorus atom's four valence electrons are locked up in covalent bond with valence electrons of four neighboring Si atoms. However, the 5th valence electron of phosphorus atom does not find a binding electron and thus remains free to float. When a voltage is applied across the silicon-phosphorus mixture, free electrons migrate toward the positive voltage end.
- When phosphorus is added to Si to yield the above effect, we say that Si is doped with phosphorus. The resulting mixture is called N-type silicon (N: negative charge carrier silicon).
- The pentavalent impurities are referred to as donor impurities.



P-Type Silicon —I

- Trivalent impurities e.g., boron, aluminum, indium, and gallium have 3 valence electrons.
- When boron is added to Si, every boron atom's three valence electrons are locked up in covalent bond with valence electrons of three neighboring Si atoms. However, a vacant spot "hole" is created within the covalent bond between one boron atom and a neighboring Si atom. The holes are considered to be positive charge carriers. When a voltage is applied across the silicon-boron mixture, a hole moves toward the negative voltage end while a neighboring electron fills in its place.
- When boron is added to Si to yield the above effect, we say that Si is doped with boron. The resulting mixture is called P-type silicon (P: positive charge carrier silicon).
- The trivalent impurities are referred to as acceptor impurities.



P-Type Silicon —II

- The hole of boron atom points towards the negative terminal.
- The electron of neighboring silicon atom points toward positive terminal.
- The electron from neighboring silicon atom falls into the boron atom filling the hole in boron atom and creating a "new" hole in the silicon atom.
- It appears as though a hole moves toward the negative terminal!

Diode

•A diode is a 2 lead semiconductor that acts as a one way gate to electron flow.

– Diode allows current to pass in only one direction.

•A pn-junction diode is formed by joining together n-type and p-type silicon.

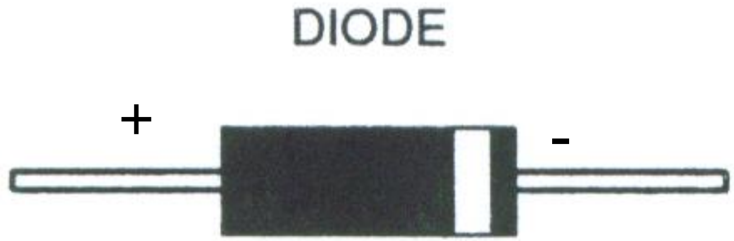
•In practice, as the n-type Si crystal is being grown, the process is abruptly altered to grow p-type Si crystal. Finally, a glass or plastic coating is placed around the joined crystal.

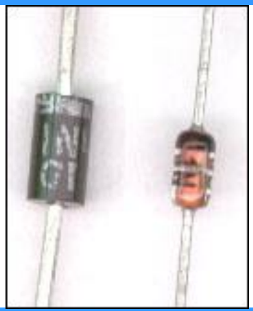
•The p-side is called anode and the n-side is called cathode.

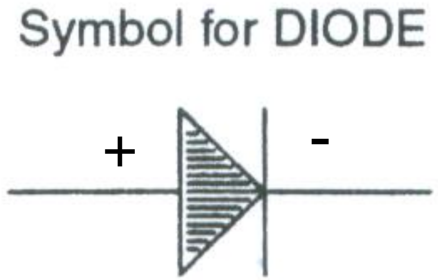
•When the anode and cathode of a pn-junction diode are connected to external voltage such that the potential at anode is higher than the potential at cathode, the diode is said to be forward biased.

–In a forward-biased diode current is allowed to flow through the device.

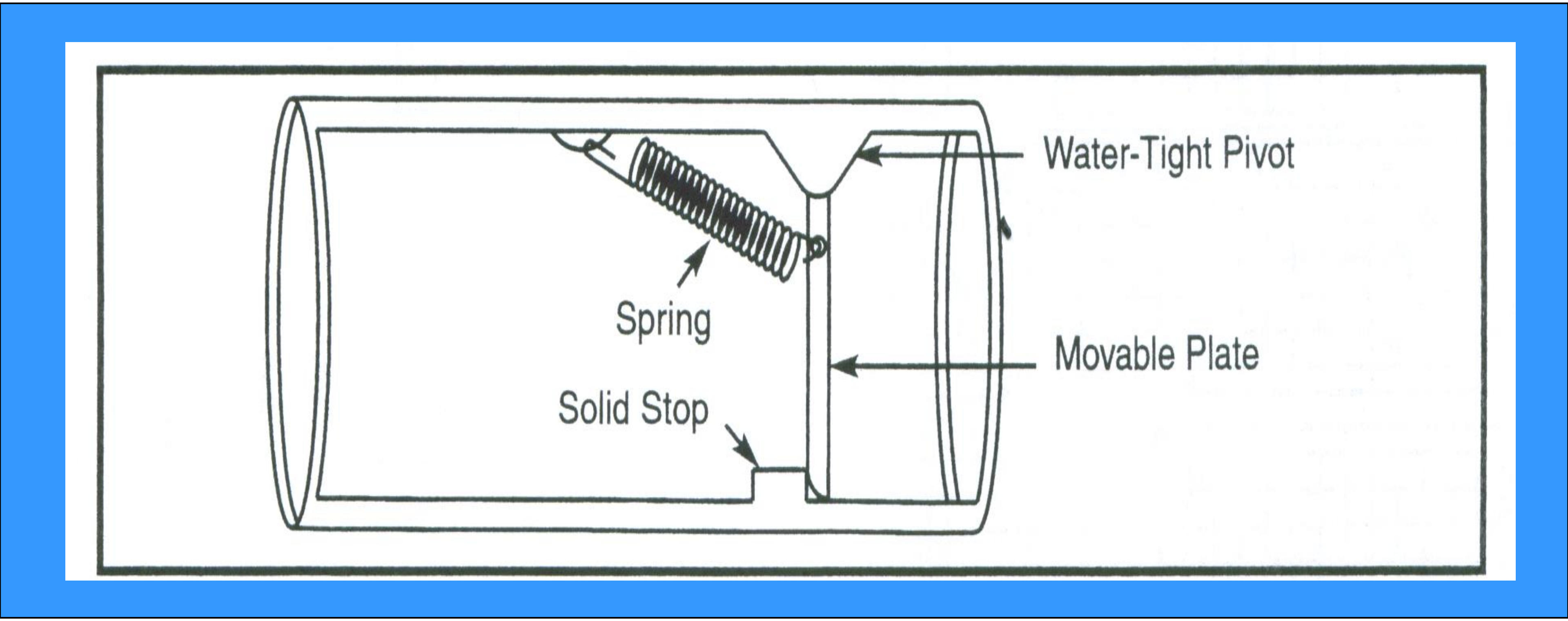
•When potential at anode is smaller than the potential at cathode, the diode is said to be reverse biased. In a reverse-biased diode current is blocked.







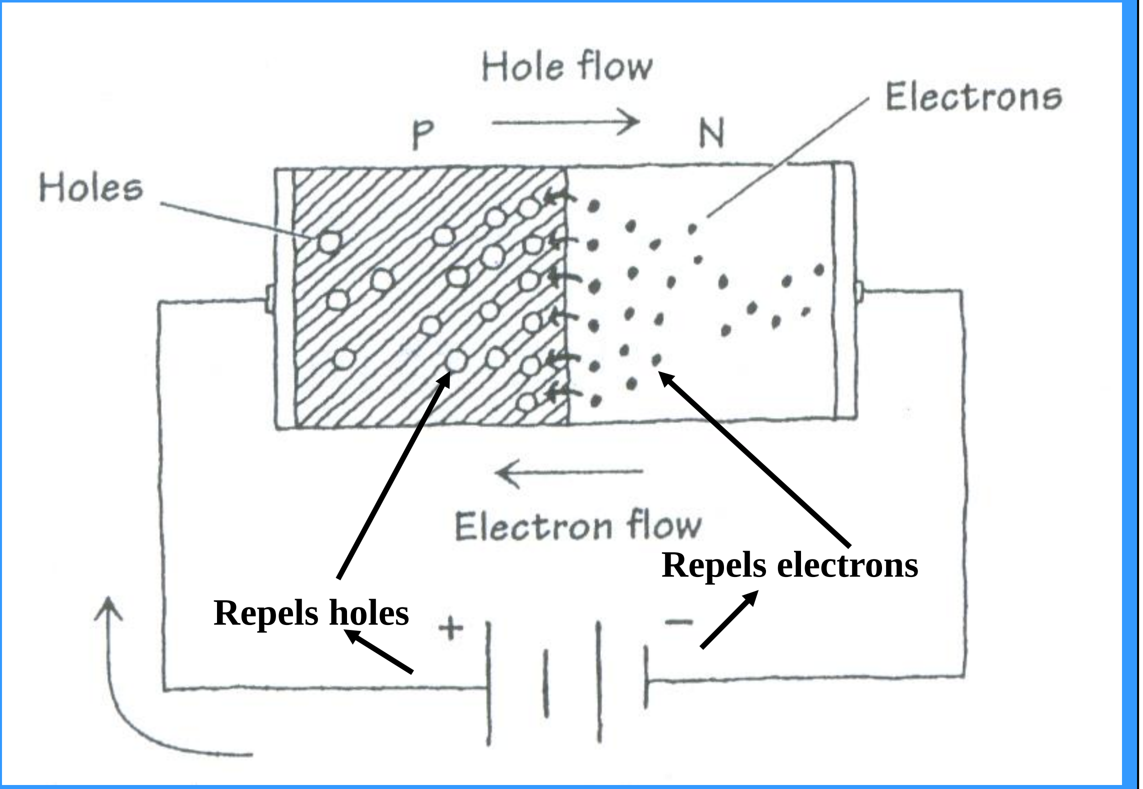
Water Analogy of Diodes



- When water pressure on left overcomes the restoring force of spring, the gate is opened and water is allowed to flow $\rightarrow$.
- When water pressure is from right to left, the gate is pressed against the solid stop and no water is allowed to flow.
- Spring restoring force is analogous to 0.6V needed to forward bias a Si diode.

Diode: How it Works —I

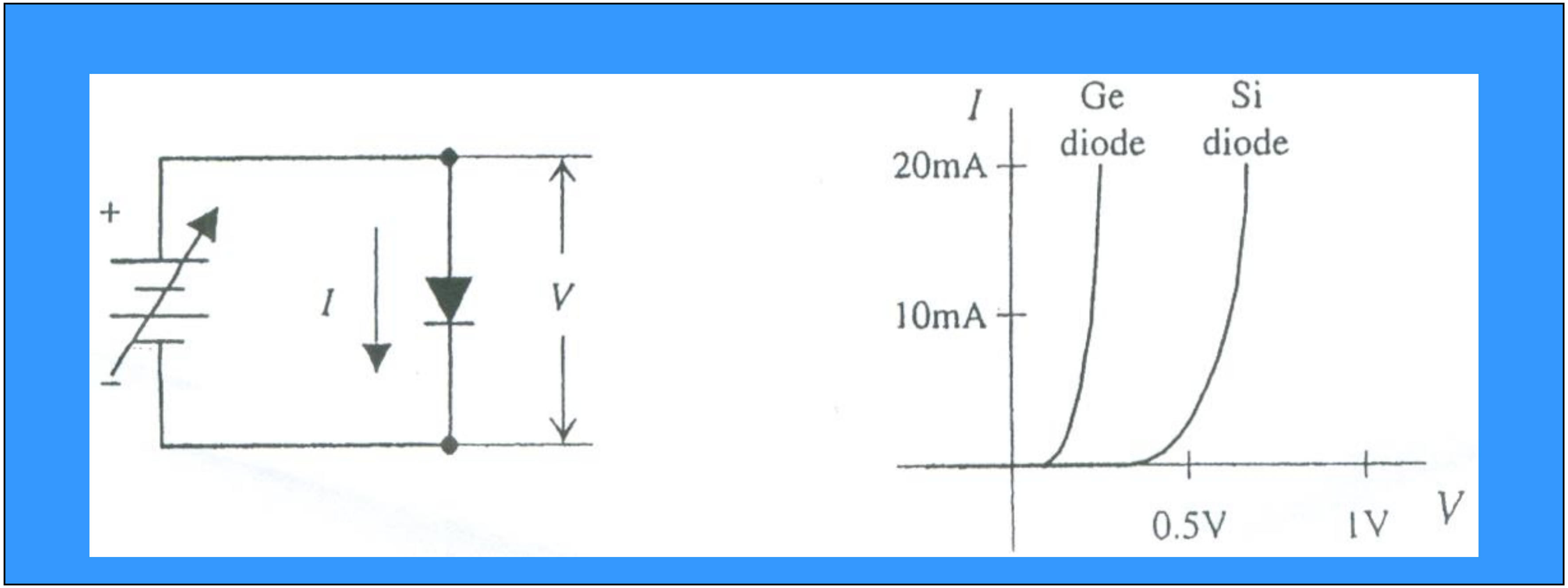
- When a diode is connected to a battery as shown, electrons from the n-side and holes from the p-side are forced toward the center by the electrical field supplied by the battery. The electrons and holes combine causing the current to pass through the diode. When a diode is arranged in this way, it is said to be <u>forward-biased</u>.



Forward-biased (“open door”)

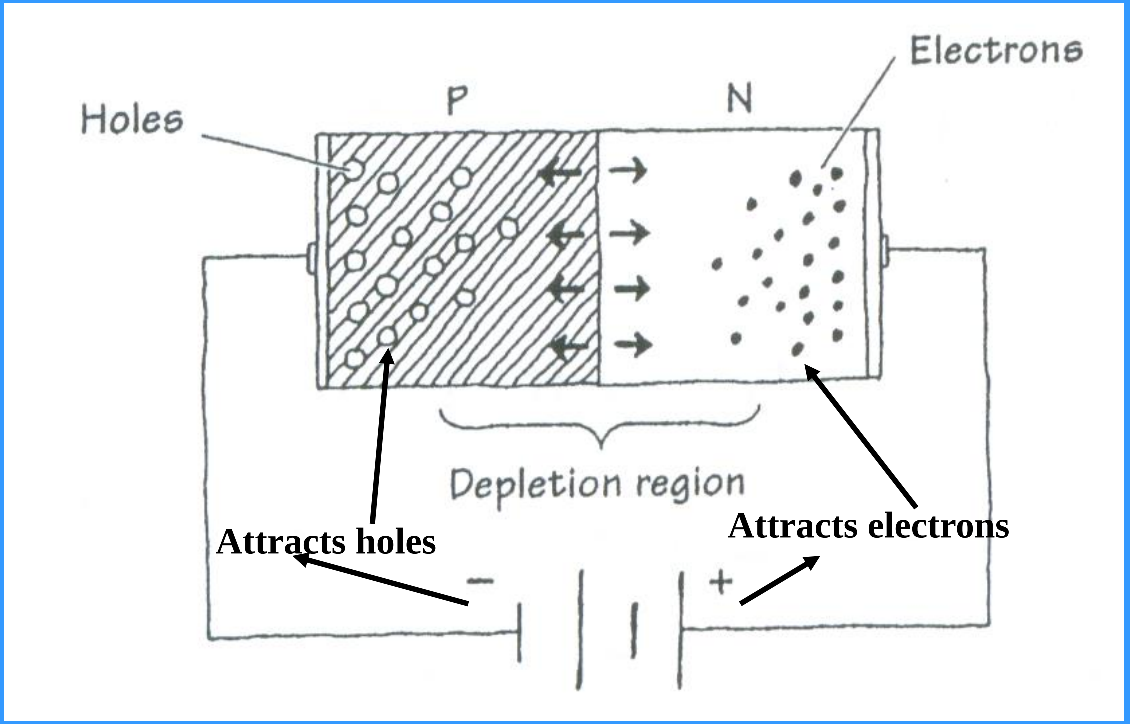
Diode: How it Works—II

- A diode's one-way gate feature does not work all the time.
- Typically for silicon diodes, an applied voltage of 0.6V or greater is needed, otherwise, the diode will not conduct.
- This feature is useful in forming a voltage-sensitive switch.
- I-V characteristics for silicon and germanium diodes is shown below.



Diode: How it doesn't work

- When a diode is connected to a battery as shown, holes in the n-side are forced to the left while electrons in the p-side are forced to the right. This results in an empty zone around the pn- junction that is free of charge carries creating a ***depletion region***. This depletion region acts as an insulator preventing current from flowing through the diode. When a diode is arranged in this way, it is said to be reverse-biased.



Reverse-biased ("closed door")

Diode Applications —Half Wave Rectifier

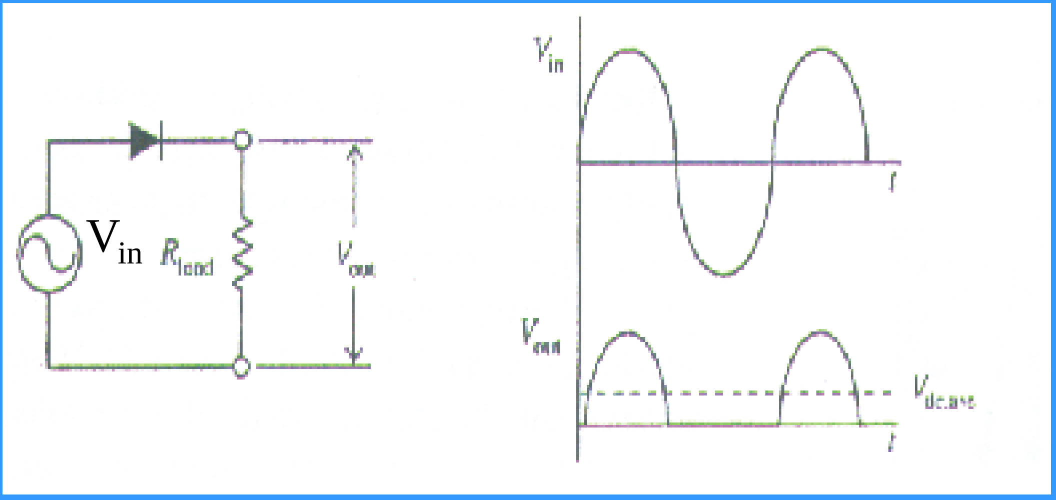
•Diode converts ac input voltage to a pulsed dc output voltage.

•Whenever the ac input becomes negative at diode’s anode, the diode blocks current flow.

$\longrightarrow$ o/p voltage become zero.

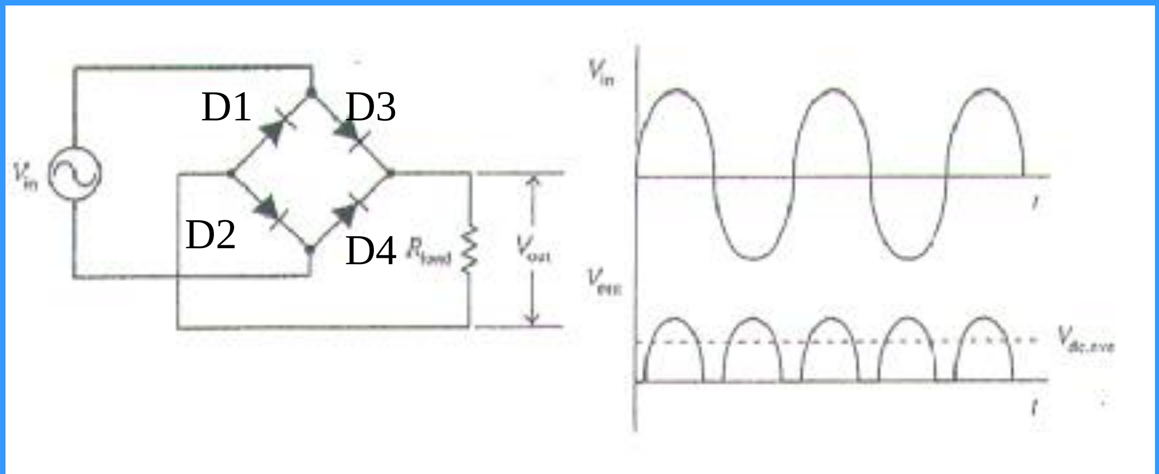
•Diode introduces a 0.6V drop so o/p peak is 0.6V smaller than the i/p peak.

•The o/p frequency is same as the i/p frequency.

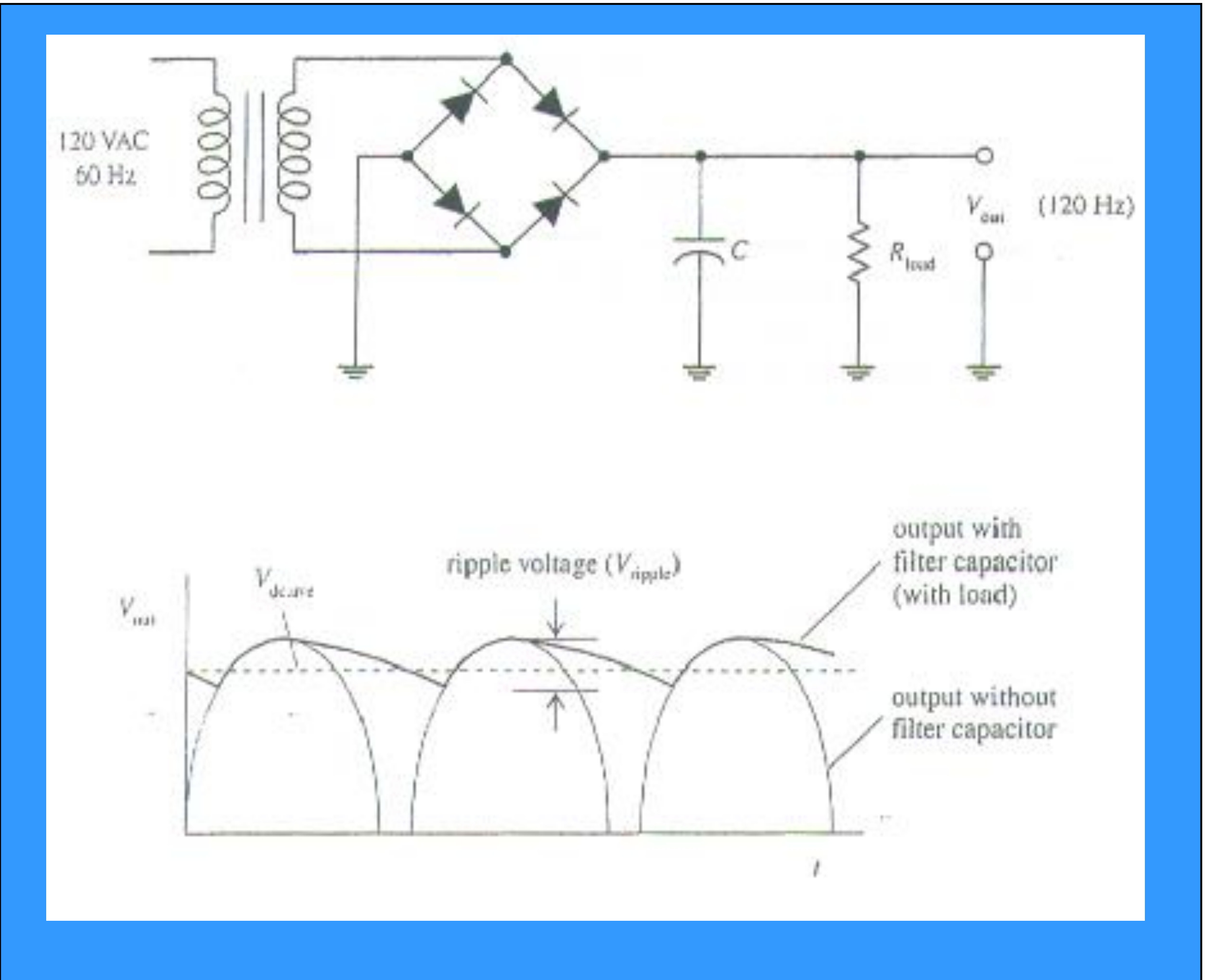


Diode Applications —Full Wave Rectifier

- A full-wave rectifier does not block negative swings in the i/p voltage, rather it transforms them into positive swings at the o/p.
- To gain an understanding of device operation, follow current flow through pairs of diodes in the bridge circuit.
- It is easily seen that one pair (D3-R_{out}-D2) allows current flow during the +ve half cycle of V_{in} while the other pair (D4-R_{out}-D1) allows current flow during the -ve half cycle of V_{in}.
  - $\rightarrow$ o/p voltage peak is 1.2V below the i/p voltage peak.
  - The o/p frequency is twice the i/p frequency.



Diode Applications —AC2DC Power Supply



•An AC2DC power supply is built using a transformer and a full-wave rectifier.

•Transformer is used to step down the voltage i/p.

•Rectifier converts AC to pulsed DC.

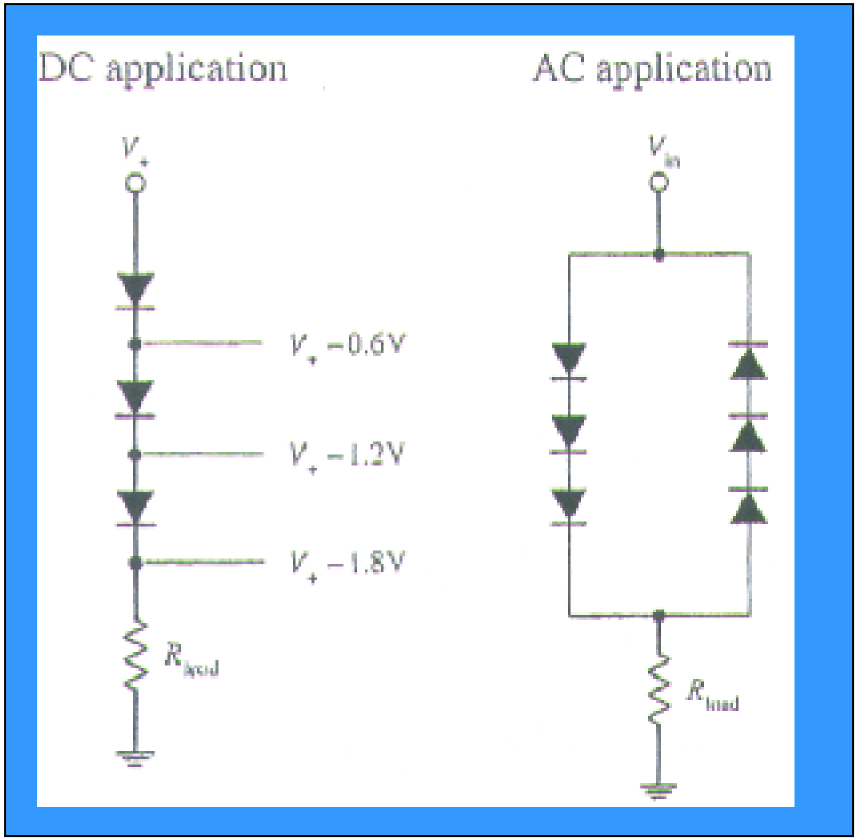
•A filter capacitor is used to smooth out the pulses.

•Capacitor must be large enough to store sufficient charge so as to provide a steady current supply to the load:

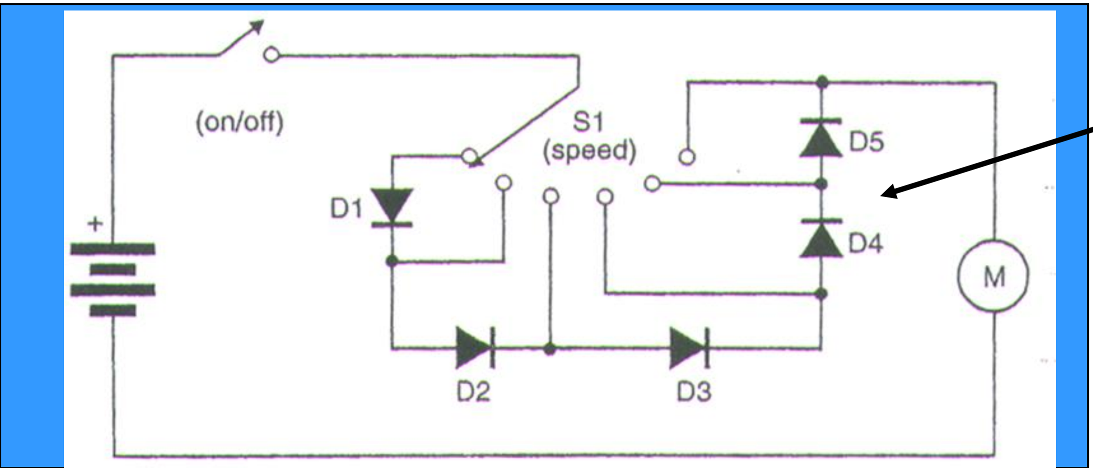
$$R_{Load}C >> 1/f$$

f is rectified signal's frequency (120Hz).

Diode Applications —Voltage Dropper

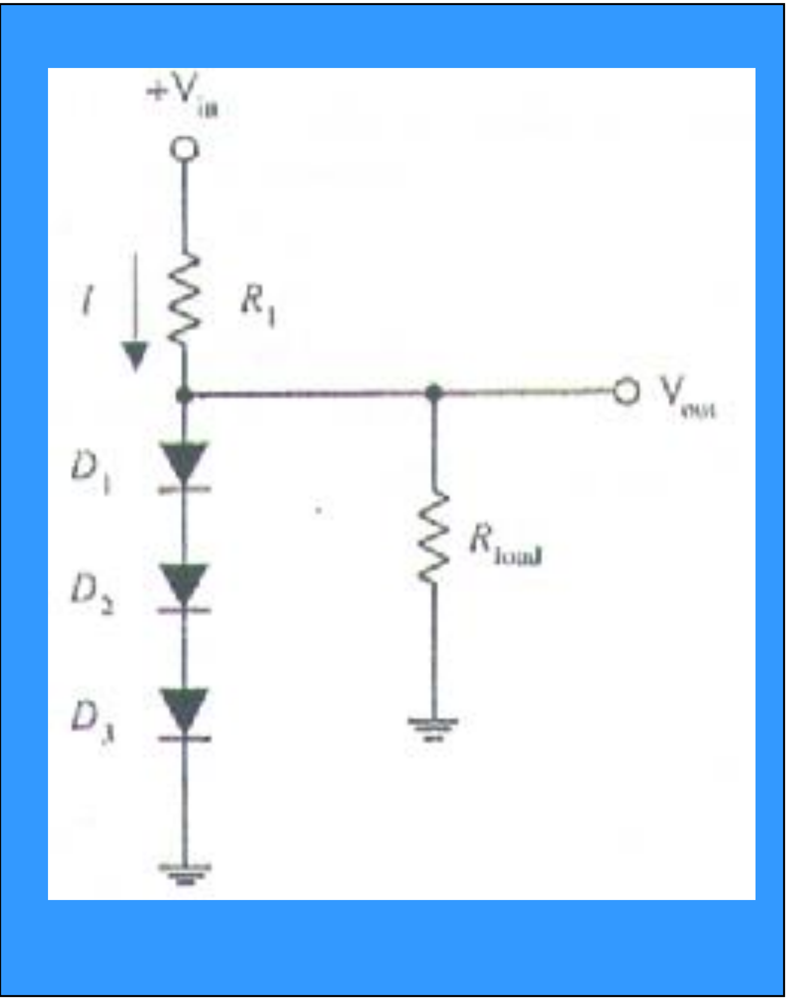


- When current passes through a Si diode, the voltage is lowered by 0.6V.
- By using a number of diodes in series, one can create a desired voltage drop (total voltage drop=sum of voltage drops across each diode).
- For AC applications, two sets of diodes can be placed in opposite directions.



Motor speed control using voltage dropper

Diode Applications —Voltage Regulator

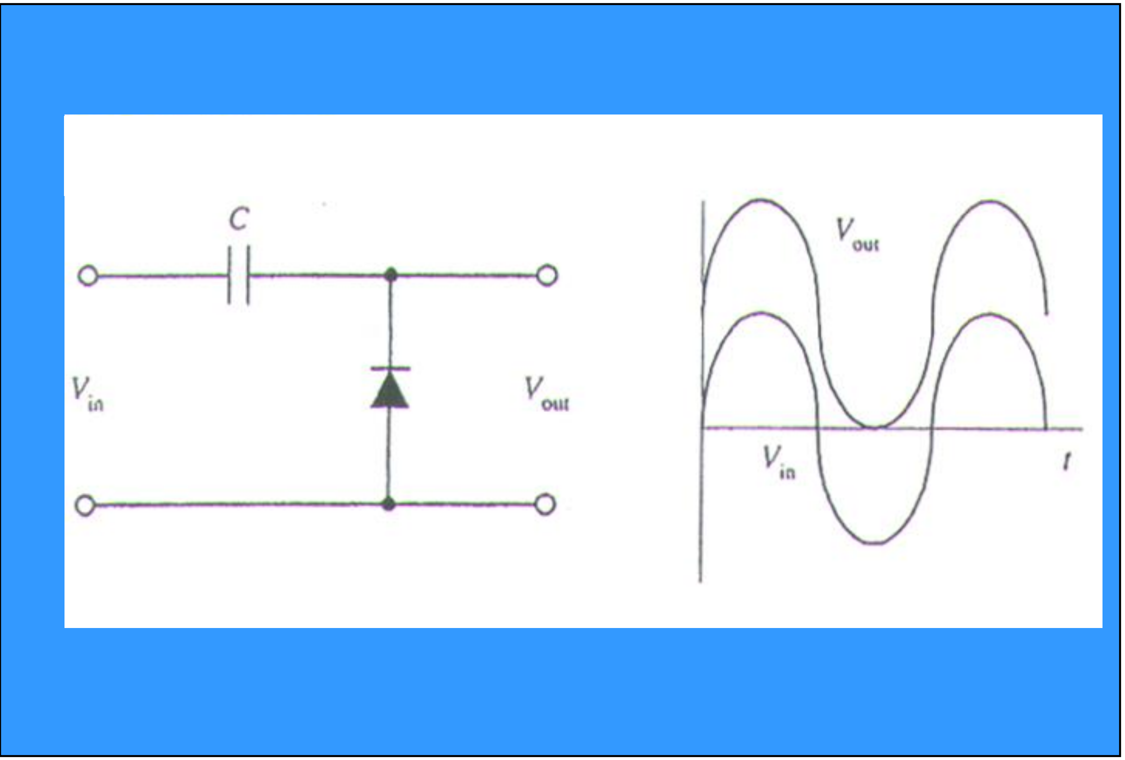


- A voltage regulator can be created by using several forward-biased diodes as shown.
- The circuit will supply steady o/p voltage equal to sum of forward bias voltage of the three diodes in the diagram.
- If D1, D2, and D3 are Si-diodes, each of them will cause a 0.6V voltage drop. Thus, V_{out} is 1.8V.
- Resistor R_1 is sized to prevent diodes from burning out. In particular, if R_{Load} is very large or if R_{load} is removed, use of R_1 prevents the diodes from frying!

$$R_1 = \frac{V_{in} - V_{out}}{I}$$

where I is allowable current through diodes.

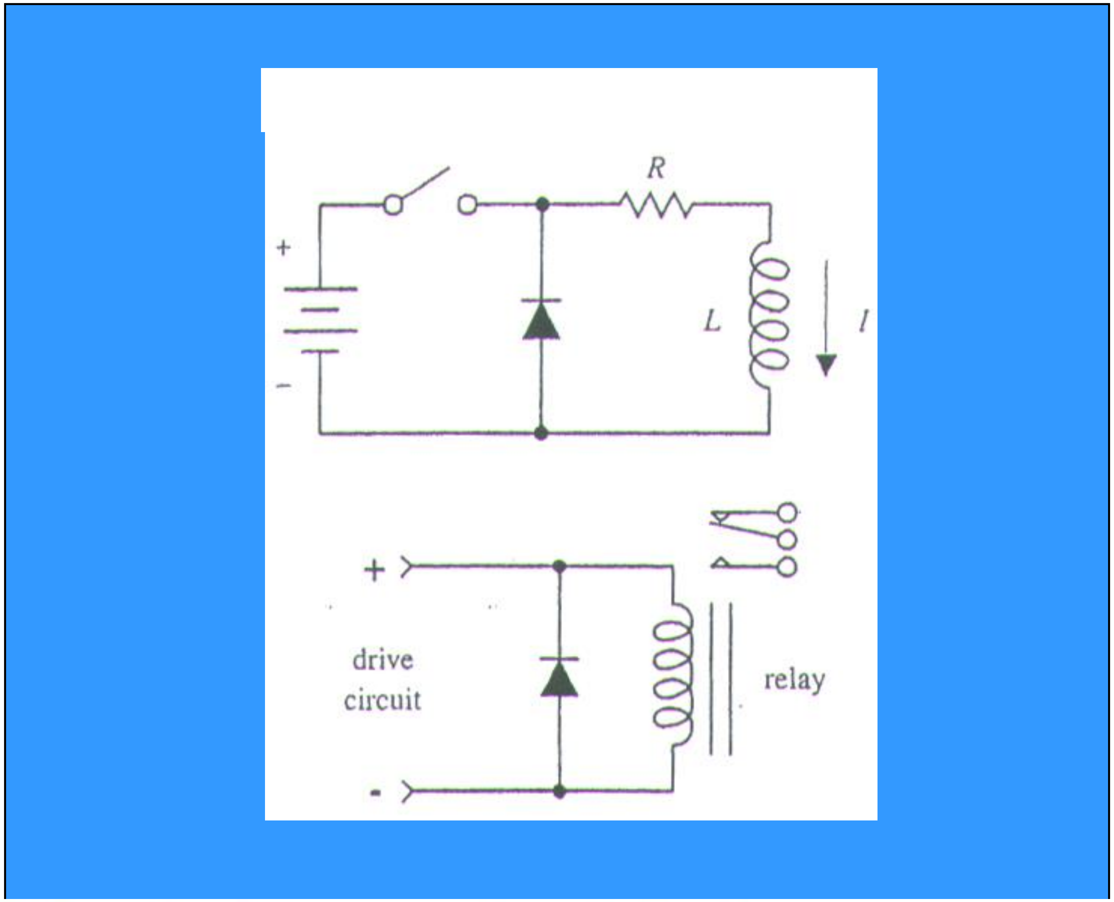
Diode Applications — Diode Clamp



- The diode clamp offsets a periodic AC i/p that oscillates between +ve and –ve values and displaces it such that it is either always +ve or always –ve.
- The capacitor charges up to a DC voltage equal to 0-to-peak value of V_{in}. The capacitor is made large enough so that it appears as a short circuit for the AC components of V_{in}.
- When V_{in} is sinusoidal input,

  $V_{out}=V_{in}$+dc voltage on capacitor.
- If the diode connections are reversed, V_{out} will be displaced downward.

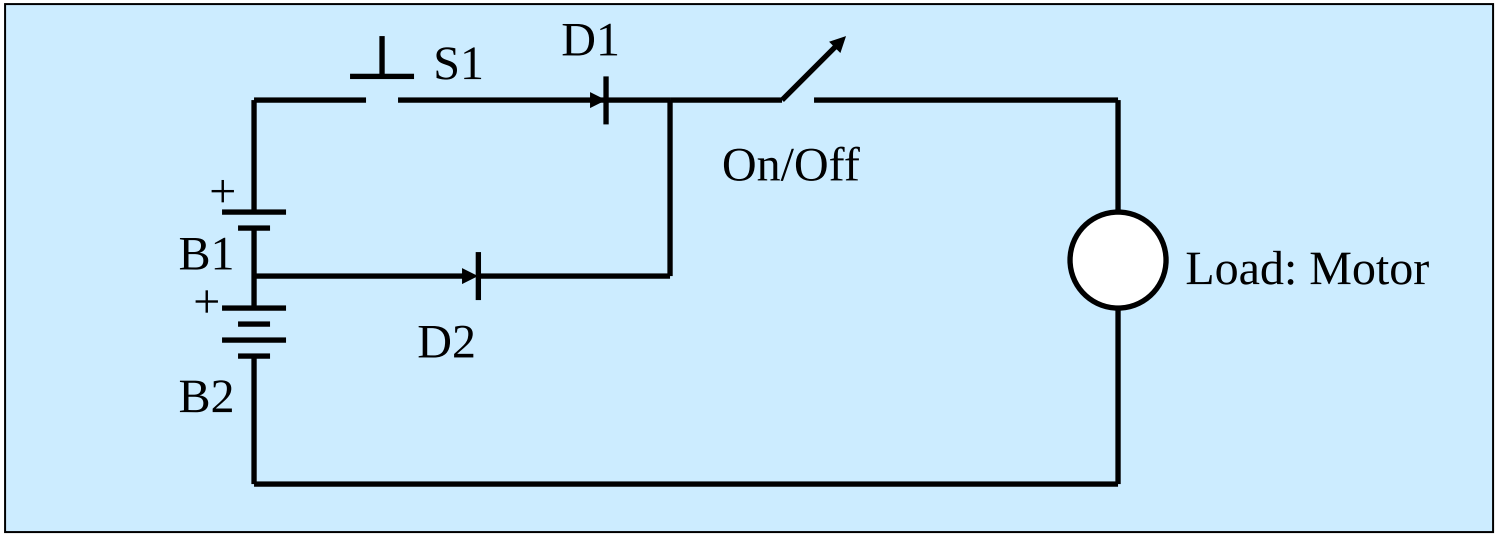
Diode Applications —Transient Protector



Placing a diode in the reverse-biased direction across an inductive load eliminates voltage spikes by going into conduction before a large voltage can form across the load. The diode must be rated to handle the current, equivalent to the maximum current that would have been flowing through the load before the current supply was interrupted. The lower network shows how a diode can be used to protect a circuit from voltage spikes that are produced when a dc-actuated relay suddenly switches states.

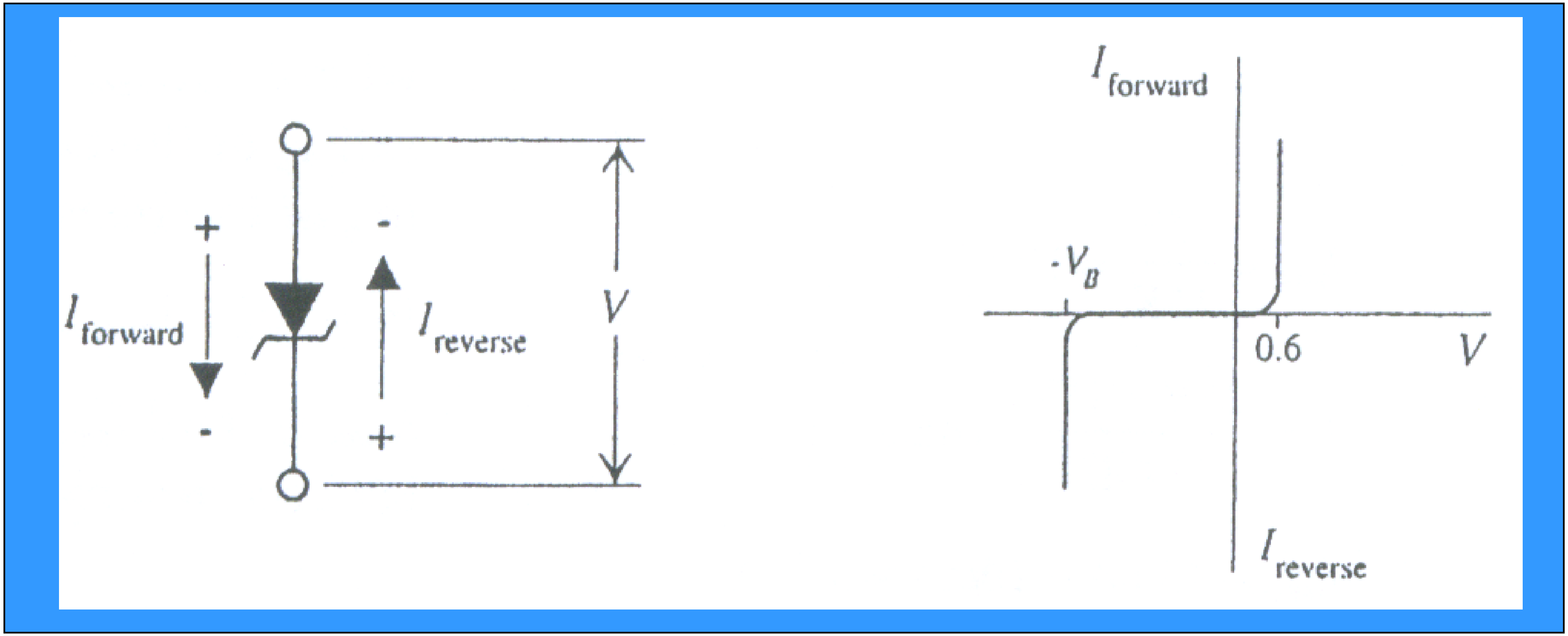
Diode Applications —Power Booster

- In some applications, a motor runs at a speed governed by the load to be driven.
- If, however, the load momentarily increases, the motor may stall unless it is provided a boost in power.
  - Example: a robot encounters an uphill terrain/obstacle and may require power boost.
- The power boot to the motor can be provided by momentarily increasing the input voltage to motor.
- Example:
  - When S1 is not engaged, B2 powers the motor.
  - An increase in load closes S1 momentarily, allowing B2 to provide an increased input voltage to the motor.
  - Diode D2 keeps B1 from short-circuiting when S1 is pressed.

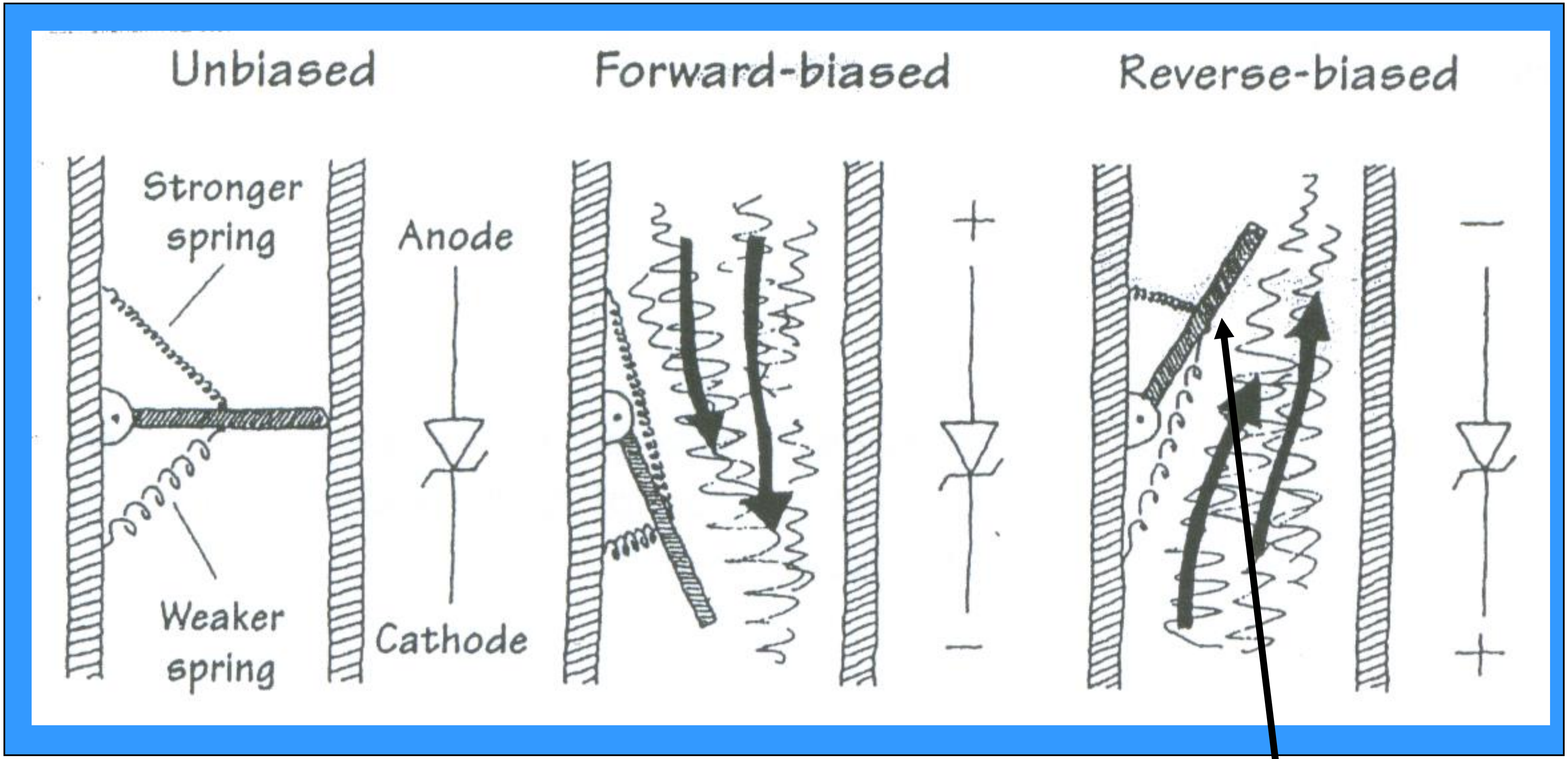


Zener Diode

- A zener diode acts as a usual pn-junction diode.
  - In addition, it conducts in the reverse-biased direction when a specific breakdown voltage is reached.
- The symbol for a zener diode is shown in the left diagram.
- The right diagram illustrates the forward and reverse V-I characteristics of a zener diode.



Zener Diode Water Analogy



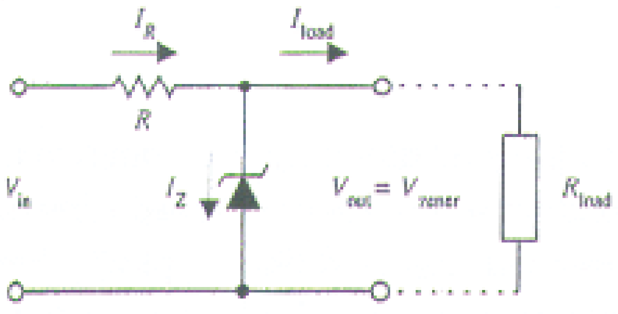
Gate opens when water pressure overcomes force of reverse-biasing spring.

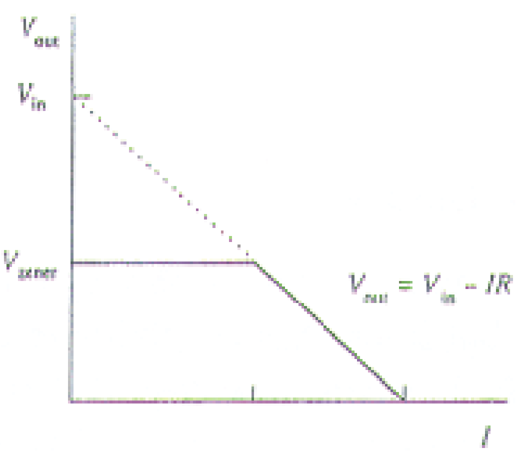
Zener Diode Applications:Voltage Regulator — I

- Suppose V_{in} attempts to push V_{out} above the zener's breakdown voltage (V_{zener}).
  - The zener draws as much current through itself in the reverse-biased direction as necessary to keep $V_{out} = V_{zener}$, despite fluctuations in V_{in}.
  - The resistor in the circuit limits the current through zener. This protects the zener from excessive current flow in case the load is removed.

$$R = \frac{V_{\text{in}} - V_{\text{zener}}}{I_{\text{max,zener}}}$$

Current rating of zener, i.e., max current allowed to pass through zener before it burns down.





$$I_{load} = \frac{V_{out}}{R_{load}} \approx \frac{V_{zener}}{R_{load}}$$

$$I_R = \frac{V_{in} - V_{out}}{R} \approx \frac{V_{in} - V_{zener}}{R}$$

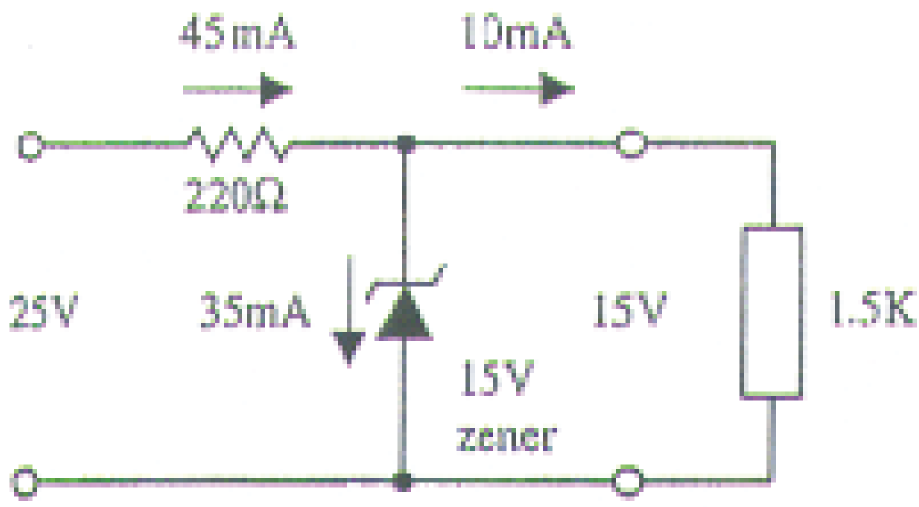
$$I_{zener} = I_R - I_{load}$$

Zener Diode Applications: Voltage Regulator — II

$$I_{load} = \frac{15V}{1.5K} = 10mA$$

$$I_R = \frac{25V - 15V}{220\Omega} = 45mA$$

$$I_{zener} = 45mA - 10mA = 35mA$$

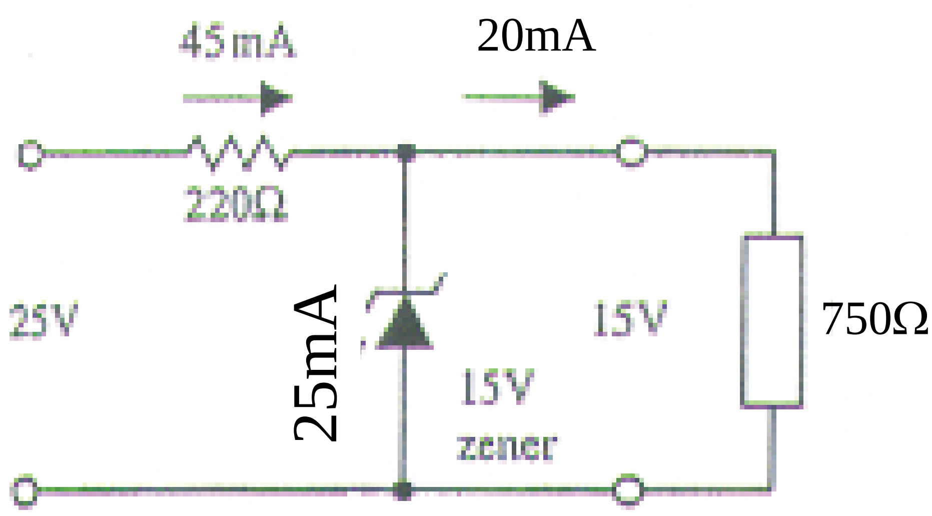


Zener Diode Applications: Voltage Regulator — III

$$I_{load} = \frac{15V}{750\Omega} = 20mA$$

$$I_R = \frac{25V - 15V}{220\Omega} = 45mA$$

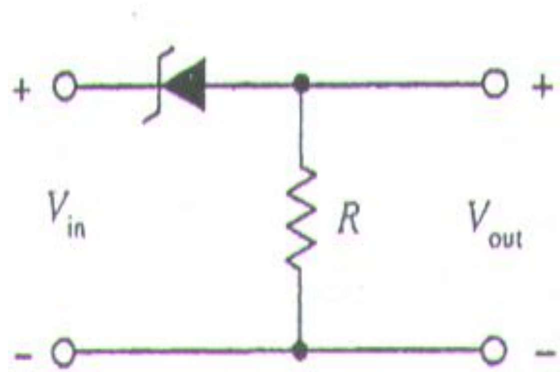
$$I_{zener} = 45mA - 20mA = 25mA$$

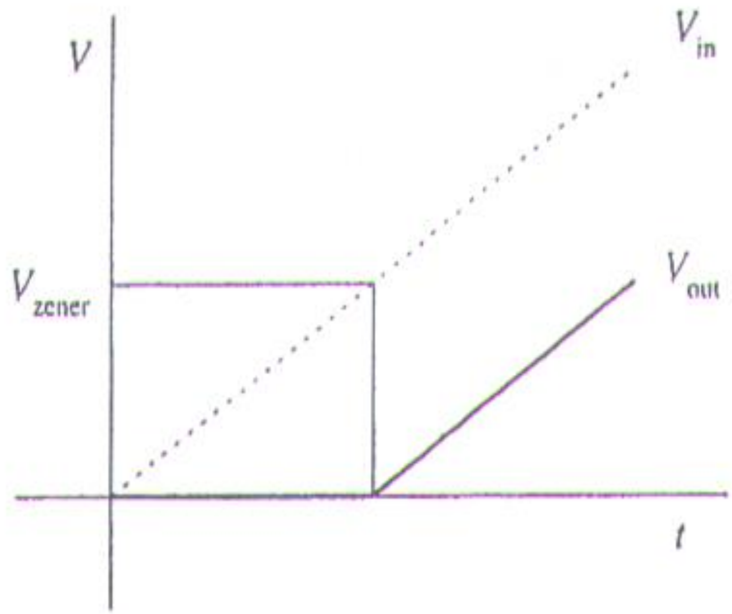


Zener Diode Applications —Voltage Shifter

- The voltage shifter circuit lowers the input voltage V_{in} at the output by an amount equal to the breakdown voltage of zener. Thus,

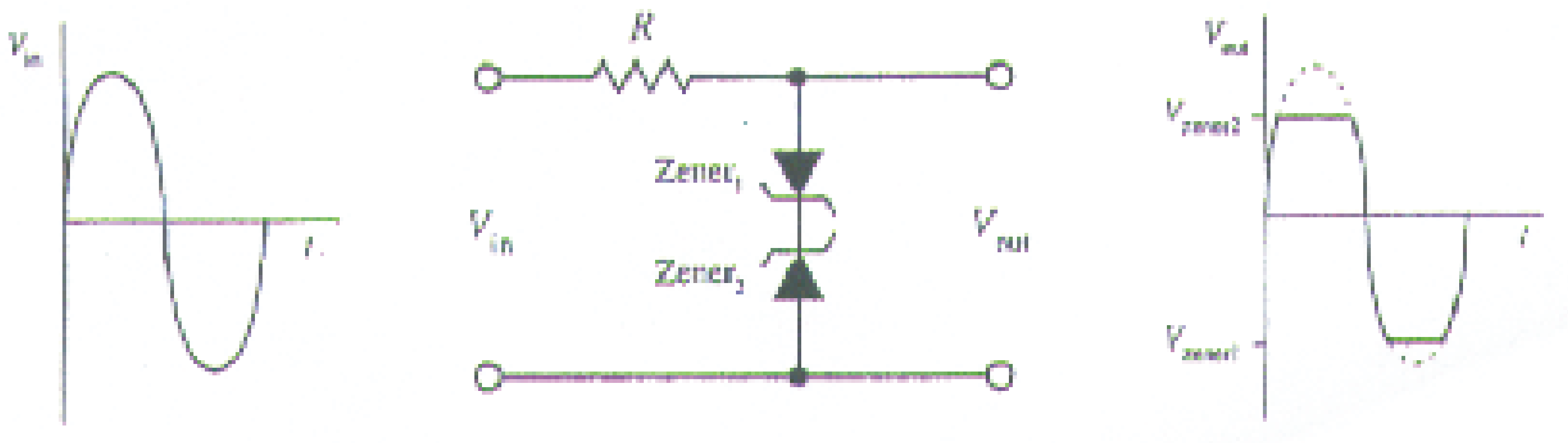
$$V_{out} = V_{in} - V_{zener}$$





Zener Diode Applications —Waveform Clipper

- Two zeners connected in series with opposite directions clip both halves of an input signal.
  - Effectively, a sinusoidal input signal is converted to a near square signal.
- In order to prevent a circuit from voltage spikes of a power supply, this circuit can be used.
  - Select the breakdown voltages of the two diodes for your particular application appropriately.



Sample Diode Specs

1N914/4148

- 1N914/4148: popular silicon switching diode
- Hermetically sealed leaded glass SOD27
- DO-35 package
- High switching speed: max. 4 ns
- General application
- Continuous reverse voltage: max. 75 V
- Repetitive peak reverse voltage: max. 75 V
- Repetitive peak forward current: max. 450mA
- Applications include small signal detectors, high-speed switching, and high-speed clamps

Silicon Revolution: Some History — I

TRAILING EDGE

LESSONS FROM INNOVATIONS PAST

COURTESY OF THE PENNSYLVANIA STATE UNIVERSITY

NO P-N INTENDED

A cracked crystal launched the silicon revolution

When Russell Ohl began working at Bell Laboratories in 1927, vacuum tubes were seen as the future of electronics. It was his chance discovery, however, that led to the creation of both the transistor and the solar cell and helped spark the "silicon revolution."

In the late 1930s Ohl was a radio researcher trying to create a receiver that would be more effective than vacuum tubes. The tubes easily picked up low-frequency radio signals, but had trouble with higher frequencies such as those being tested in radar—a technology that was gaining importance as war brewed overseas. Ohl thought an alternative might lie in the crystal receiver, an antiquated radio device from the 1920s. He devoted himself completely to his research: when his workweek was shortened during the Depression, Ohl used his extra time to study crystal structure.

Crystal receivers were tricky, poorly understood devices. To get a signal, an operator would search the surface of a crystal with a metal strand for the "hot spot," which caused current flow in only one direction. After exhaustive experimentation, Ohl concluded that the best receivers were the elements now known as semiconductors. He theorized that purer materials would make better receivers and had special samples prepared for his tests.

Early in 1940 Ohl examined a silicon sample that had a crack down its middle. Something was strange about that crystal: when it was exposed to light, the current flowing between the two sides of the crack jumped significantly. Baffled, Ohl showed the bizarre sample to his Bell colleagues, who were equally amazed. No one had ever seen a photovoltaic reaction like it.

The researchers discovered that the crack was a dividing line between two impurities in the silicon. One type of silicon had an excess of electrons, the other a deficit. They named them p-type for positive and n-type for negative, and the barrier between the two was dubbed the p-n junction. Gradually, the group realized that photons give the excess electrons in the n-type material enough of an energy boost to cross the junction and produce a current.

Although Ohl's original crystals didn't produce nearly enough power for commercial use, his research into p- and n-type silicon led to Bell Labs' creation of the first modern solar cell in 1954. The first transistors also were based on the p-n junction. When Ohl held his unusual crystal to the light in 1940, he unwittingly began the transition from vacuum tubes to integrated circuits. —*Lisa Scanlon*

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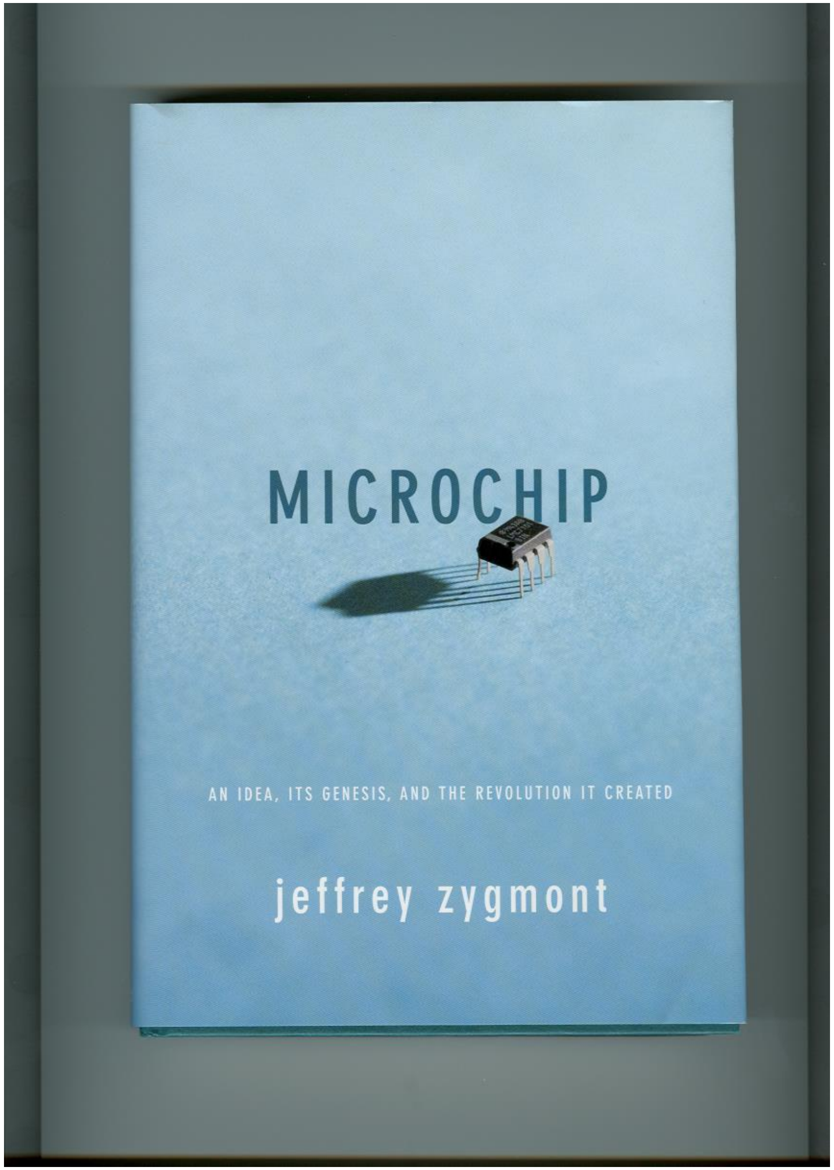
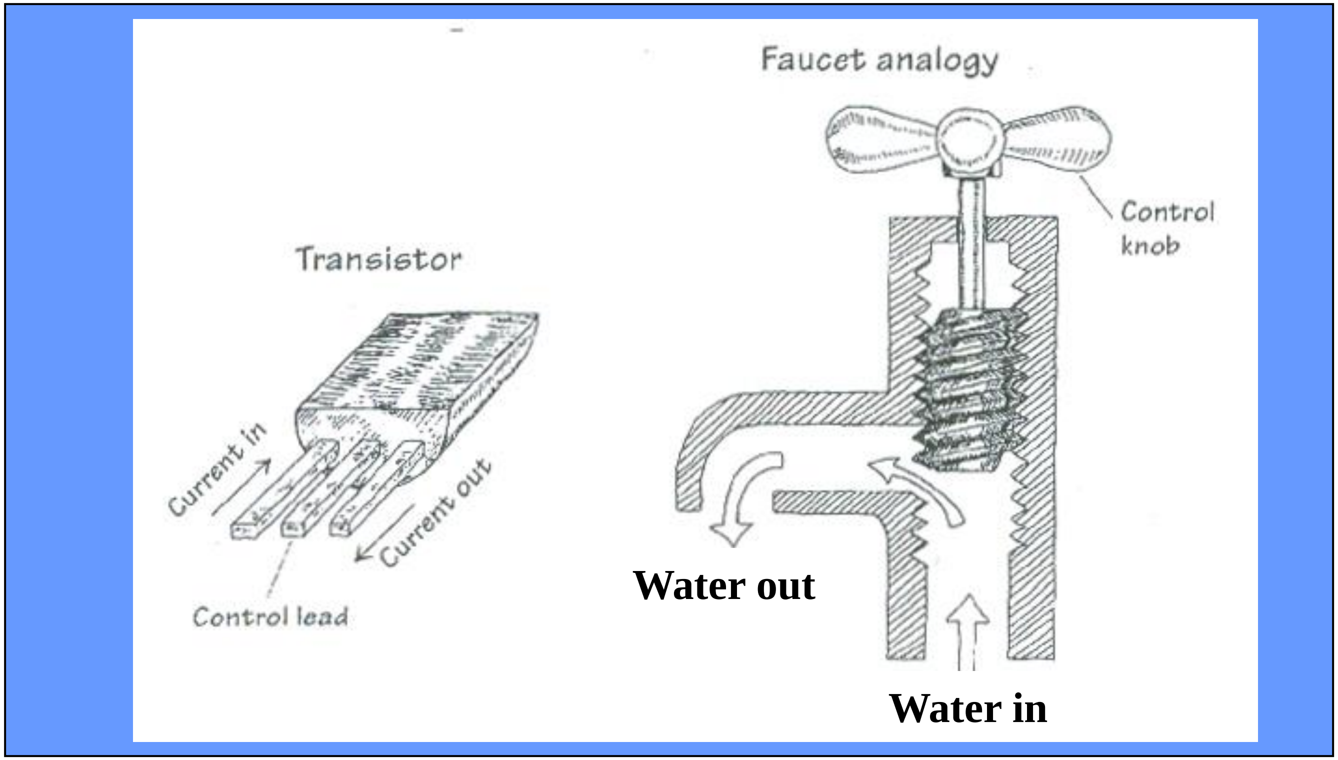
Silicon Revolution: Some History — II



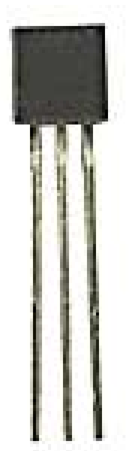
Transistor

- A three lead semiconductor device that acts as:
  - an electrically controlled switch, or
  - a current amplifier.
- Transistor is analogous to a faucet.
  - Turning faucet's control knob alters the flow rate of water coming out from the faucet.
  - A small voltage/current applied at transistor's control lead controls a larger current flow through its other two leads.

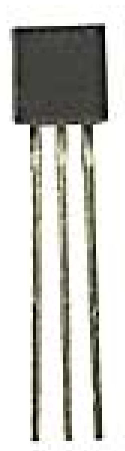


Transistor Types: BJT, JFET, and MOSFET

- **B**ipolar **J**unction **T**ransistor **(BJT)**
  - NPN and PNP
- **J**unction **F**ield **E**ffect **T**ransistor **(JFET)**
  - N-channel and P-channel
- **M**etal **O**xide **S**emiconductor **FET (MOSFET)**
  - Depletion type (n- and p-channel) and enhancement type (n- and p-channel)



BJT

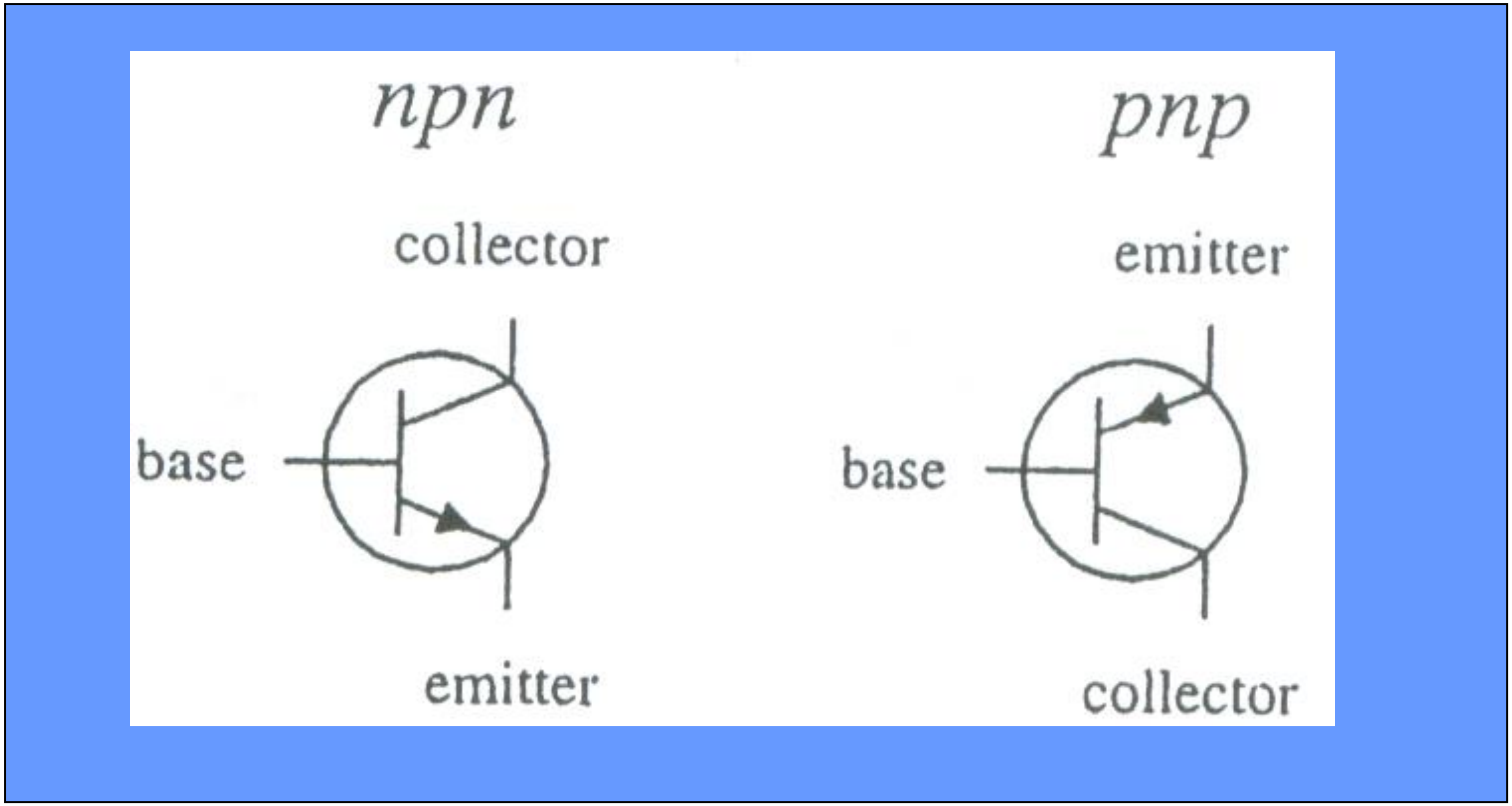


JFET

MOSFET

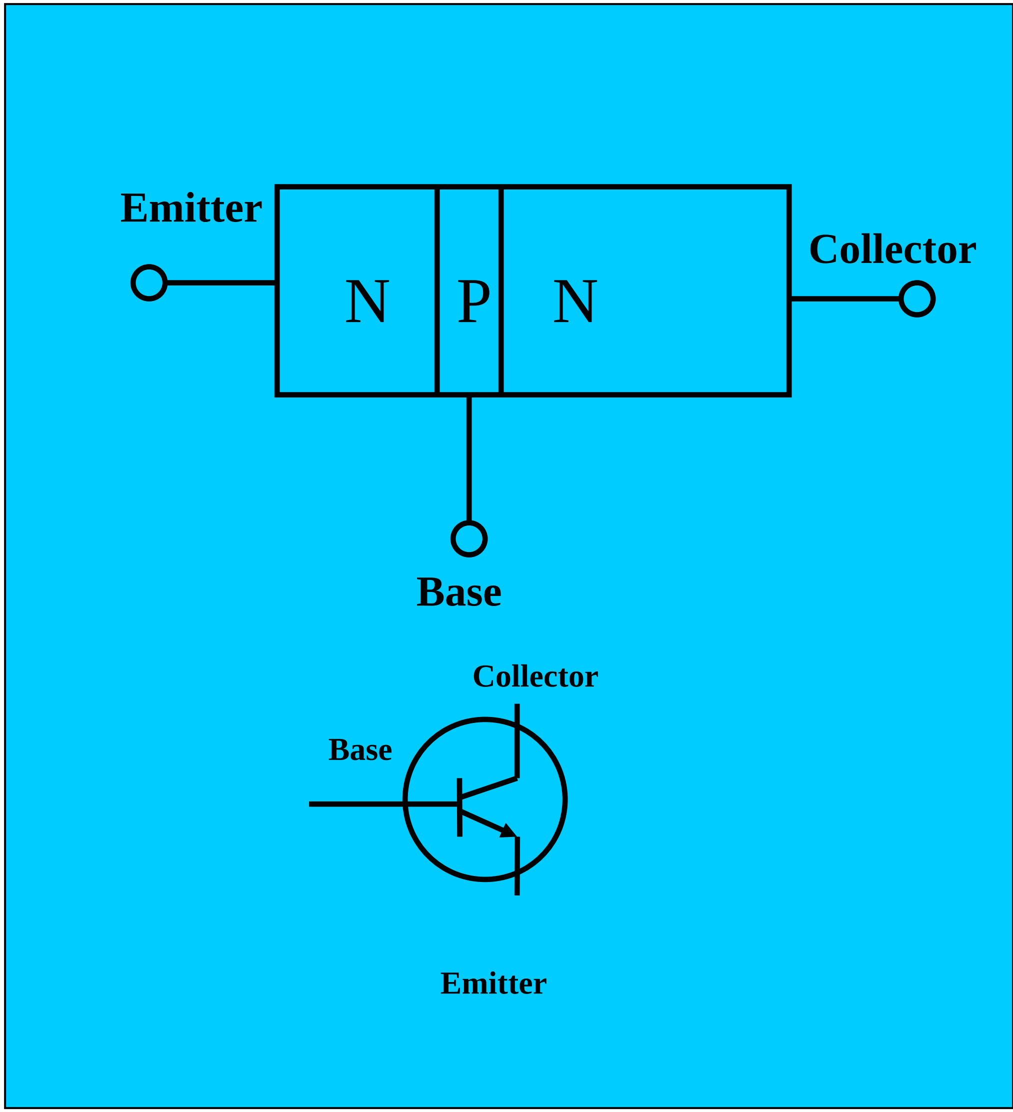
BJT Types

- NPN and PNP.
  - NPN: a small input current and a positive voltage applied @ its base (with $V_B > V_E$) allows a large current to flow from collector to emitter.
  - PNP: a small output current and a negative voltage @ its base (with $V_B < V_E$) allows a much larger current to flow from emitter to collector.



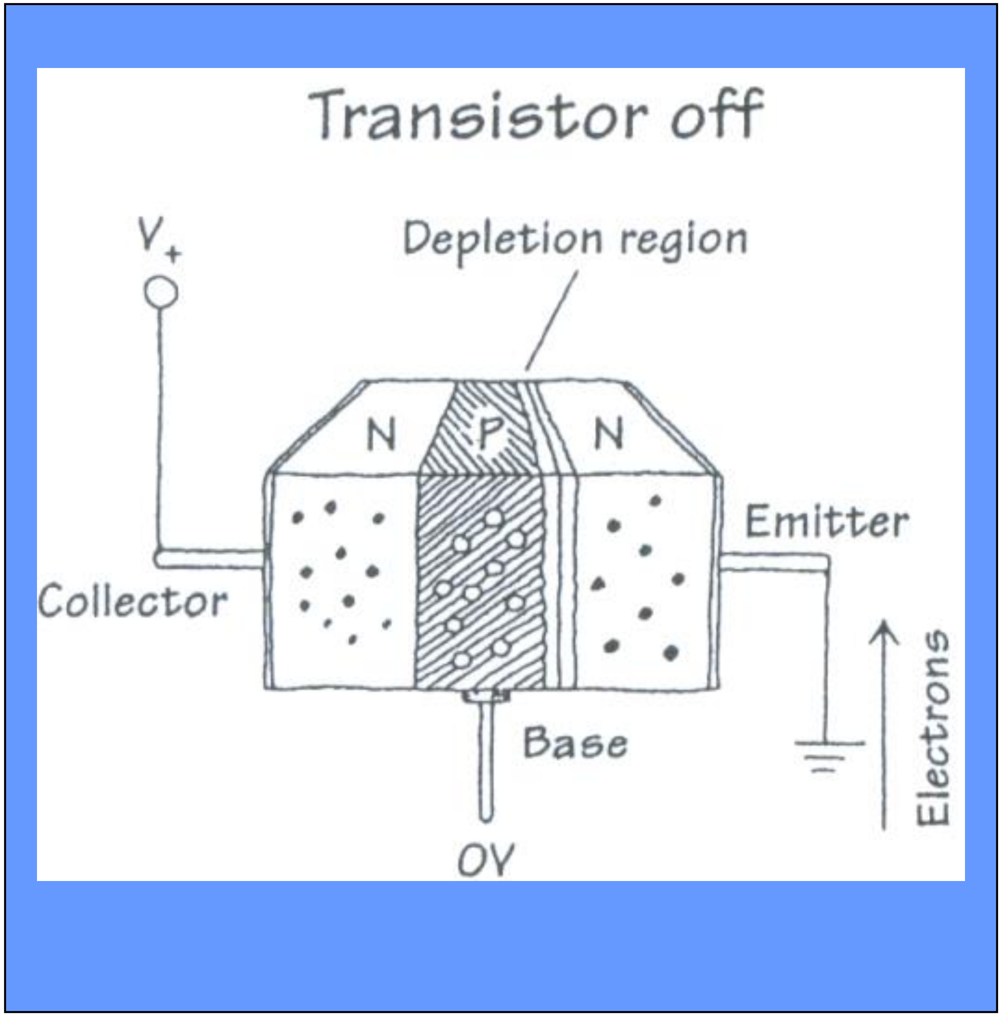
NPN BJT: Construction

- An npn transistor is made by sandwiching a thin slice of p-type semiconductor between two n-type semiconductors.
- Emitter is heavily doped and gives off electrons easily.
- Base is lightly doped and receives most electrons.
- Collector is moderately doped.



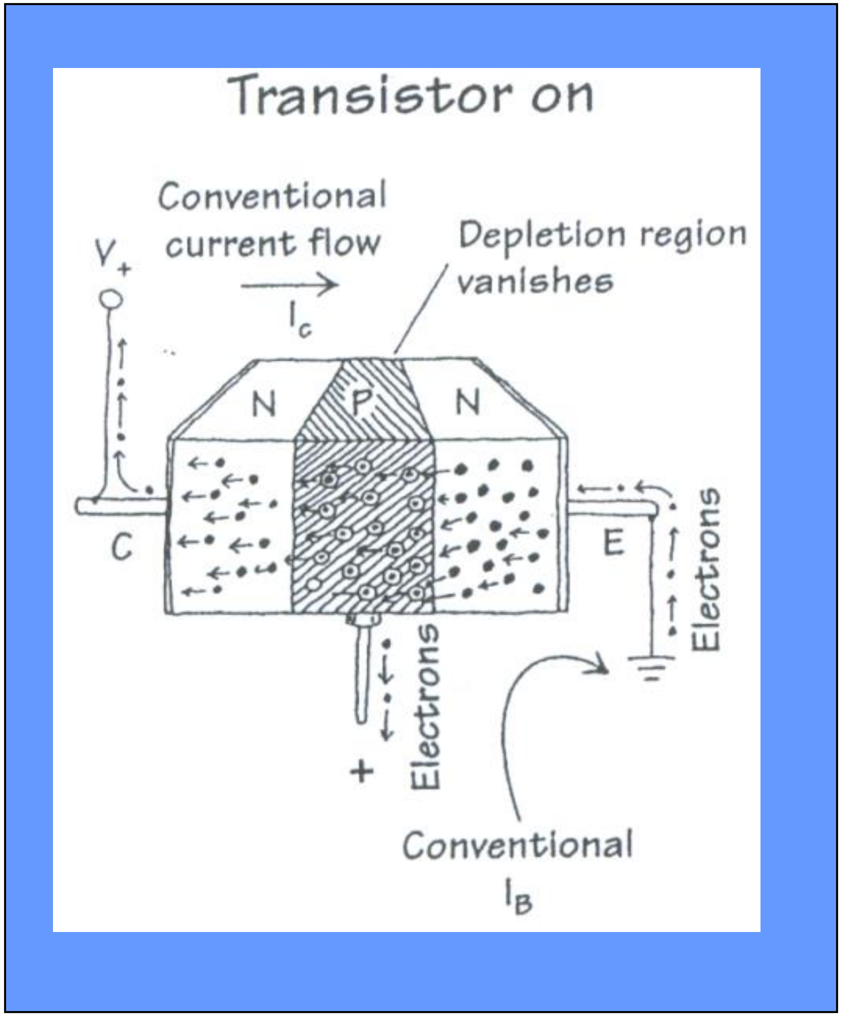
NPN BJT: How it works — I

- When no voltage is applied at transistor’s base, electrons in the emitter are prevented from passing to the collector side because of the pn junction.
- If a negative voltage is applied to the base, things get even worse as the pn junction between the base and emitter becomes reverse-biased resulting in the formation of a depletion region that prevents current flow.

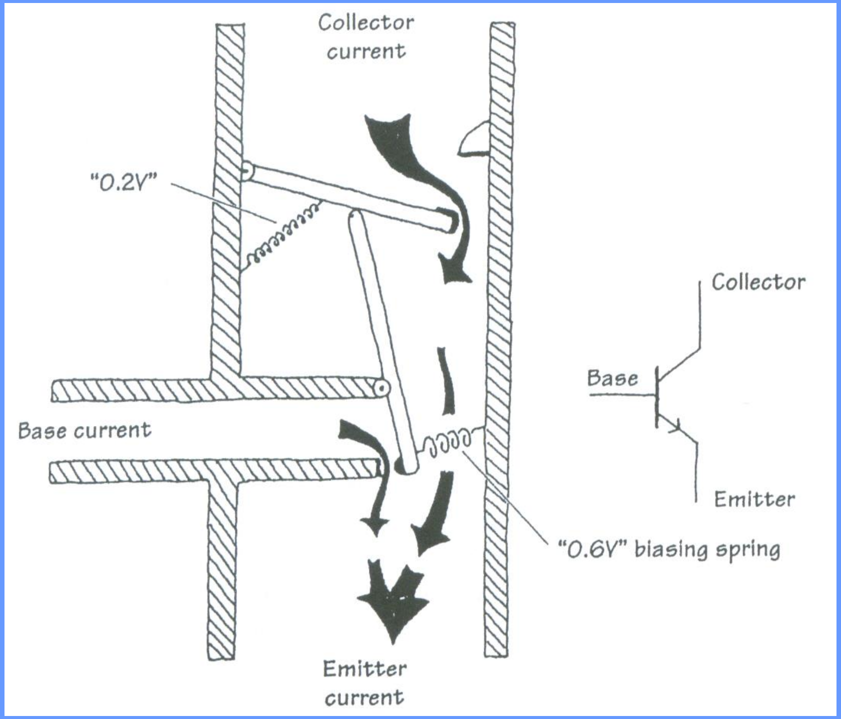


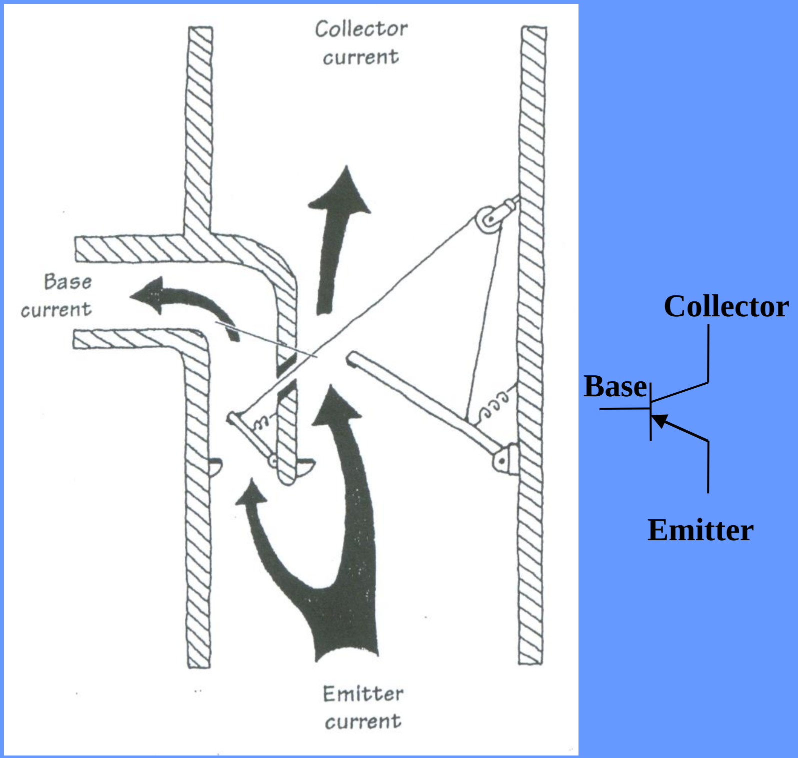
NPN BJT: How it works — II

- If a positive voltage (>0.6V) is applied to the base of an npn transistor, the pn junction between the base and emitter becomes forward-biased. During forward bias, escaping electrons are drawn to the positive base.
- Some electrons exit through the base, but because the p-type base is so thin, the onslaught of electrons that leave the emitter get close enough to the collector side that they begin jumping into the collector. Increasing the base voltage increases the emitter-to-collector electron flow.
- Recall, positive current flow is in the direction opposite to the electron flow →current flows from collector to emitter.



BJT Water Analogy



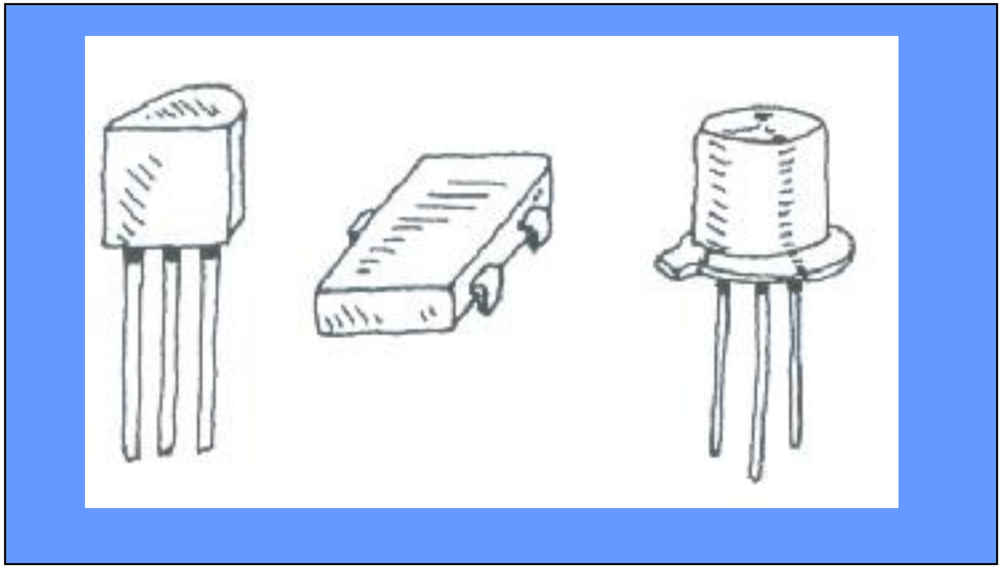


NPN ($V_B > V_E$)

PNP ($V_B < V_E$)

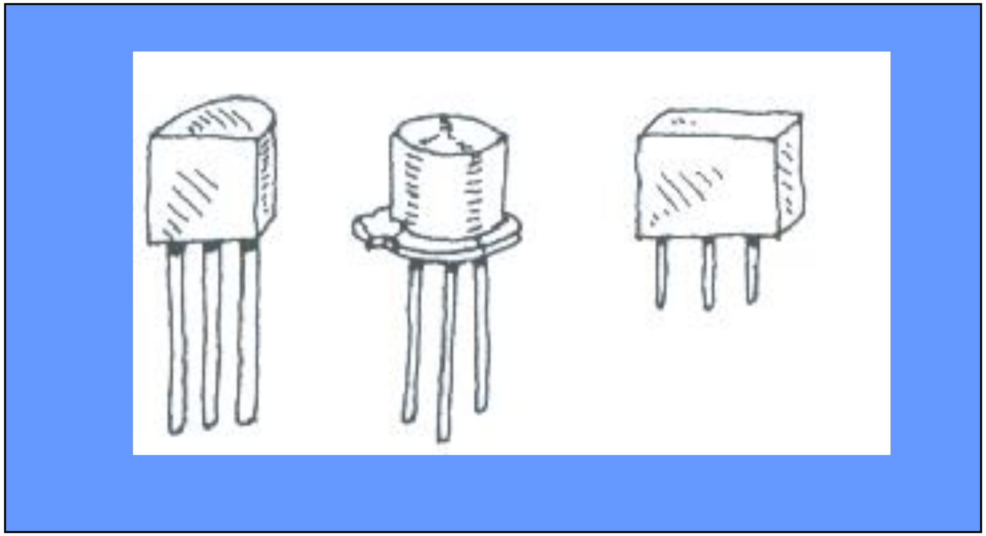
Types of BJT — Small Signal

- Typical usage:
  - Amplification of low-level signal.
  - Switching application.
- Typical h_{FE} (transistor gain) in the range of 10 to 500.
- Maximum I_c rating from 80 to 600mA.
- Maximum operating frequencies: from 1 to 300MHz.
- Available in both npn and pnp forms.



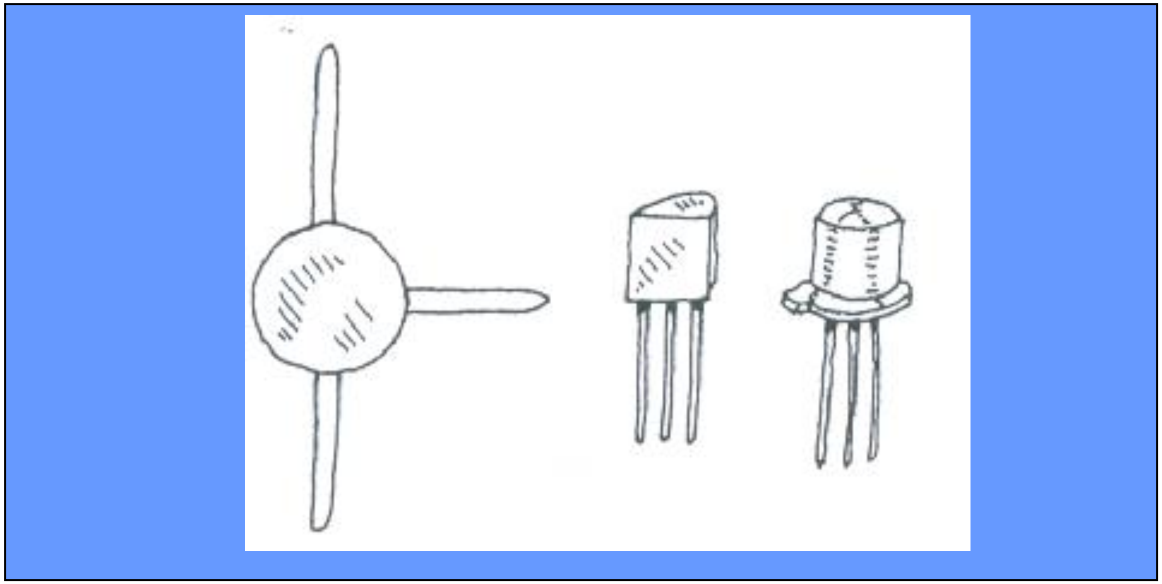
Types of BJT —Switching

- Typical usage:
  - Switching application.
  - Amplifiers.
- Typical h_{FE} in the range of 10 to 200.
- Maximum I_c rating from 80 to 1000mA.
- Maximum operating frequencies: from 10 to 2000MHz.
- Available in both npn and pnp forms.



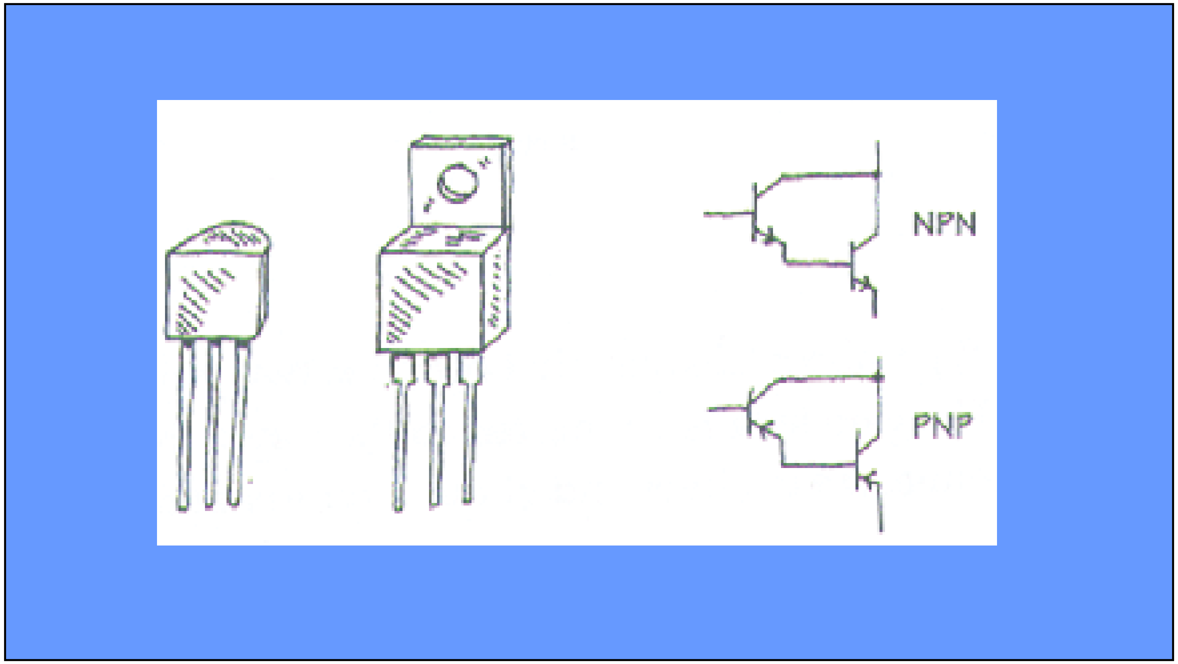
Types of BJT —High Frequency (RF)

- Typical usage:
  - High speed switching applications involving high frequency small signals.
  - HF, VHF, UHF, CATV, and MATV amplifiers and oscillator applications.
- Thin base region.
- Chip size quite small.
- Maximum I_c rating from 10 to 600mA.
- Maximum operating frequencies: 2000MHz.
- Available in both npn and pnp forms.



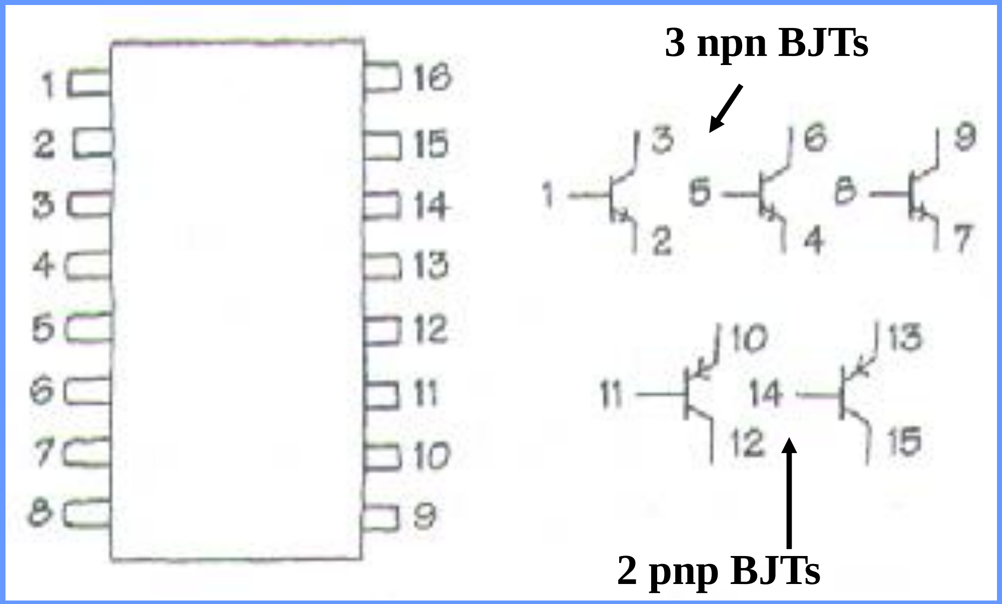
Types of BJT —Darlington Pair

- Two transistors in one!
- Darlington pair transistors provide more stability at higher current level.
- Effective h_{FE} much higher than that of a single transistor:
  - $\rightarrow$ larger current gain!
- Available in both npn (D-npn) and pnp (D-pnp) forms.



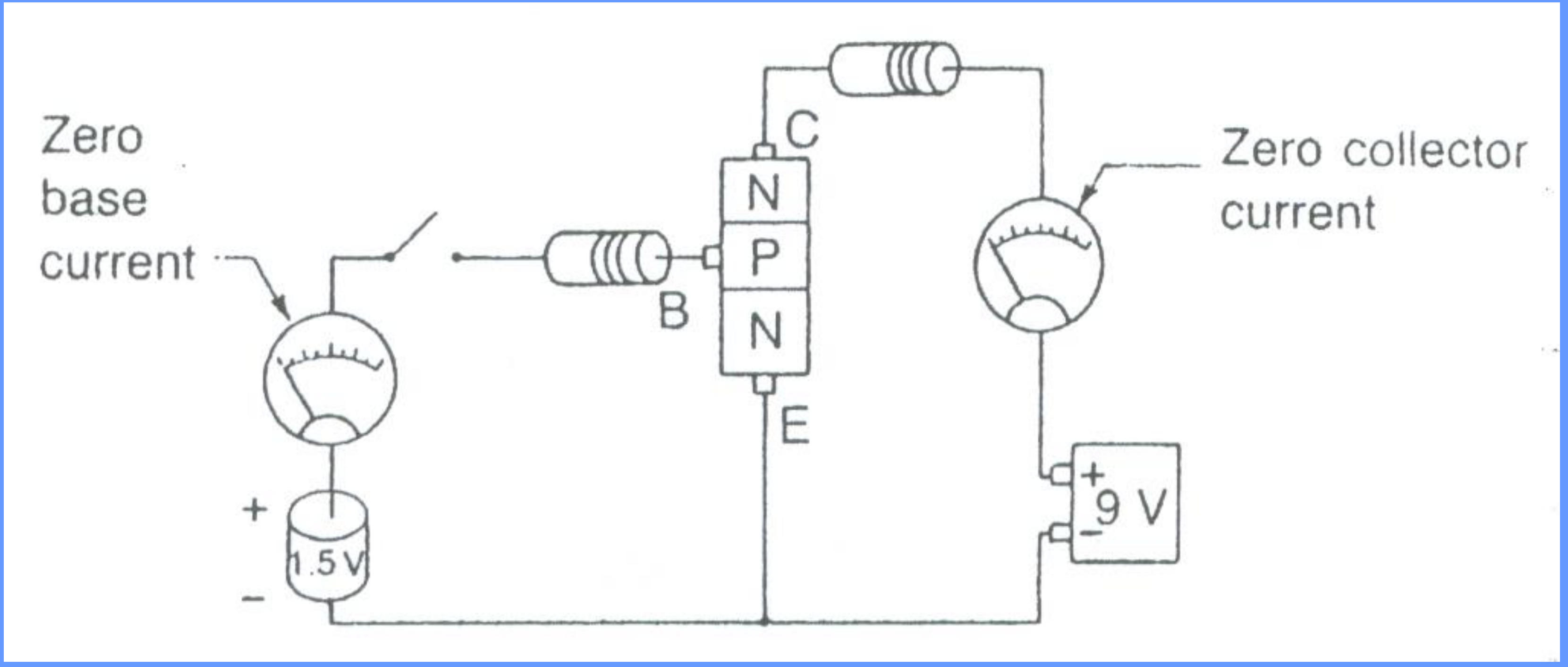
Types of BJT —Transistor Array

- Integrated package consisting of multiple transistors.
- Example transistor array consists of
  - 3 npn transistors and 2 pnp transistors.



NPN Transistor in a Complete Circuit —I

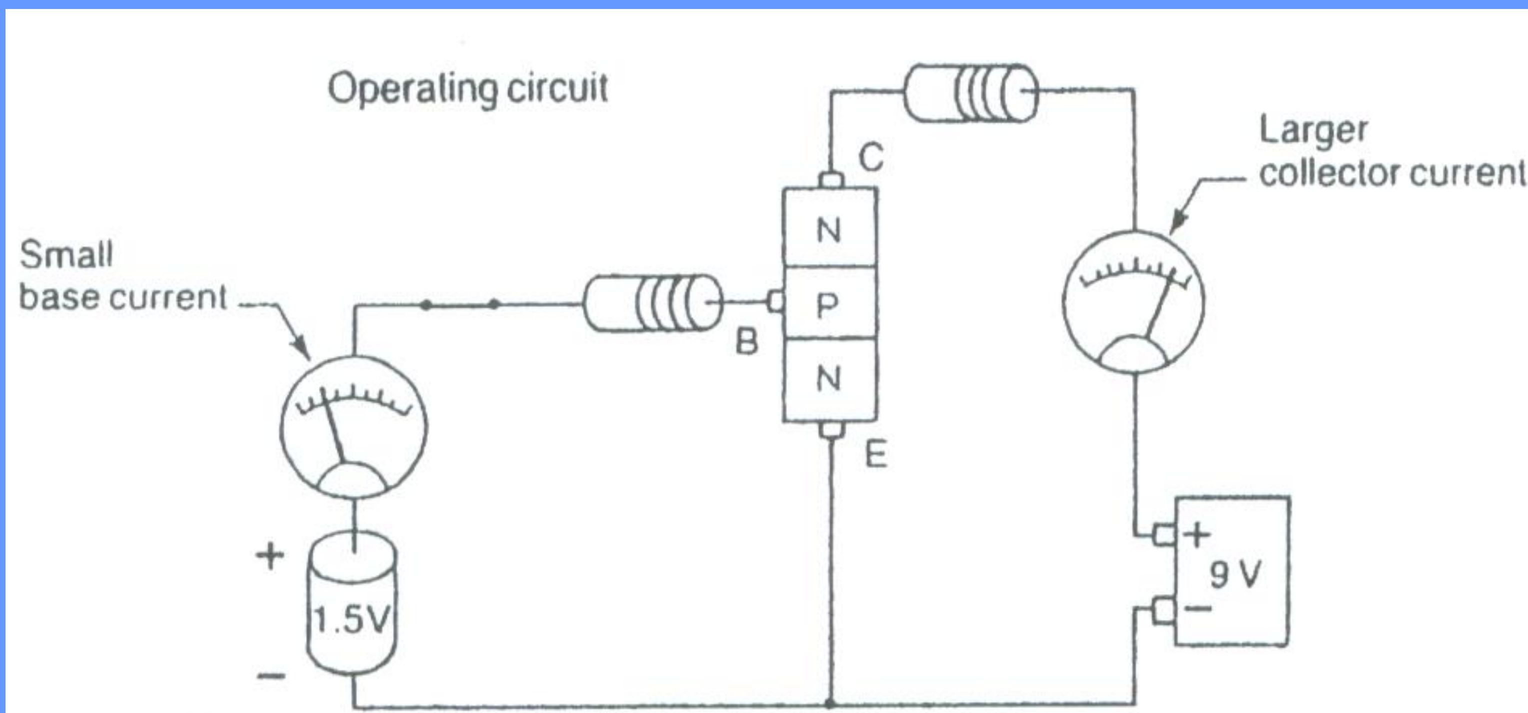
- Normally OFF.
- No current passes from collector to emitter when base is not activated.



NPN: $V_B = V_E \rightarrow$ OFF

NPN Transistor in a Complete Circuit —II

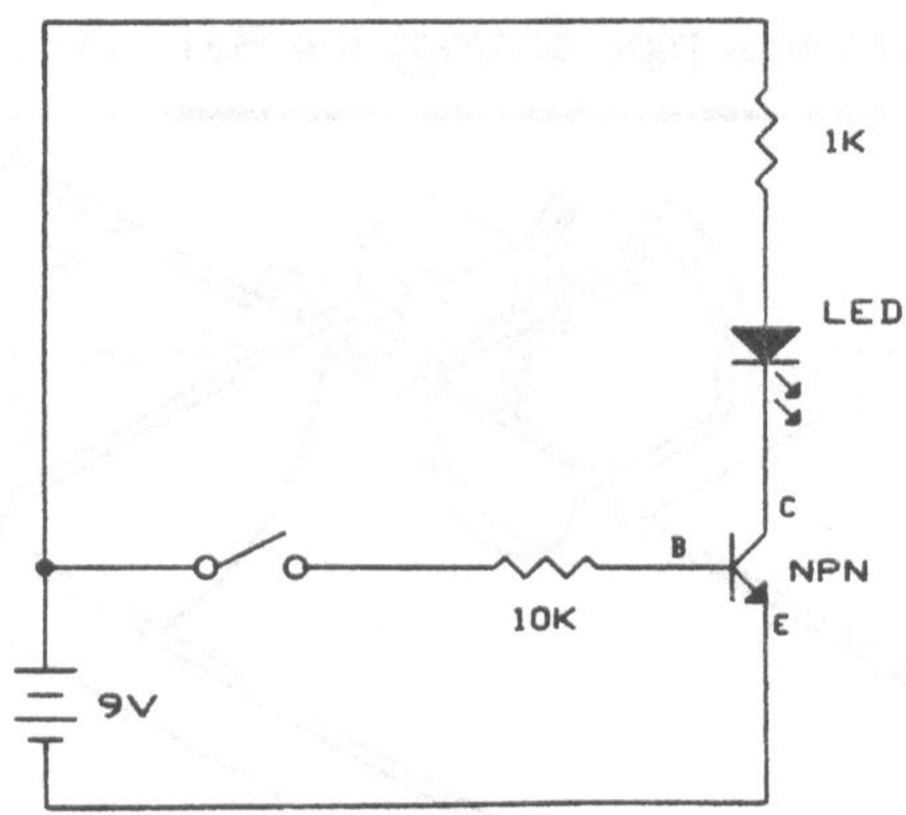
- When $\mathbf{V_B > V_E}$ we have an operating circuit.
- Current passes from collector to emitter when base is activated.



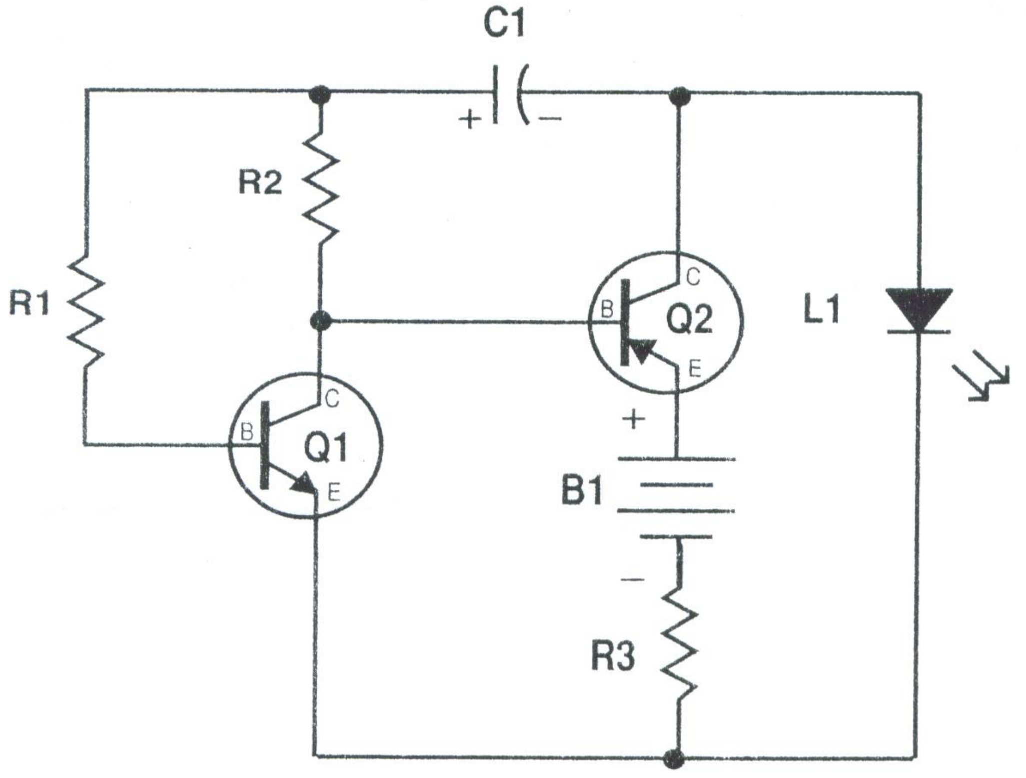
NPN: $V_B > V_E \rightarrow$ON

Transistor Experiment — LED On/Off

- Turning the switch on/off turns the LED on/off.



Transistor Experiment —Oscillator



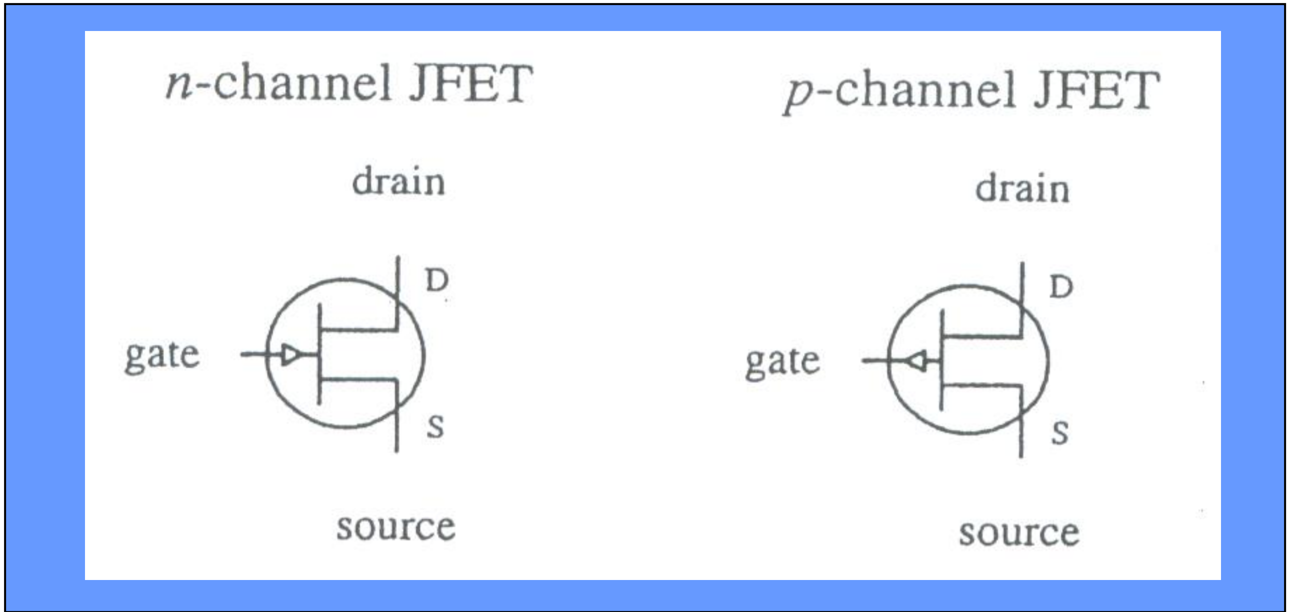
C1	1uF
L1	LED
Q1	NPN transistor
Q2	PNP transistor
R1	4.7kΩ
R2	10MΩ
R3	100Ω

JFET

- Junction field effect transistors like BJTs are three lead semiconductor devices.
- JFETs are used as:
  - electrically controlled switches,
  - current amplifiers, and
  - voltage-controlled resistors.
- Unlike BJTs, JFETs do not require a bias current and are controlled by using only a voltage.
- JFETs are normally on when V_G - V_S = 0.
- When V_G - $V_S \neq 0$, then JFETs become resistive to current flow through the drain-source pair $\rightarrow$ "JFETs are depletion devices."

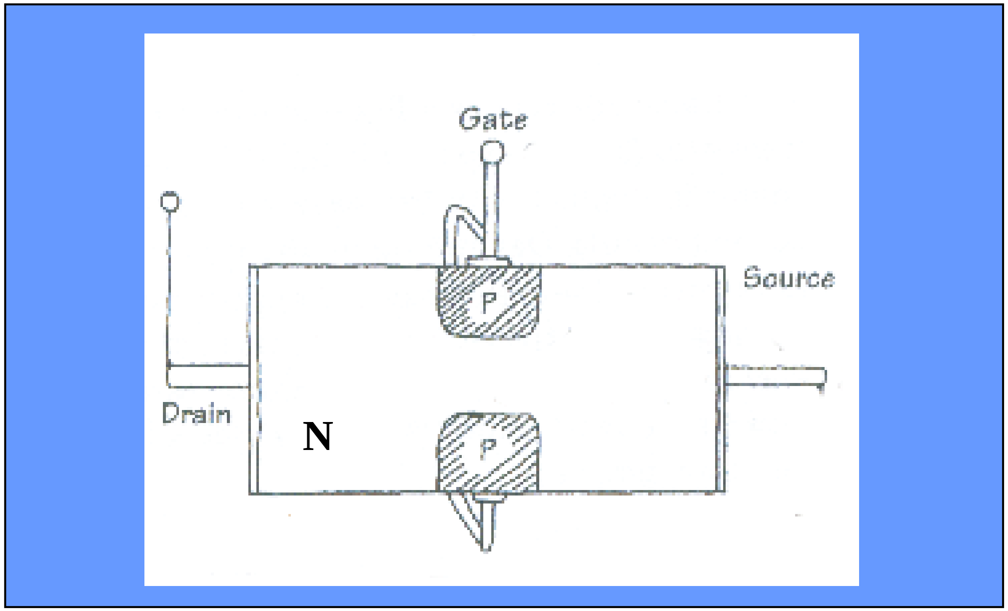
JFET Types

- Two types of JFETs:
  - n-channel and p-channel.
- In n-channel JFET, a –ve voltage applied @ its gate (with $V_G < V_S$) reduces current flow from drain to source. It operates with $V_D > V_S$.
- In p-channel JFET, a +ve voltage applied @ its gate (with $V_G > V_S$) reduces current flow from source to drain. It operates with $V_S > V_D$.
- JFETs have very high input impedance and draw little or no input current
  - → if there is any circuit/component connected to the gate of a JFET, no current is drawn away from or sunk into this circuit.



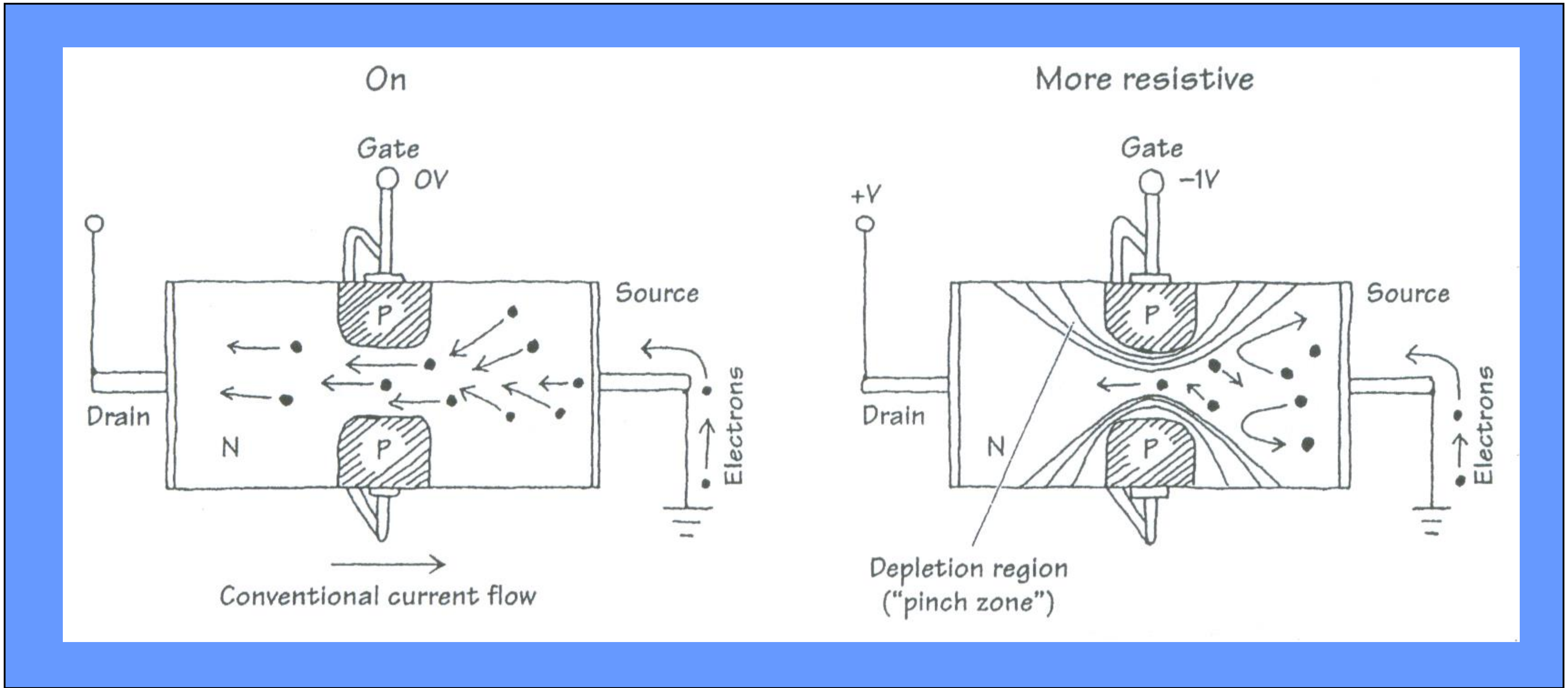
Construction of N-Channel JFET

- An n-channel JFET is made with an n-type silicon channel that contains two p-type silicon bumps on either side.
- The gate lead is connected to the p-type bumps.
- The source and drain leads are connected to the either end of the n-type channel.



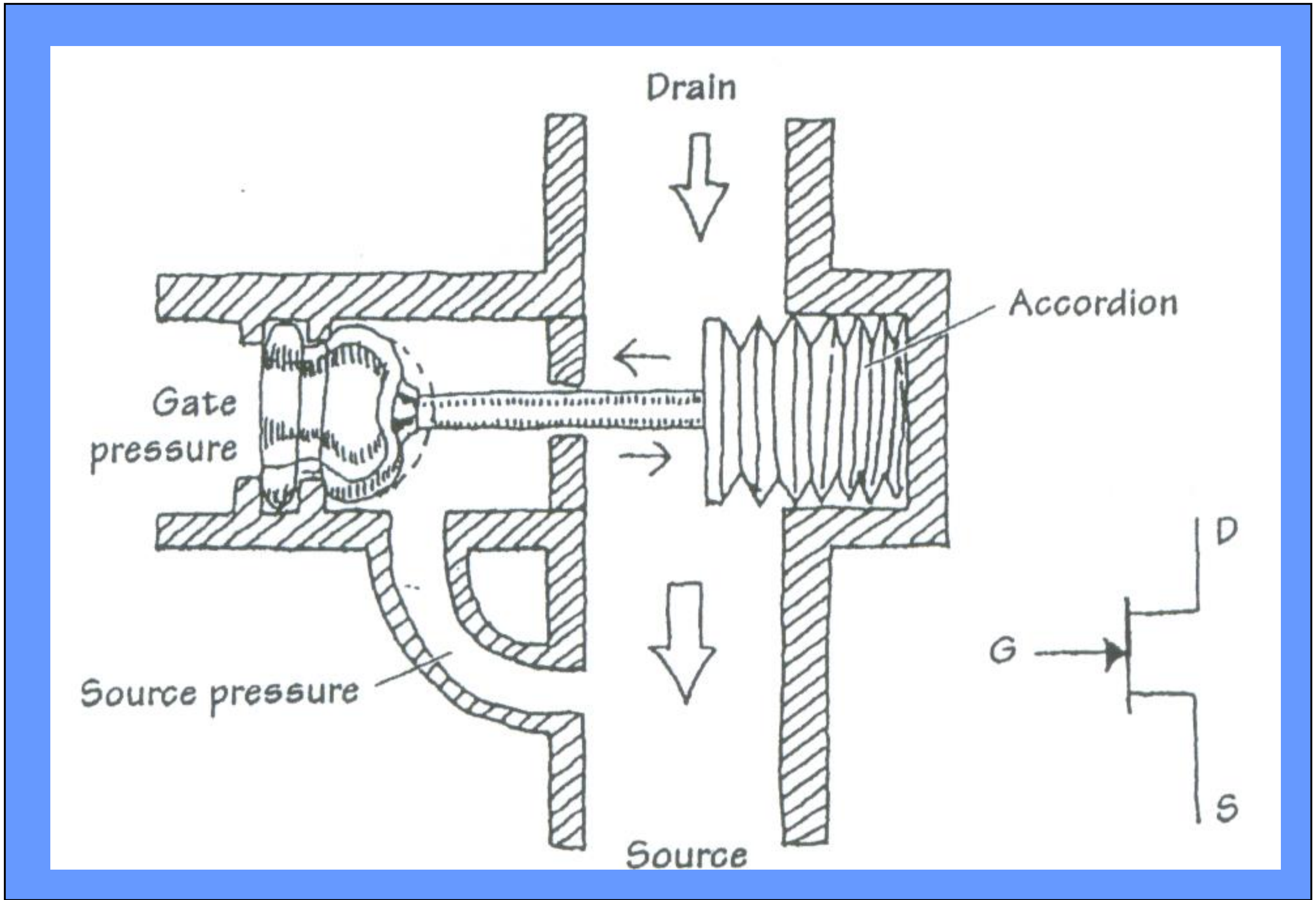
How N-Channel JFET Works

- With source at ground, when no voltage is applied to the gate, electrons flow from source to drain through n-channel without any problem.
- When the gate is set at a negative voltage relative to the source, the area between the two p-type bumps forms two reversed-biased junctions creating a depletion region that extends into the channel.
- The greater the negative voltage at the gate, the larger the depletion region.
  - $\rightarrow$ The depletion region blocks the flow of electrons from the source to drain.

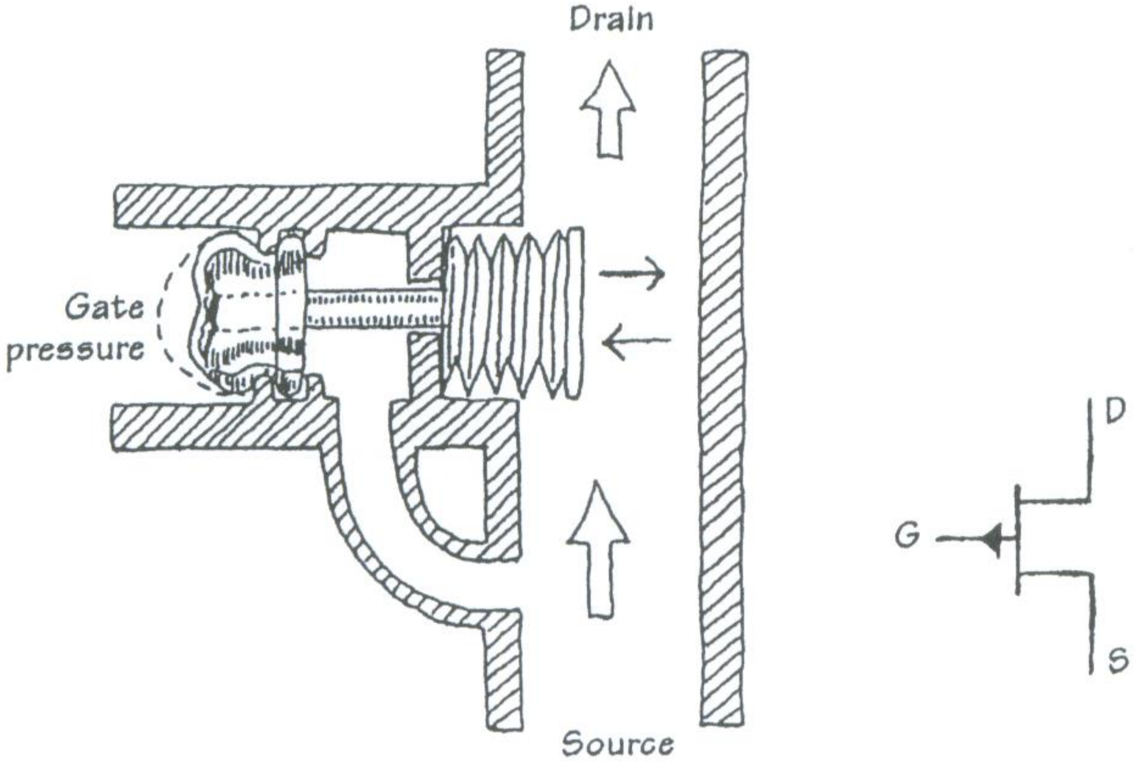


N-Channel JFET Water Analogy

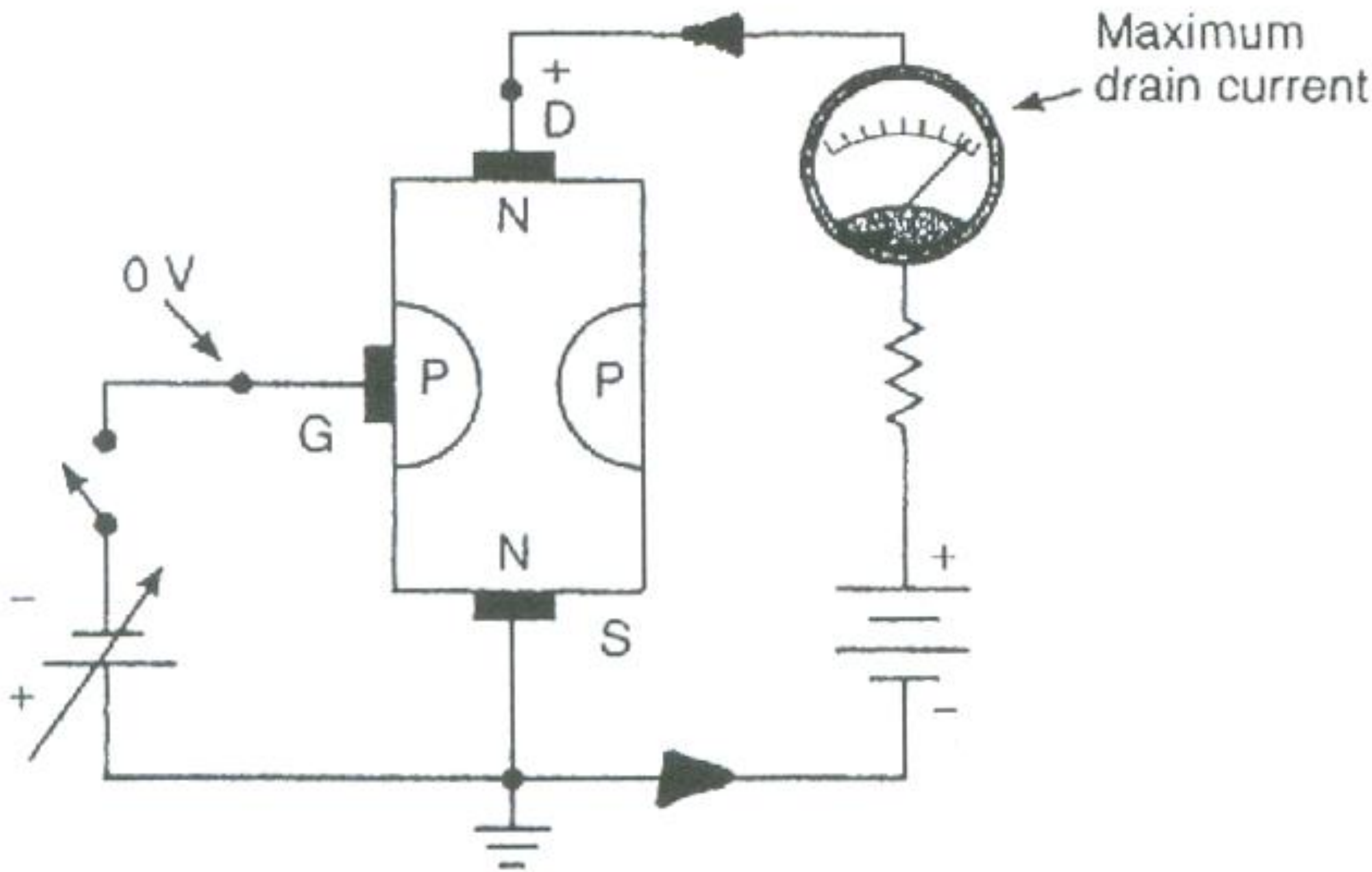
- With gate pressure w.r.t. to source is zero, the drain-source channel is open allowing water flow.
- Plunger prevents water flow from source to gate!
- With gate pressure w.r.t. source is negative, plunger is forced leftward, opening the accordion which blocks the drain-source channel effectively shutting down water flow.



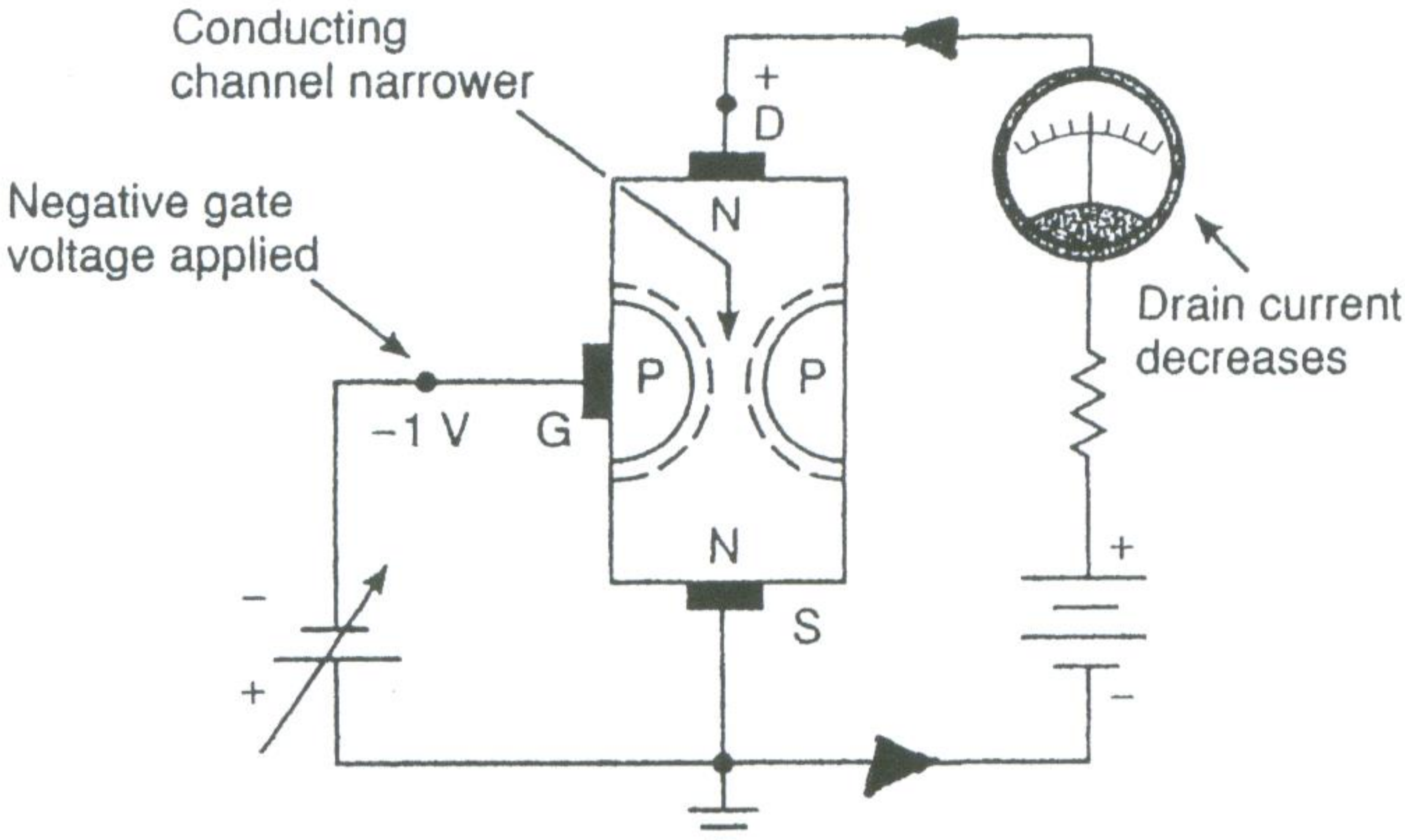
P-Channel JFET Water Analogy



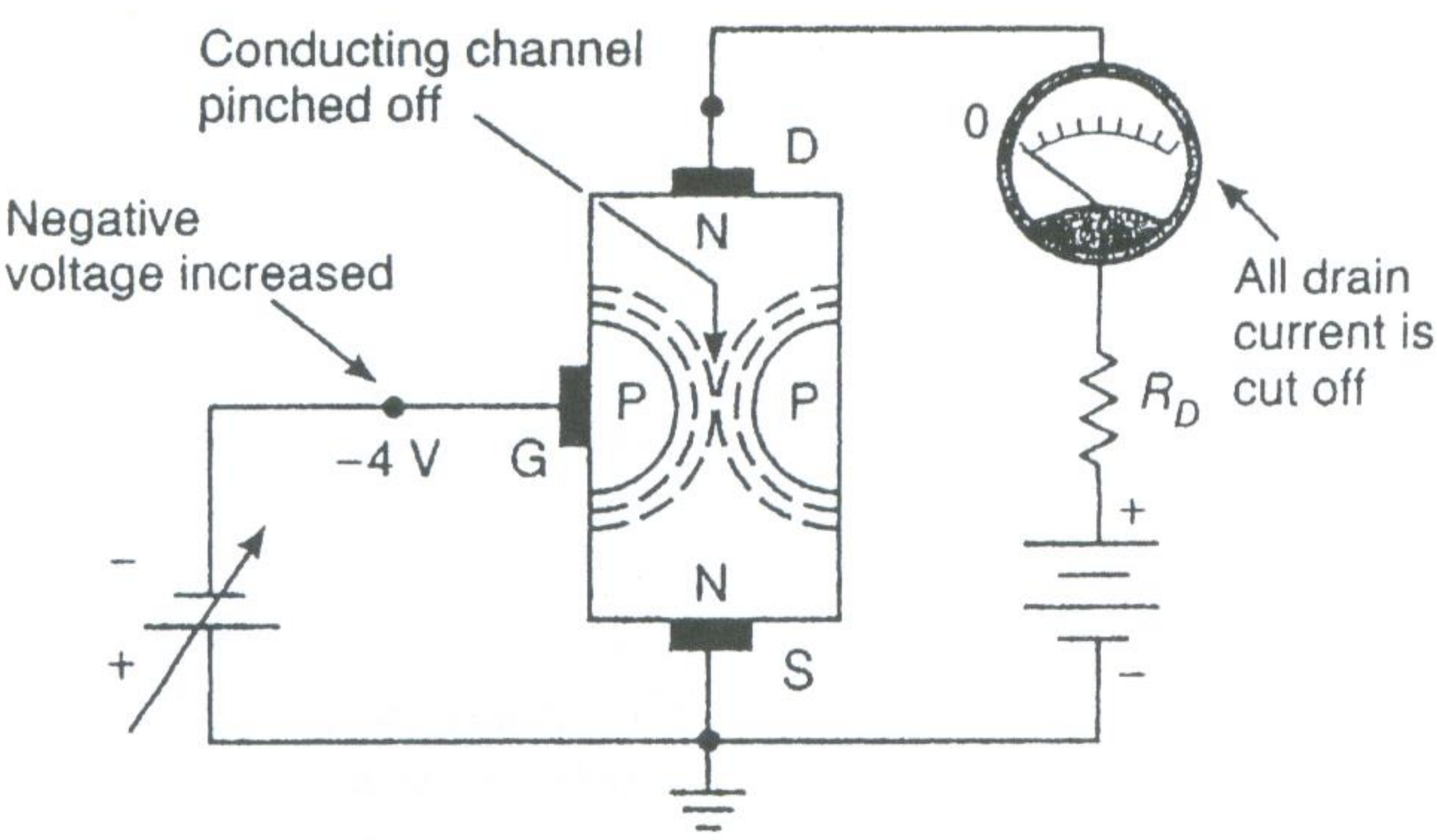
JFET Currents — Full Current Flow with Inactive Gate



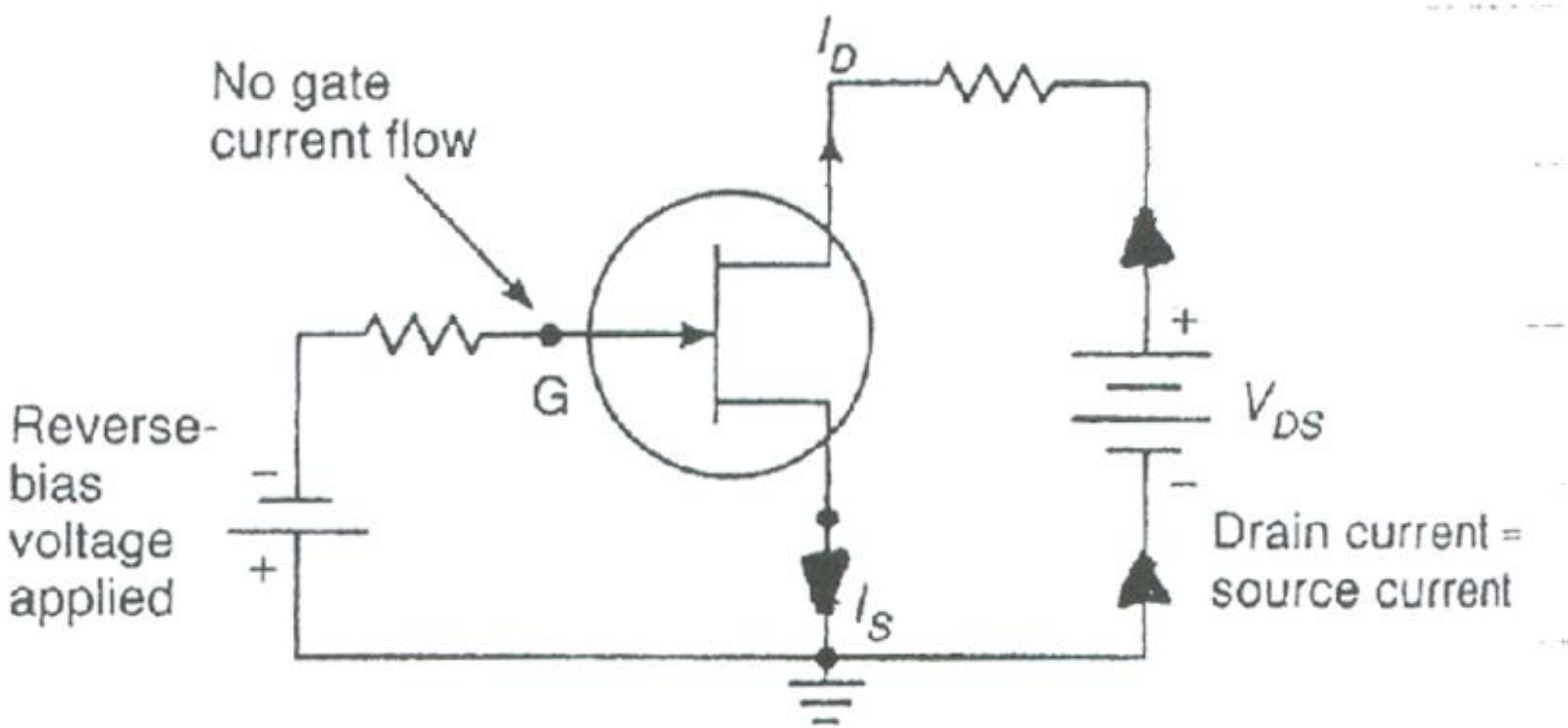
JFET Current —Reduced Drain Current with Partially Active Gate



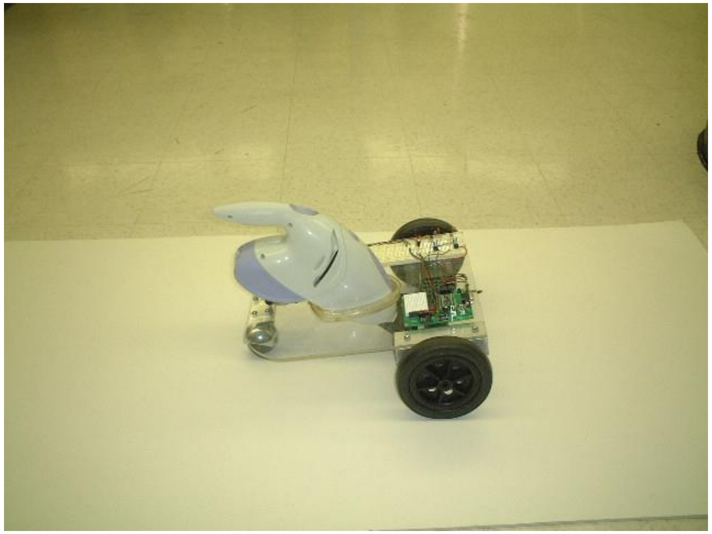
JFET Current —Current Cut-off with Fully Active Gate

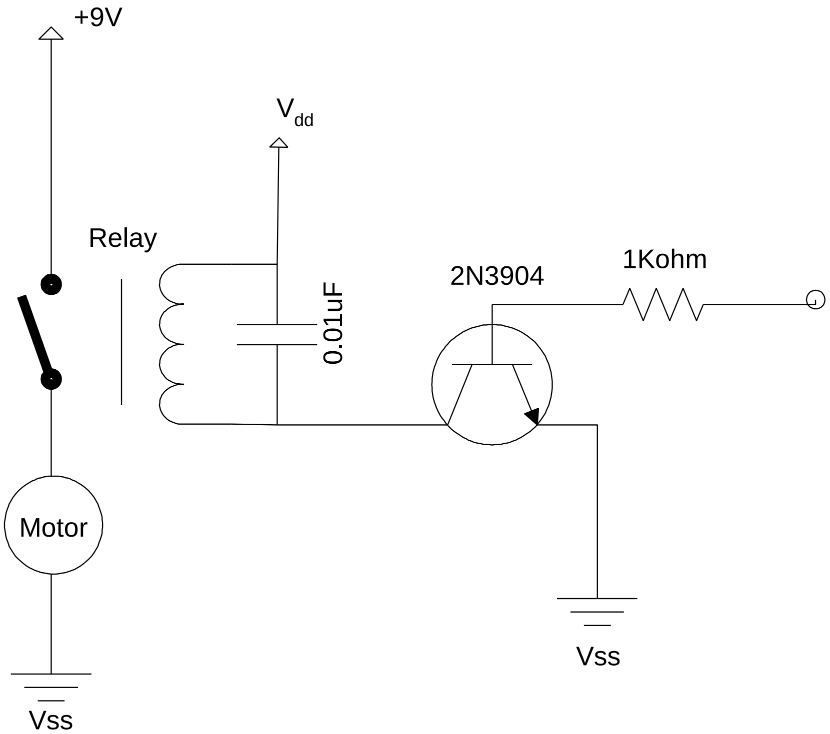


JFET Currents



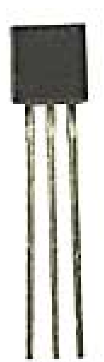
Example Usage of Transistors—I





- This circuit is used for the Robotic Vacuum Cleaner to turn on/off the motor controlling one wheel

Example Usage of Transistors—II

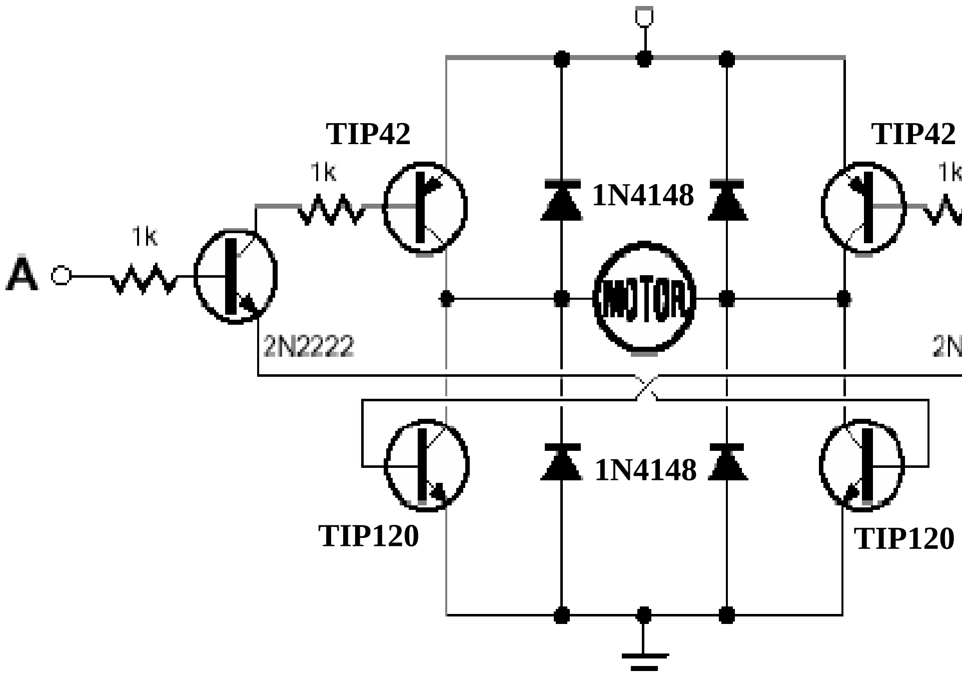


2N3904

- To-92 case
- NPN
- Vceo: 40
- Min. h_{FE} @ Ic: 100 @ .01A

Example Usage of Transistors— III

H-Bridge for Motor Control



A	B	
0	0	stop
0	1	forward
1	0	reverse
1	1	PROHIBITED

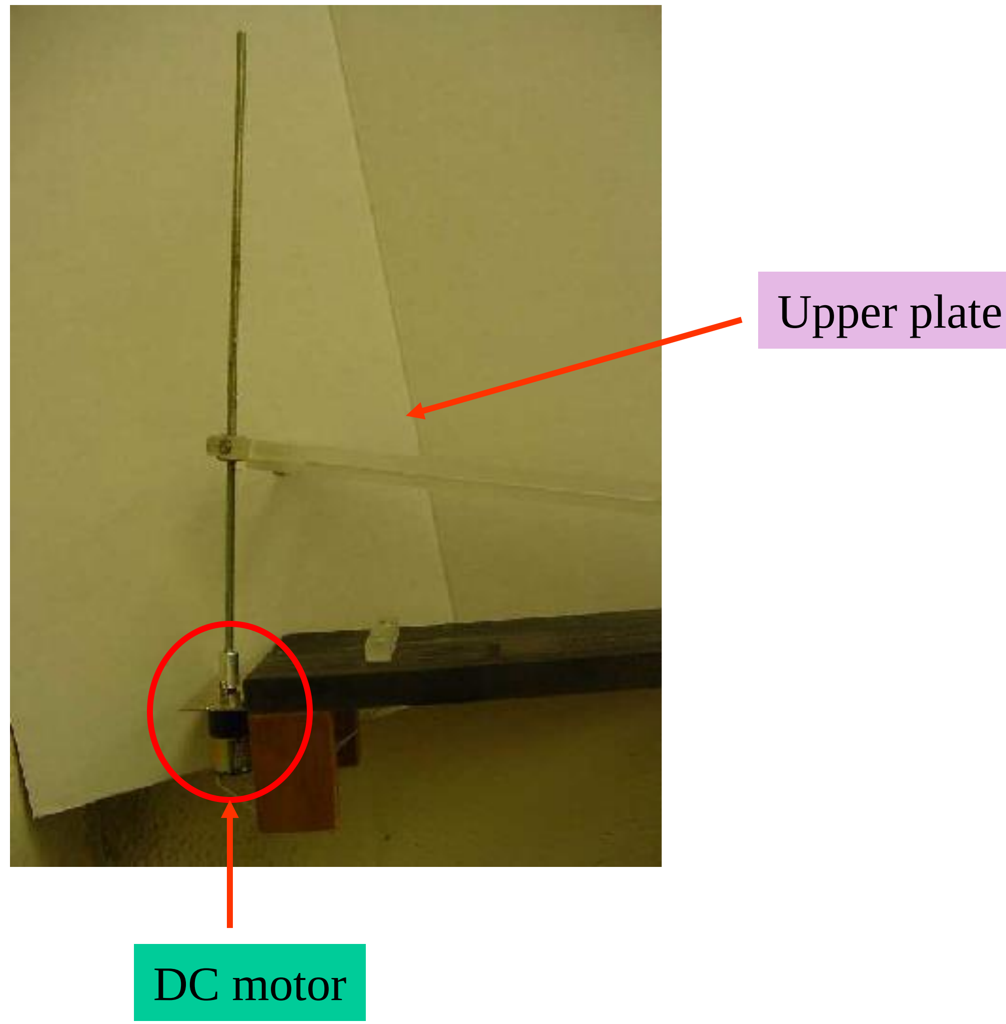
CAUTION: Add diodes to prevent inductive kick-off generated by the motor's coil when the power is switched on and off. Inductive kick-off "flyback voltage" can be many times higher than the supply voltage! If you don't use diodes, you could burn out your transistors

This H-Bridge circuit is used to control a DC motor.

TIP120 is an NPN transistor, TIP42 is PNP transistor, 2N2222 is a general purpose NPN transistor, and 1N4148 is a diode.

Example Usage of Transistors— IV

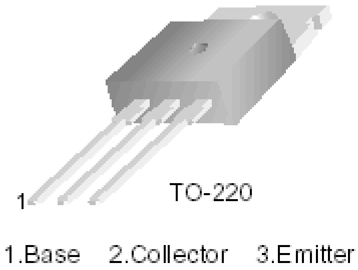
When the angle between the upper plate and the platform is smaller than the input angle, the DC motor will rotate in a direction that moves the upper plate upwards, thereby correcting the angle. If the angle is larger than the input angle, the DC motor will run in a direction that moves the upper plate downwards, thereby correcting the angle. H-bridge allows control of turning direction of the motor.

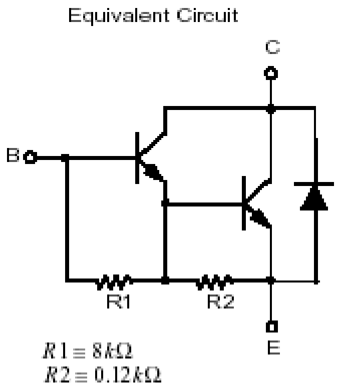


Example Usage of Transistors—V

TIP120

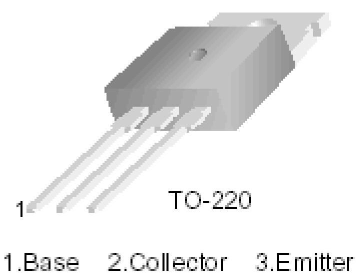
- TO-220 case
- NPN power darlington
- Vceo: 60
- Min. h_{FE}@Ic: 1k @ 3A
- NTE/ECG No.: 261

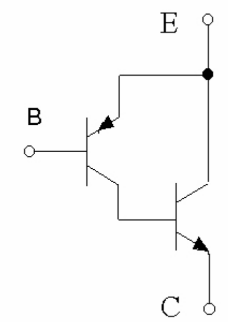




TIP42

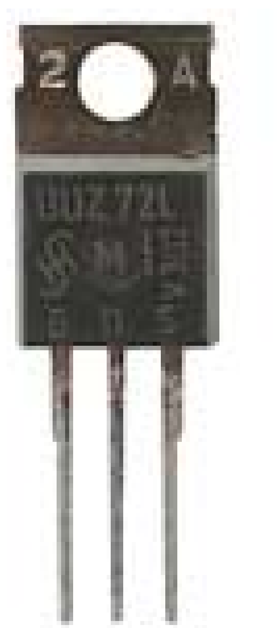
- TO-220 case
- PNP power darlington
- Vceo: 60
- Min. h_{FE}@Ic: 15 @ 3A
- NTE/ECG No.: 332





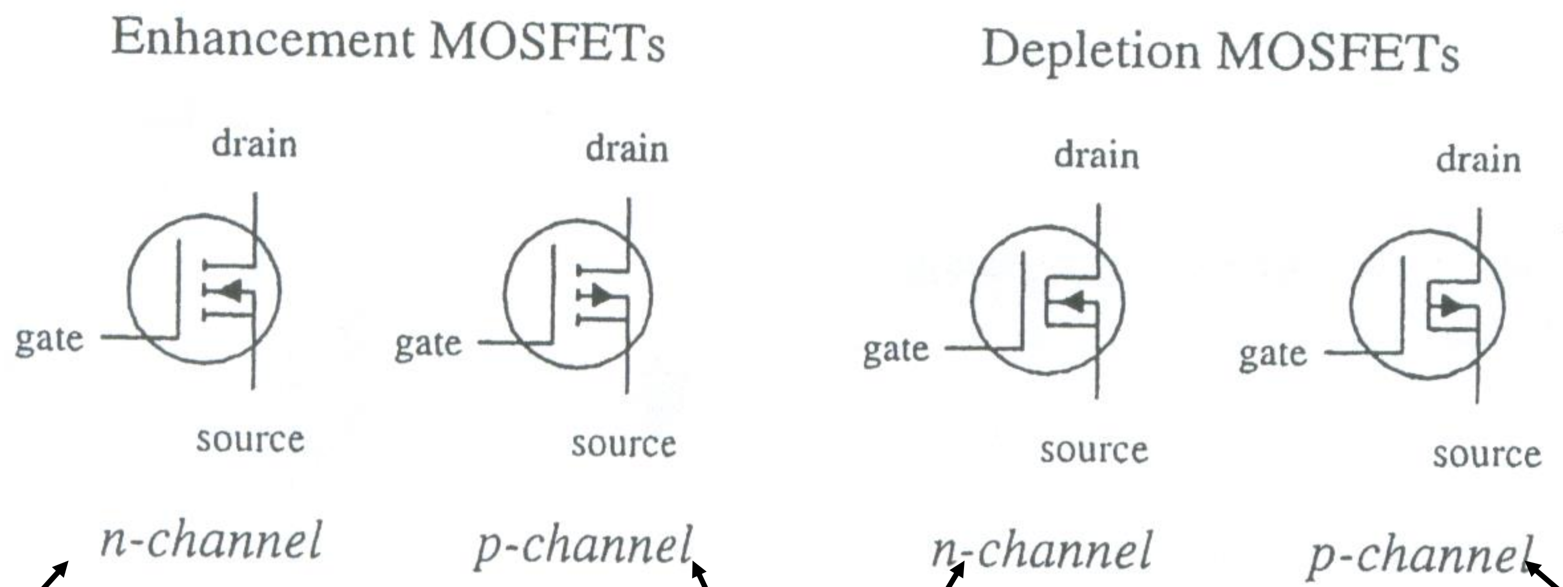
MOSFET

- Metal oxide semiconductor FET.
- Similar to JFET.
- A metal oxide insulator is placed @ the gate to obtain a high input impedance @ the gate
  - gate input impedance approx. $10^{14}\Omega$.
- Use of insulator as described above yields a low gate-to-channel capacitance.
  - If too much static electricity builds up on the gate, then the MOSFET may be damaged.



MOSFET Types

- Enhancement type:
  - Normally off, thus no current flows through drain-source channel when $V_G = V_S$.
  - When a voltage applied @ the gate causes $V_G \neq V_S$ the drain-source channel reduces resistance to current flow.
- Depletion type:
  - Normally on, thus maximum current flows through drain-source channel when $V_G = V_S$.
  - When a voltage applied @ the gate causes $V_G \neq V_S$ the drain-source channel increases resistance to current flow.



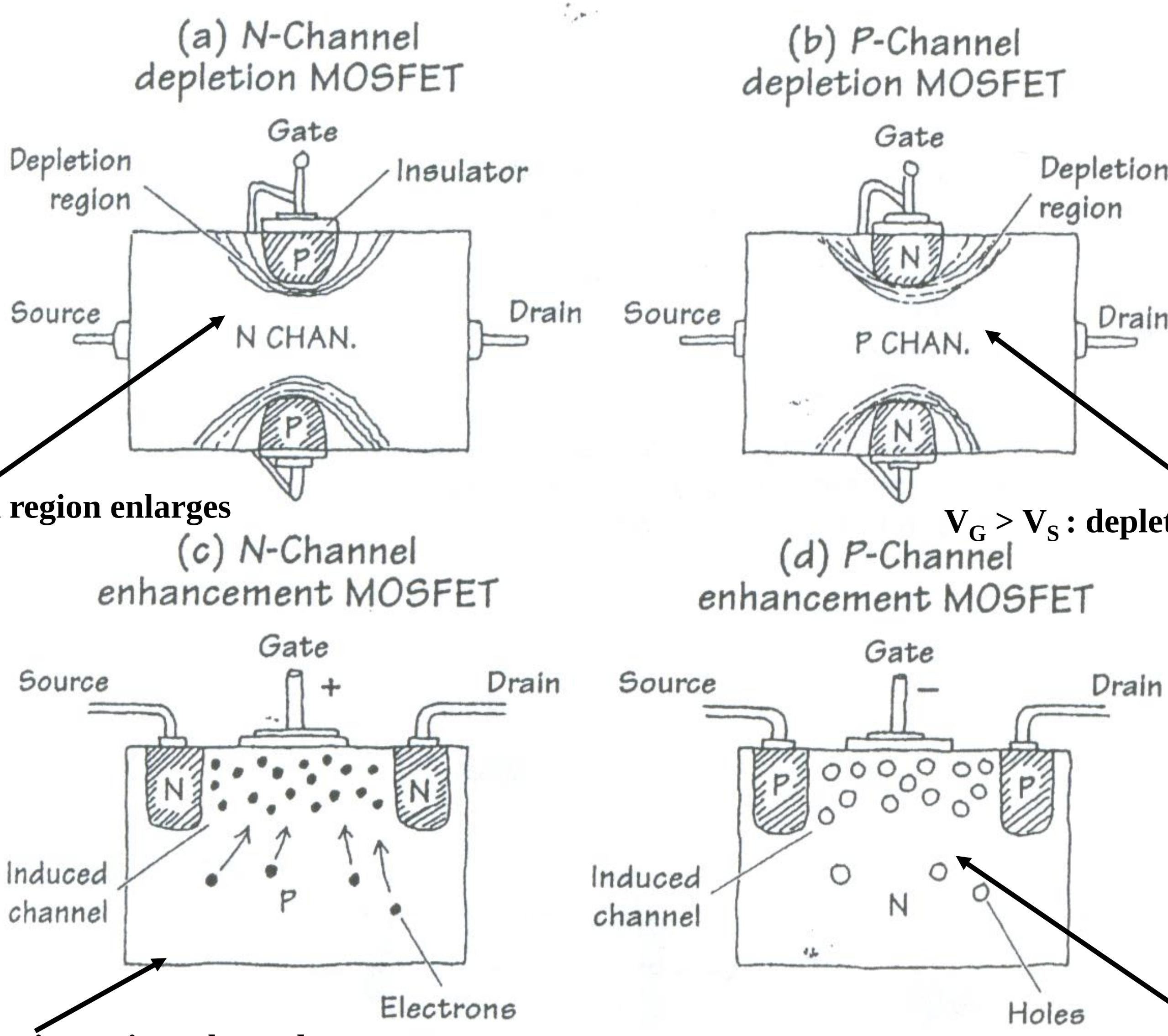
Current flow increases with:

$V_G > V_S$ $V_G < V_S$

Current flow decreases with:

$V_G < V_S$ $V_G > V_S$

How MOSFETs Work



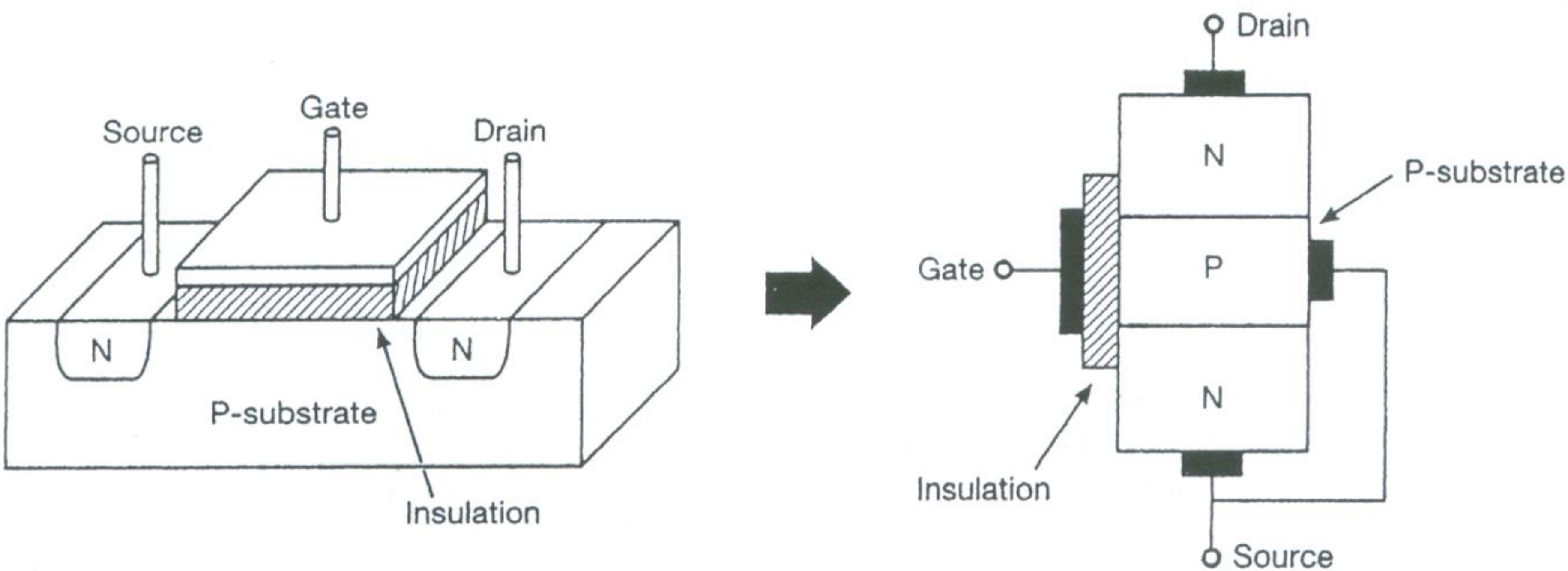
$V_G < V_S$: depletion region enlarges

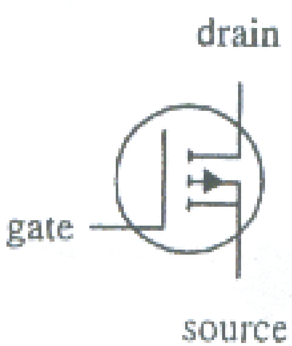
$V_G > V_S$: depletion region enlarges

$V_G > V_S$: electrons migrate into channel, channel conductance increases

$V_G < V_S$: holes migrate into channel, channel conductance increases

P-channel Enhancement MOSFET



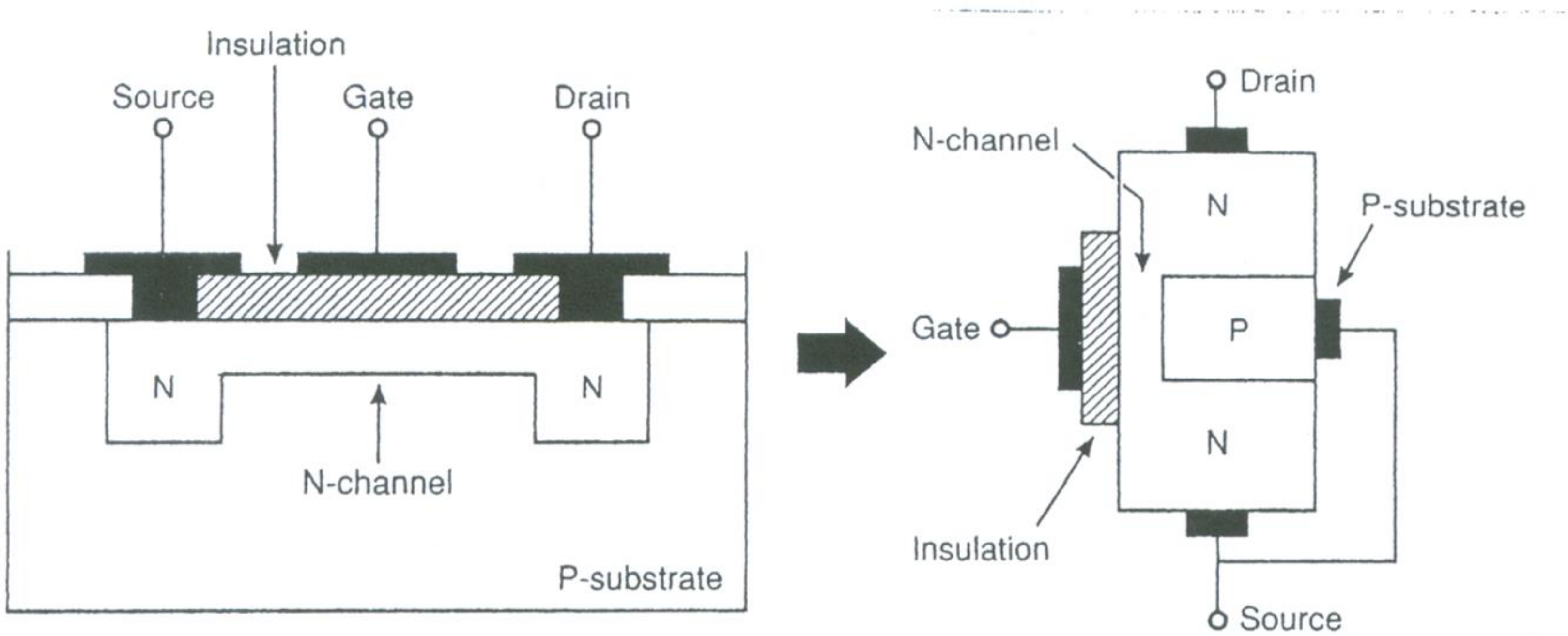


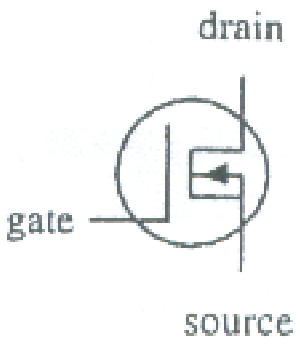
p-channel

•Broken line for channel signifies normally open channel with device OFF.

•In n-channel enhancement MOSFET, the arrow points in the opposite direction.

N-channel Depletion MOSFET





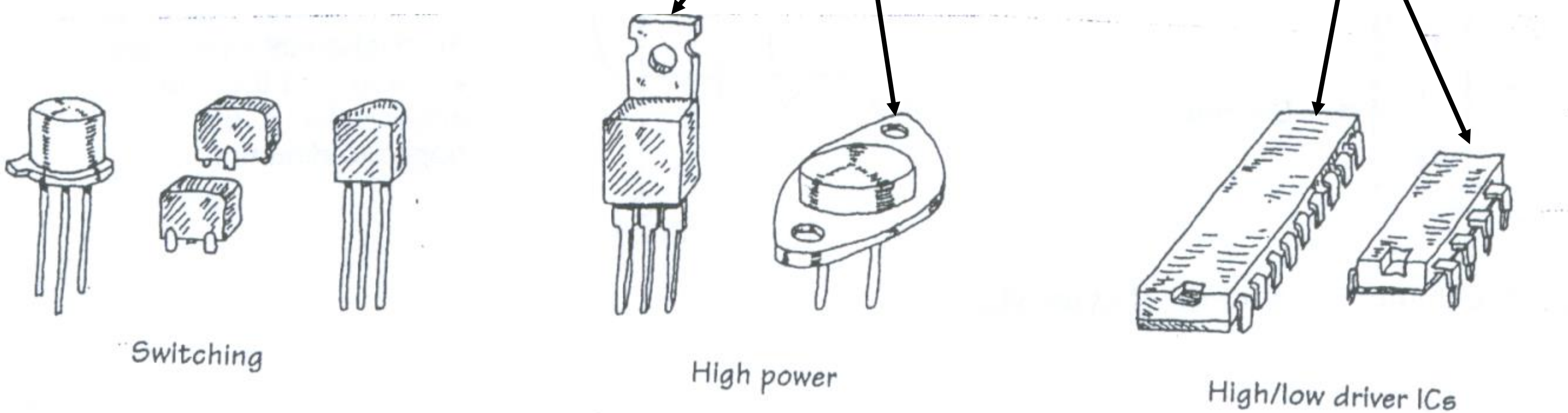
n-channel

- Vertical line on the right of gate represents the channel.
- Solid line for channel signifies normally closed channel with device ON.
- In p-channel depletion MOSFET, the arrow points in the opposite direction.

Kinds of MOSFETs

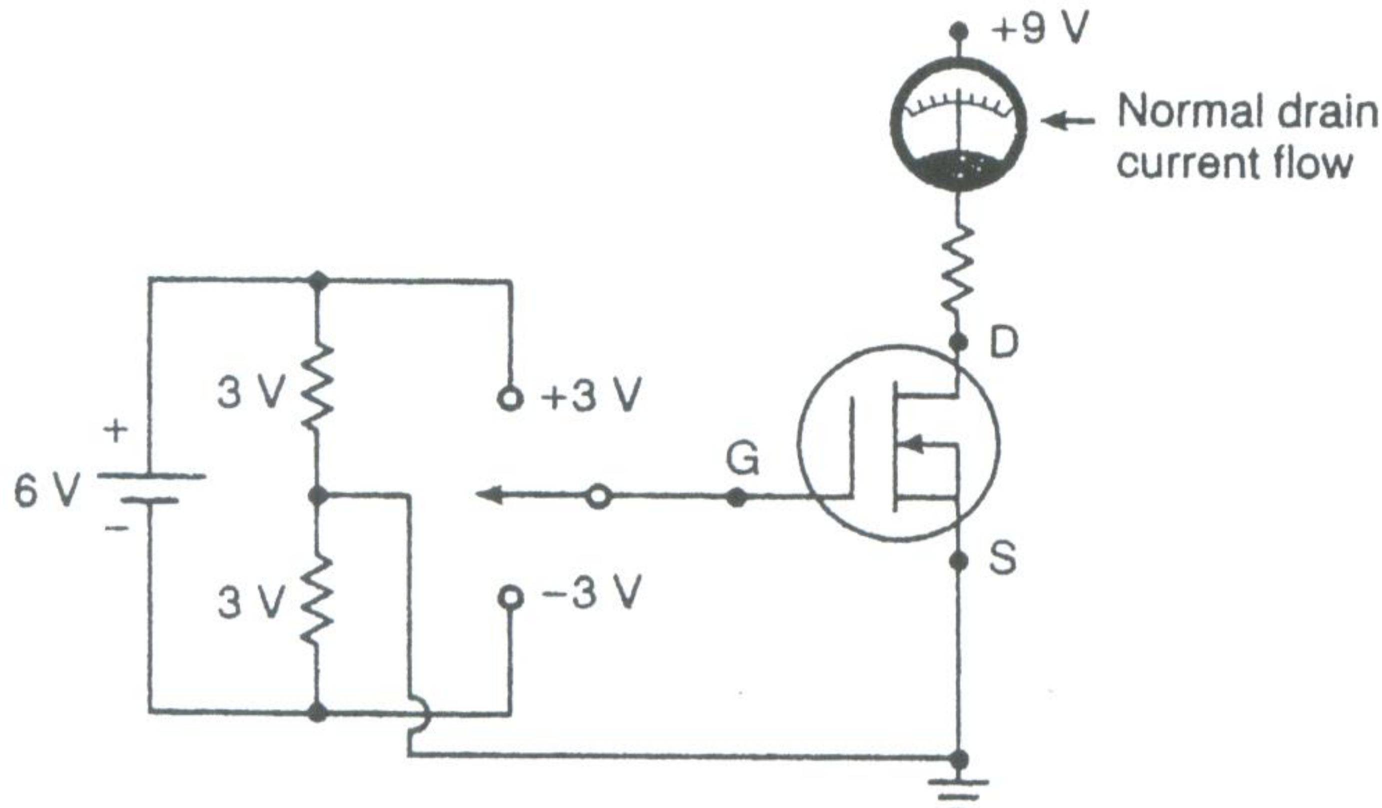
Metal tabs to fasten to heat sink

Operate with logic signals



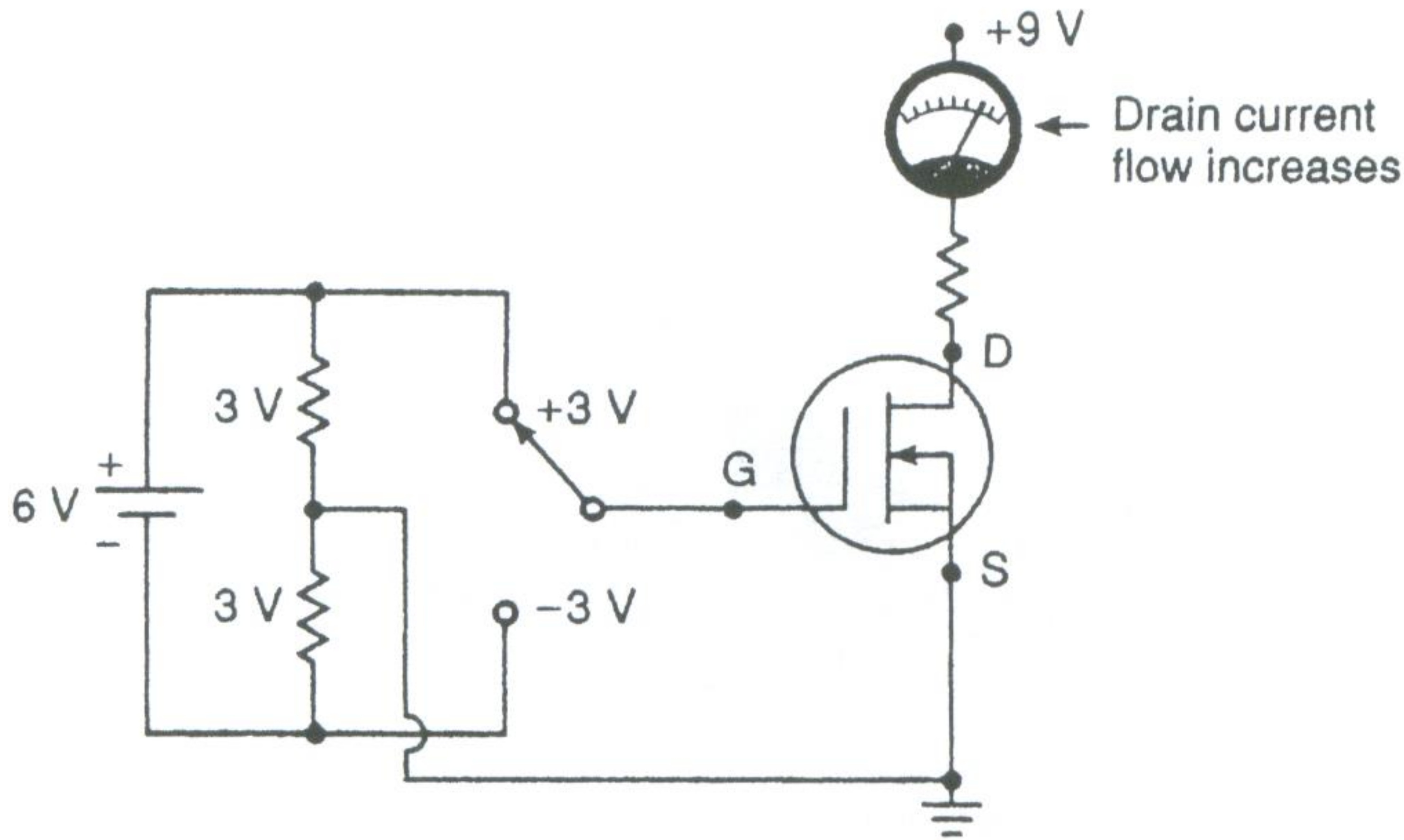
Important: Electrostatic discharge protection!

MOSFET Experiment —I



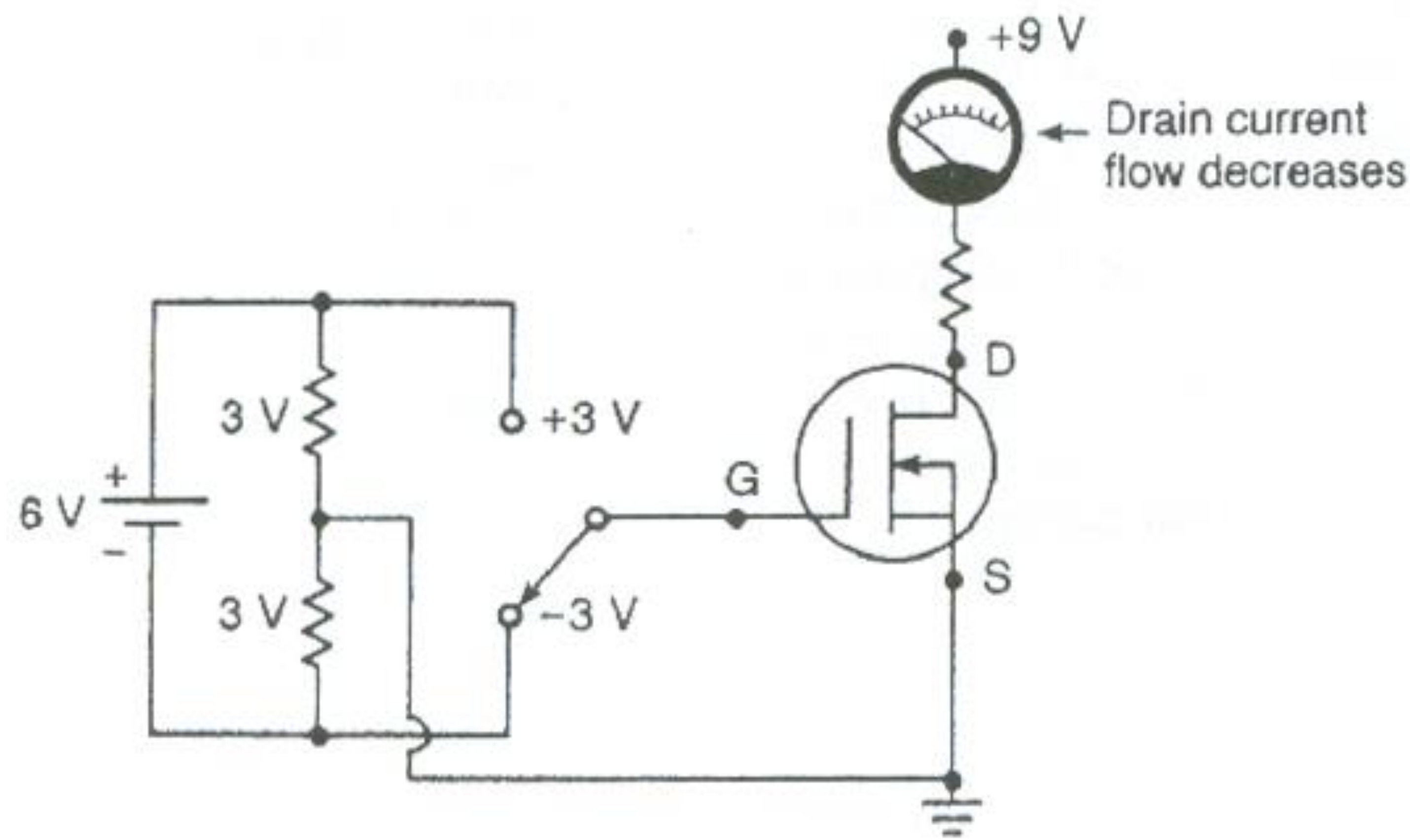
Because of the insulated gate, MOSFETs can withstand a positive voltage at the gate without damage. When the gate-to-source voltage is zero, normal drain current flows as indicated by the milliameter.

MOSFET Experiment —II



When a positive voltage is applied to the gate, the channel becomes slightly more conductive and the drain current flow increases.

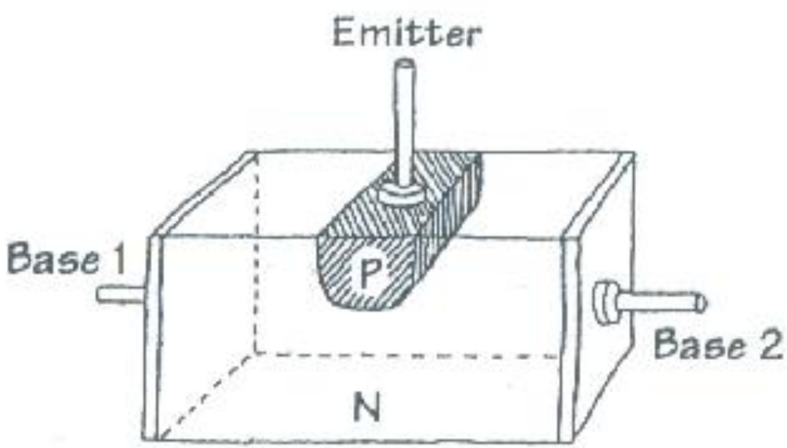
MOSFET Experiment —III

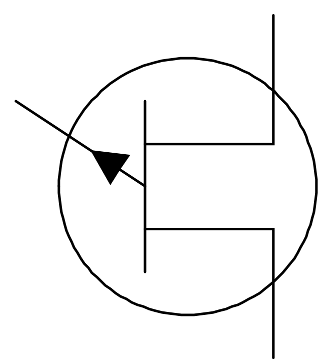


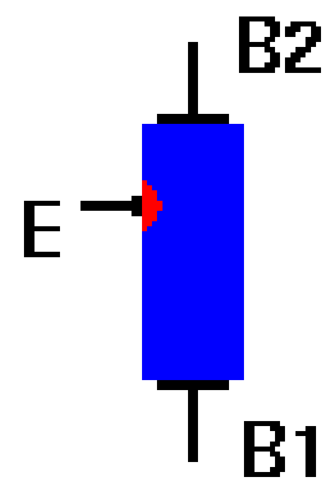
When a negative voltage is applied to the gate, channel resistance increases and the drain current flow drops. If the negative voltage is high enough, no current flow will be conducted between the source and drain.

Unijunction FET (UJT)

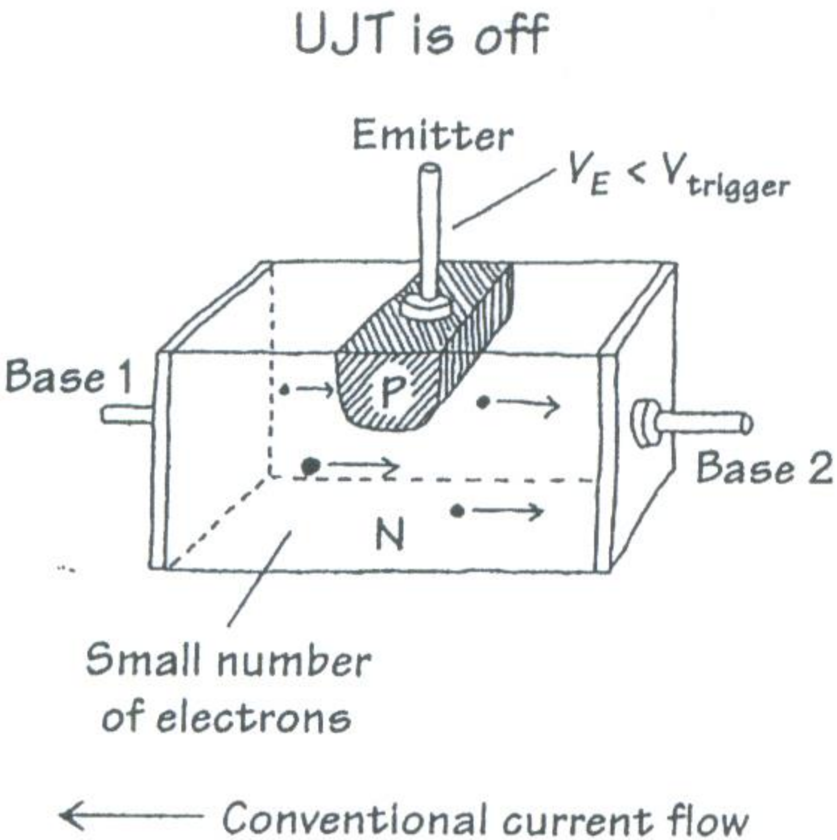
- UJT is a three-terminal device with a single PN junction.
- It consists of a single n-type semiconductor bar with a p-type semiconductor bump in the middle.
- The two ends of the bar make two terminals and the bump represents the emitter terminal.
- UJT cannot amplify an applied signal, however, it can be used as the active element in an oscillator circuit.





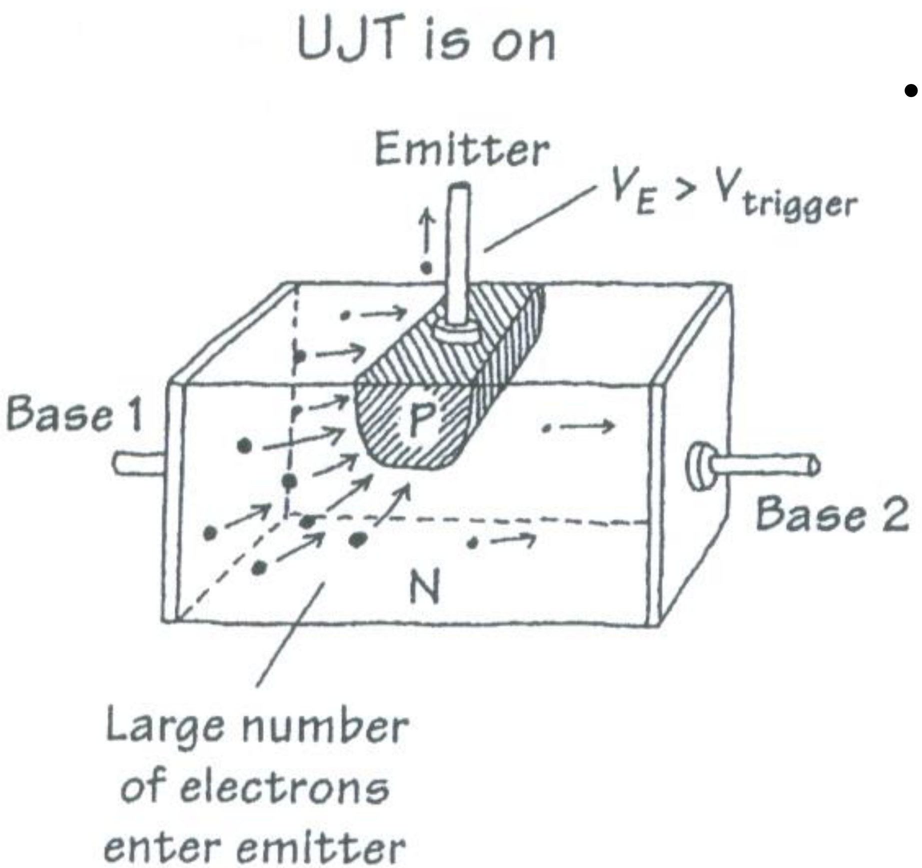


UJT: How it Works —I



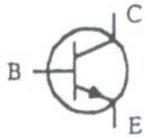
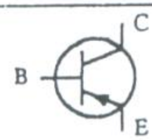
- With no voltage applied to the emitter, only a relatively small number of electrons makes it through the n-region between base 1 and base 2. Normally, both connectors to base 1 and 2 are resistive (few kΩ).

UJT: How it Works —II

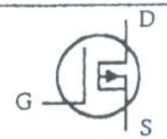
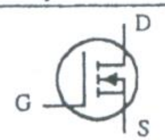
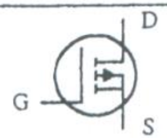
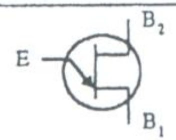


- When a sufficiently large voltage is applied to the emitter, the emitter-channel pn junction is forward-biased. This in turn allows a large number of base 1 electrons to exit through the emitter. A large conventional current flows from emitter to base 1.

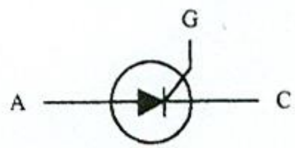
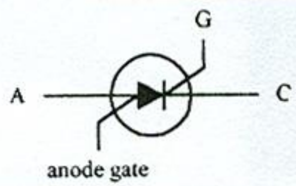
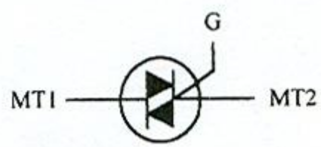
Summary of Transistors —I

TRANSISTOR TYPE	SYMBOL	MODE OF OPERATION
Bipolar	 *npn*	Normally off, but a small input current and a small positive voltage at its base (B)—relative to its emitter (E)—turns it on (permits a large collector-emitter current). Operates with $V_C > V_E$. Used in switching and amplifying applications.
	 *pnp*	Normally off, but a small output current and negative voltage at its base (B)—relative to its emitter (E)—turns it on (permits a large emitter-collector current). Operates with $V_E > V_C$. Used in switching and amplifying applications.
Junction FET	 *n-channel*	Normally on, but a small negative voltage at its gate (G)—relative to its source (S)—turns it off (stops a large drain-source current). Operates with $V_D > V_S$. Does not require a gate current. Used in switching and amplifying applications.
	 *p-channel*	Normally on, but a small positive voltage at its gate (G)—relative to its source (S)—turns it off (stops a large source-drain current). Operates with $V_S > V_D$. Does not require a gate current. Used in switching and amplifying applications.

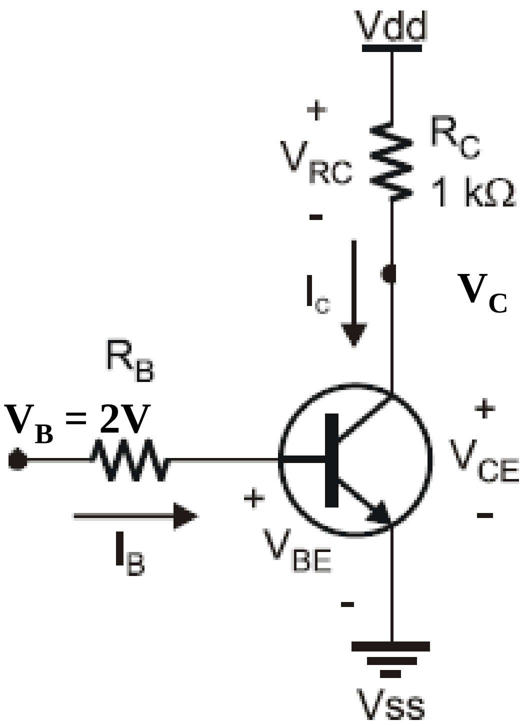
Summary of Transistors —II

Metal oxide semiconductor FET (MOSFET) (depletion)	 *n-channel*	Normally on, but a small negative voltage at its gate (G)—relative to its source (S)—turns it off (stops a large drain-source current). Operates with $V_D > V_S$. Does not require a gate current. Used in switching and amplifying applications.
	 *p-channel*	Normally on, but a small positive voltage at its gate (G)—relative to its source (S)—turns it off (stops a large source-drain current). Operates with $V_S > V_D$. Does not require a gate current. Used in switching and amplifying applications.
Metal oxide semiconductor FET (MOSFET) (enhancement)	 *n-channel*	Normally off, but a small positive voltage at its gate (G)—relative to its source (S)—turns it on (permits a large drain-source current). Operates with $V_D > V_S$. Does not require a gate current. Used in switching and amplifying applications.
	 *p-channel*	Normally off, but a small negative voltage at its gate (G)—relative to its source (S)—turns it on (permits a large source-drain current). Operates with $V_S > V_D$. Does not require a gate current. Used in switching and amplifying applications.
Unijunction FET (UJT)	 *UJT*	Normally a very small current flows from base 2 (B_2) to base 1 (B_1), but a positive voltage at its emitter (E)—relative to B_1 or B_2—increases current flow. Operates with $V_{B2} > V_{B1}$. Does not require a gate current. Only acts as a switch.

Summary of Other Semiconductors

TYPE	SYMBOL	MODE OF OPERATION
Silicon-controlled rectifier (SCR)		Normally off, but when a small current enters its gate (*G*), it turns on. Even when the gate current is removed, the SCR remains on. To turn it off, the anode-to-cathode current flow must be removed, or the anode must be set to a more negative voltage than the cathode. Current flows in only one direction, from anode (*A*) to cathode (*C*).
Silicon-controlled switch (SCS)		Similar to an SCR, but it can be made to turn off by applying a positive voltage pulse to a four-lead, called the *anode gate*. This device also can be made to trigger on when a negative voltage is applied to the anode-gate lead. Current flows in one direction, from anode (*A*) to cathode (*C*).
Triac		Similar to a SCR, but it can switch in both directions, meaning it can switch ac as well as dc currents. A triac remains on only when the gate is receiving current, and it turns off when the gate current is removed. Current flows in both directions, through *MT1* and *MT2*.
Four-layer diode		It has only two leads. When placed between two points in a circuit, it acts as a voltage-sensitive switch. As long as the voltage difference across its leads is below a specific breakdown voltage, it remains off. However, when the voltage difference exceeds the breakdown point, it turns on. Conducts in one direction, from anode (*A*) to cathode (*C*).
Diac		Similar to the four-layer diode but can conduct in both directions. Designed to switch either ac or dc.

NPN Transistor: Sample Calculation



- I_B = 10μA, h_{FE} = 200, V_{dd} = 5V

$$I_C = h_{FE} \times I_B = 200 \times (10 \times 10^{-6})$$
$$= 2 \times 10^{-3} A = 2mA$$
$$V_C = V_{dd} - R_c I_c = 5 - (1000) \times (0.002) = 3V$$
$$V_E = V_B - 0.6 = 2 - 0.6 = 1.4V$$