Introduction

In this lecture series, the subject we are going to discuss is VLSI technology.

What is the scope of the subject? Let us start the discussion with that. VLSI - this is an acronym and when expanded, this actually means Very Large Scale Integration or Very Large Scale Integrated Circuits. So to start with, let us first see what is an integrated circuit? What is a circuit? When i say circuit, what comes to your mind? Something like this?

A printed circuit board with different components soldered on to that - capacitors, transistors, diodes, resistors, connecting wires, yes? This is a discrete circuit; a discrete circuit that is, where I have discrete components, right, discrete components - capacitors resistors, transistors, like that. In contrast, in an integrated circuit, the entire circuitry that is, the active and passive elements, by active elements I mean the transistors; it can be bipolar junction transistors or field effect transistors. There can be diodes, there can be resistors, there can be capacitors - everything is housed on the same substrate.

This is a 4 mega bit dynamic RAM chip; 4 mega bit that is, there are 4 million transistors housed in this small bit. Depending on the complexity of the integrated circuit, we call it small scale integrated circuit or SSI, medium scale integrated circuit or MSI, large scale integrated circuit or LSI and very large scale integrated circuit or VLSI. When you are talking about a circuit which has may be 10 to 100 transistors in it, then it qualifies to be a small scale integrated circuit, SSI. Hundreds to thousands – MSI, more than ten thousand, LSI and for example, the piece you have just seen now, that is a VLSI integrated, VLSI circuit, VLSI chip which has 4 million transistors housed in that small bit. So, depending on the complexity of the circuitry, we call it LSI or MSI or VLSI as the case may be.

Now, VLSI technology, that means we are going to discuss how this very large scale, very complex integrated circuit is made. What are the processes that go into making this very large scale integrated circuit? First of all let me tell you that more than 95% of today's VLSI chips are made out of silicon. Silicon is a Group IV elemental semiconductor. It has a number of very desirable properties, why it is so chosen. So, more than 95% of the VLSI chips currently in the market is made of silicon and that too, single crystal silicon. The most important element in an integrated circuit, in any circuit for that matter, is its active element. Like I have already told you, this active element can be either a bipolar junction transistor or a MOSFET. When we are talking about very high speed circuits, we usually have them in bipolar junction transistors.

BJT's have very high speed and when you talk about very high packing density, we usually talk about MOSFET like the DRAM chip I just now showed you. This is based on MOSFET technology. 4 mega bit DRAM; 4 million transistors in a given area of integrated circuit, given area of silicon.

Silicon

As we know, an integrated circuit also refered to as IC, a chip or a microchip is a set of electronic circuits on one small flat piece (or chip) of semi conductor material, normally silicon.

Silicon lattice

- Silicon is a semiconductor.
- Transistors are built on a silicon substrate
- Forms crystal lattice with bonds to four neighbors.
- Silicon is a Group IV material.

Dopants.

- Pure silicon has no free carriers and conducts poorly.
- Adding dopants increases the conductivity.
- Group V : extra electron (n-type) phosphorus or arsenic.

silicon lattice

- Group III : missing electron, called hole (p-type).

- N-type doping : Phosphorus or arsenic is added to silicon in small quantities.
  - Phosphorus and arsenic have 5 outer electrons, so they are out of place when they get into the silicon lattice. The 5th electron has nothing to bond to, so it's free to move around. So small amount of impurity is enough to create free electrons thus allow it to conduct electricity. N-type is a good conductor. Electrons have negative charge, hence the name n-type.

P-type doping: Boron or gallium is the dopant. They have only 3 electrons in the outer shell.

When mixed ~~with~~ into silicon lattice they form "holes" in the lattice where silicon electron has nothing to bond to.

The absence of an electron creates the effect of a positive charge, hence the name P-type.
Holes can conduct current.
P-type silicon is a good conductor.

Transistor

- It is a miniature electronic component that can do two different jobs. It can work either as an amplifier or a switch.

- When it works as an amplifier, it takes in a tiny electric current at one end (input current) and produces a much bigger electric current (output current) at the other.

- Transistors can also work as switches. A tiny electric current flowing through one part of transistor can make a much bigger current flow through another part of it. In other words, small current switches on the larger one.

Two types:
- Bipolar transistors
- Metal Oxide Semiconductor Field Effect Transistors

• Bipolar transistors

· A bipolar transistor is a semiconductor device commonly used for amplification.

· It can amplify:

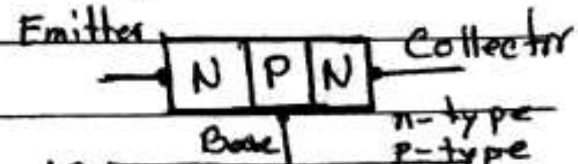
- Analog or
- Digital signals.

It can also switch DC or function as an oscillator.

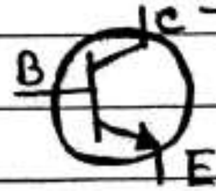
Physically, it amplifies current, but it can be connected in circuits designed to ~~amply~~ amplify voltage or power.

They are of two types:

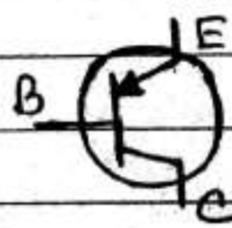
- NPN
- PNP

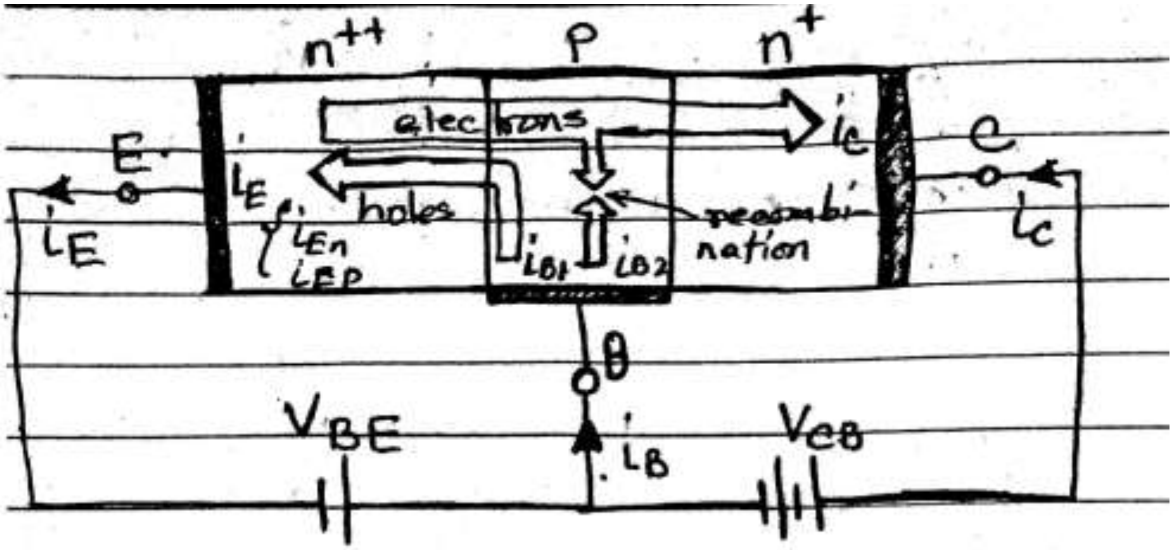


NPN →



PNP →





A transistor works when the electrons and the holes starts moving across the two junctions between the n-type and p-type silicon.

Suppose we attach a small positive voltage to the base, make the emitter negatively charged and make the collector positively charged.

Electrons are pulled from the emitter into the base and then from the base into the collector. And the transistor switches itself "on" state.

The small current that we turn on at the base makes a big current flow between the emitter and the collector.

By turning a small input current into a large output current, the transistor acts like an amplifier.

It also can act as switch. When there is no current to the base, little or no current flows between the collector and the emitter.

Turn on the base current and a big current flows.

So the base current switches the whole transistor on and off.

This type of transistor is called bipolar because two different kinds of polarities of electric charges (negative electrons and positive holes).

- Metal Oxide Semiconductor
Field Effect Transistors

- All transistors work by controlling the movement of electrons.

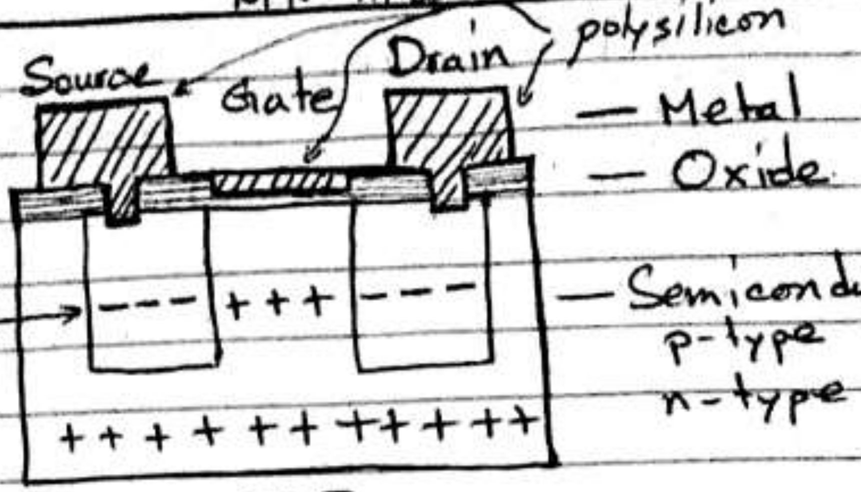
- Like a junction transistor, a FET (field effect transistor) has three different terminals:
  - Source (analogus to Emitter)
  - Drain (" " Collector)
  - Gate (" " Base)

There are 2 types:

- nMOS
- pMOS

$\Big\}$ MOSFETS

NPN – nMOS

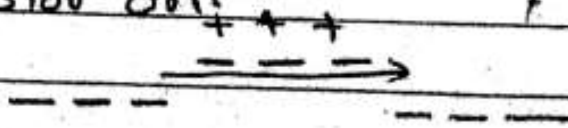


OFF

- Although there are extra electrons in the n-type source and drain, they cannot flow one to another because of the holes in the p-type gate in between them.

- If positive voltage is applied to the gate, an electric field is created, there that allows electrons to flow in a thin channel from the source to the drain.

This "field effect" allows a current to flow and switches the transistor on.



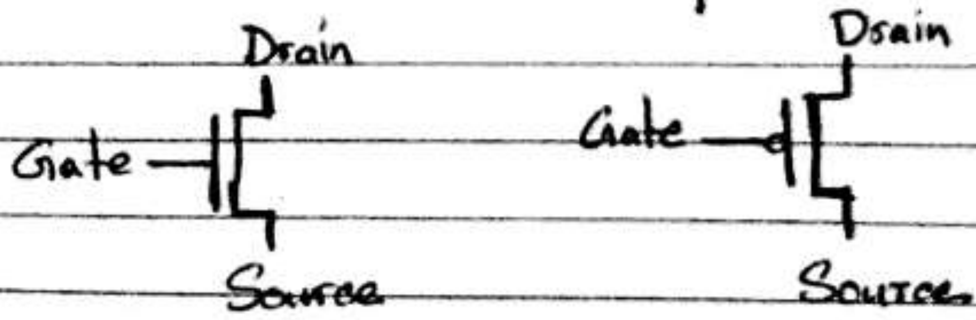
SUBJECT :

- Voltage applied to insulated gate controls current between source and drain.

- Low power allows very high integration.

MOSFET is a unipolar transistor because only one kind ("polarity") of electric charge is involved in making it work.

nMOS pMOS

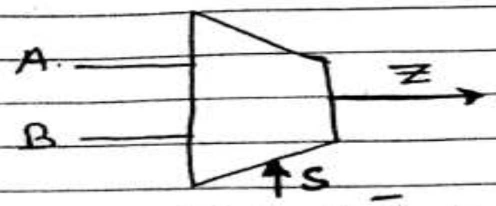


The gate terminal of early transistors was built from metal (now the gate is typically in polysilicon)

Transmission Gate Mux

A multiplexer or mux is a combinational circuits that selects several analog or digital input signals and forwards the selected input into a single output line.

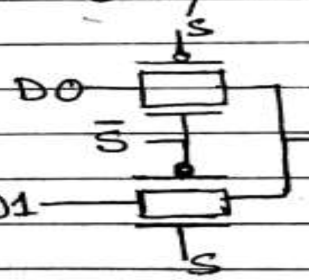
A multiplexer of 2^n input has n selected lines, are used to select which input line to send to the output.



2:1 MUX

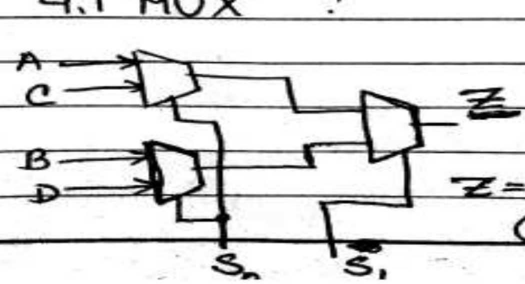
$$Z = A \cdot \bar{S} + B \cdot S$$

- Non restoring mux uses two transmission gates
- Only 4 transistors



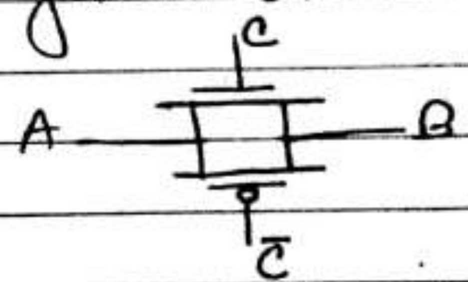
$$Y = D0 \cdot \bar{S} + D1 \cdot S$$

4:1 MUX :



$$Z = (A \cdot \bar{S}_0 \cdot \bar{S}_1) + (B \cdot \bar{S}_0 \cdot S_1) + (C \cdot S_0 \cdot \bar{S}_1) + (D \cdot S_0 \cdot S_1)$$

· Transmission gate is an electronic element and good non mechanical relay built with CMOS technology. It is made by parallel combination of nMOS and pMOS transistors with the input at the gate of one transistor (c) being complementary to the input at the gate of the other ($\bar{c}$).

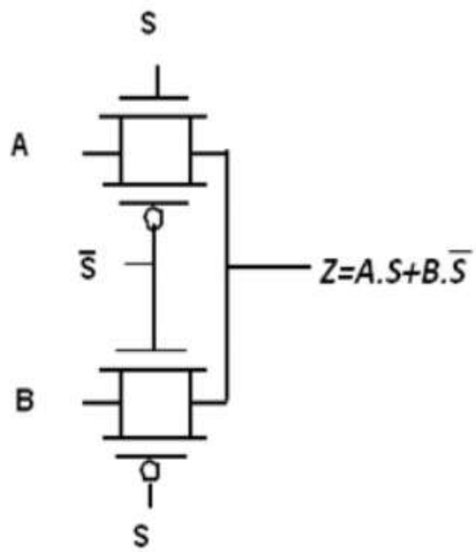


The transmission gate acts as a bidirectional switch controlled by the gate signal c.

When c=1, MOSFETs are ON, allowing the signal to pass through the gate.
In short, A=B, if c=1
if c=0, open circuit between A and C nodes.

Some logic design using Transmission Gates

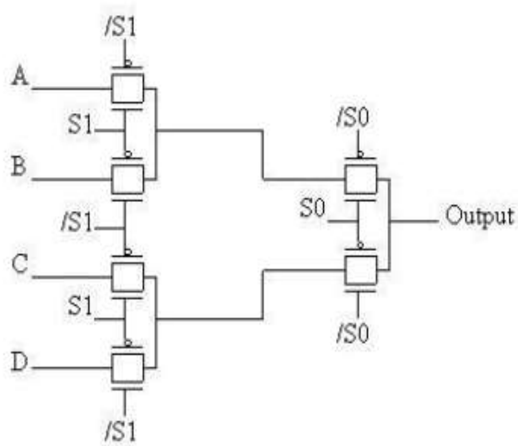
- **2:1 Multiplexer**



When S=0, $\overline{S}$ = 1, then, PMOS and NMOS of B will be ON and Z= A.0 + B.1=B

When S=1, $\overline{S}$ = 0, then, PMOS and NMOS of A will be ON and Z= A.1 + B.0=A

- **4:1 Multiplexer**



When S1=0, /S1=1, B and D turns ON, and, When S0=0, /S0=1, D is selected and appears at the output.

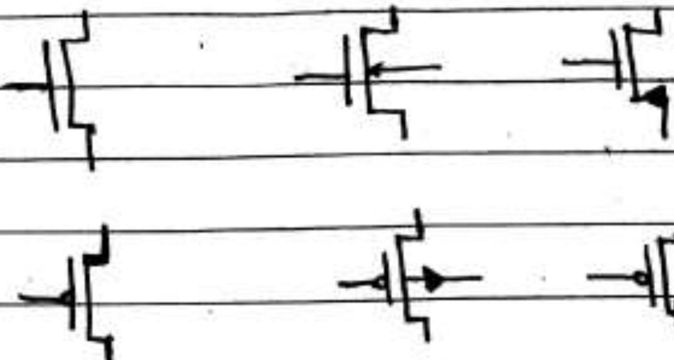
When S1=1, /S1=0, A and C turns ON, and, When S0=0, /S0=1, C is selected and appears at the output.

When S1=0, /S1=1, B and D turns ON, and, When S0=1, /S0=0, B is selected and appears at the output.

When S1=1, /S1=0, A and C turns ON, and, When S0=1, /S0=0, A is selected and appears at the output.

MOS Transistor Theory.

Symbols that are commonly used for MOS transistors.



indicates Switch logic

If the body (substrate or well) connection needs to be shown.

The MOS transistor is a majority carrier device in which the current in a conducting channel between the source and drain is controlled by a voltage applied to the gate.

In nMOS majority carriers are electrons

In pMOS majority carries are holes.

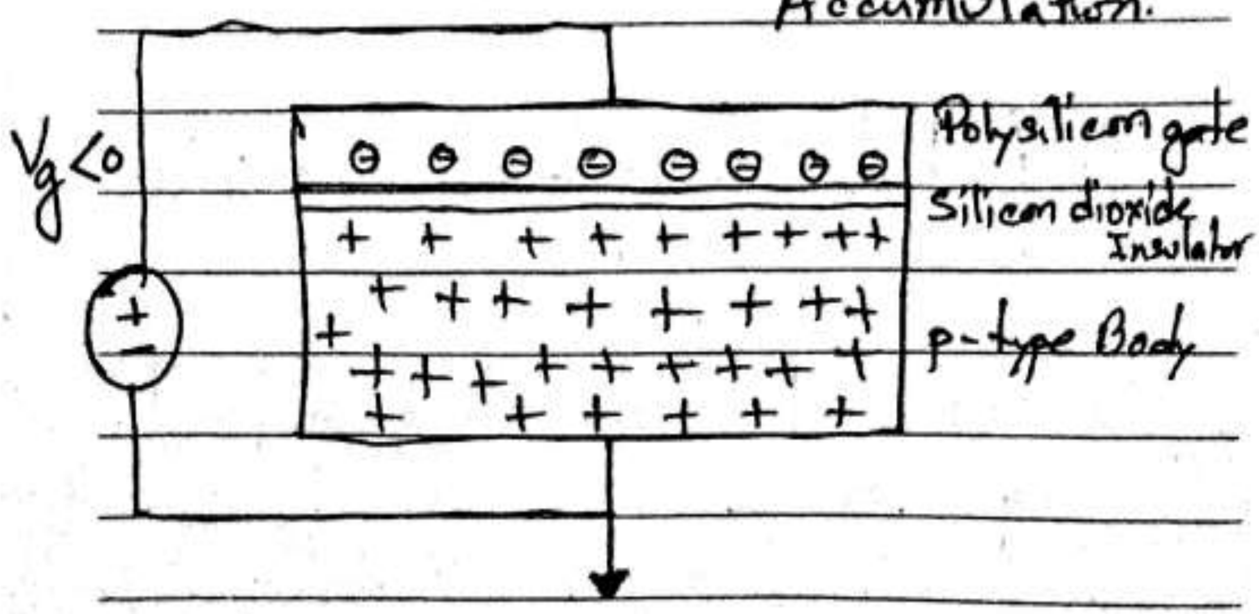
Structure:

Top layer is a good conductor called the gate.

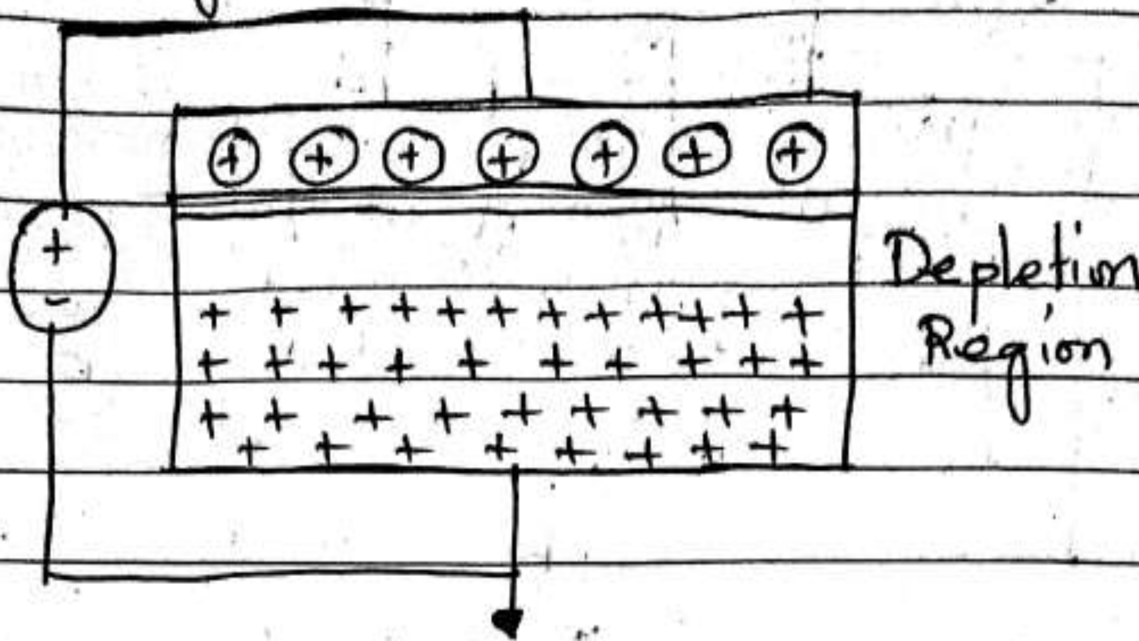
The middle layer is a very thin insulating film of SiO_2 called the gated oxide.

The bottom layer is the doped silicon body :

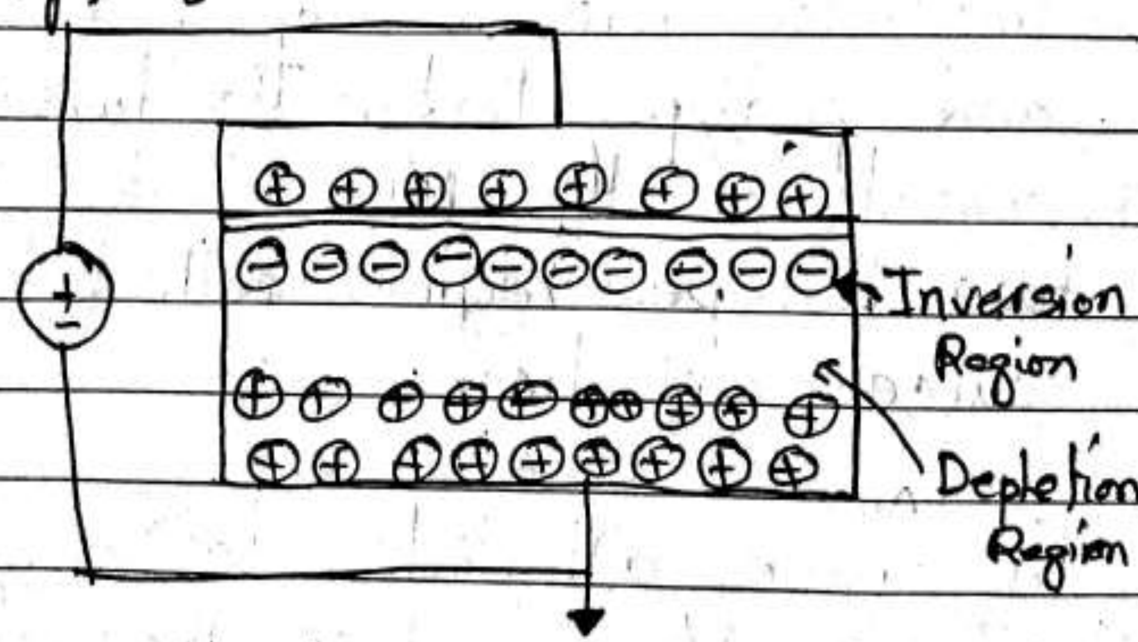
Accumulation.



$0 < V_g < V_t$



$V_g > V_t$



Working principle of a NPN MOSFET

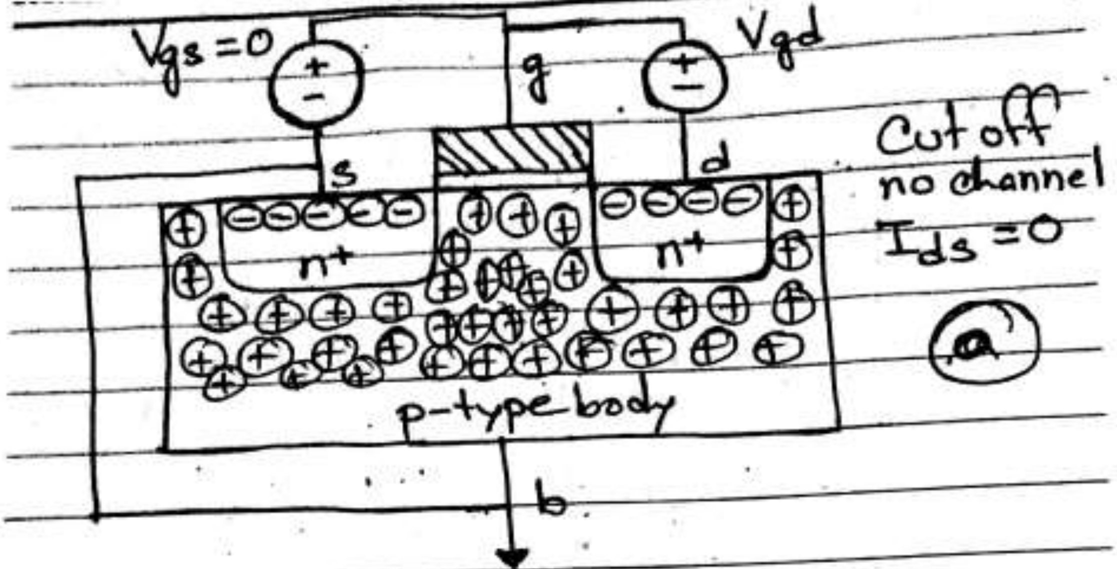


Figure (a) shows an nMOS transistor with a grounded source and p-type body. The transistor consists of the MOS stack between two n-type regions called the source and drain.

In figure (a) Gate to Source voltage V_{gs} is less than the threshold voltage.

$$V_{gs} < V_t$$

The source and drain have free electrons. The body has free holes but no free electrons.

The junctions between the body and the source or drain are reverse-biased, so almost zero current flows.

"Reversed biased, so
Zero current flows".

$I_{ds} = 0$

This mode of operation is called cut off.

In figure (b), the gate voltage is greater than the threshold voltage.

$$V_{gs} > V_t$$

Now an inversion region of electrons (majority carriers) called the channel, connects the source and drain, creating a conductive path.

The number of carriers and the conductivity increases with the gate voltage.

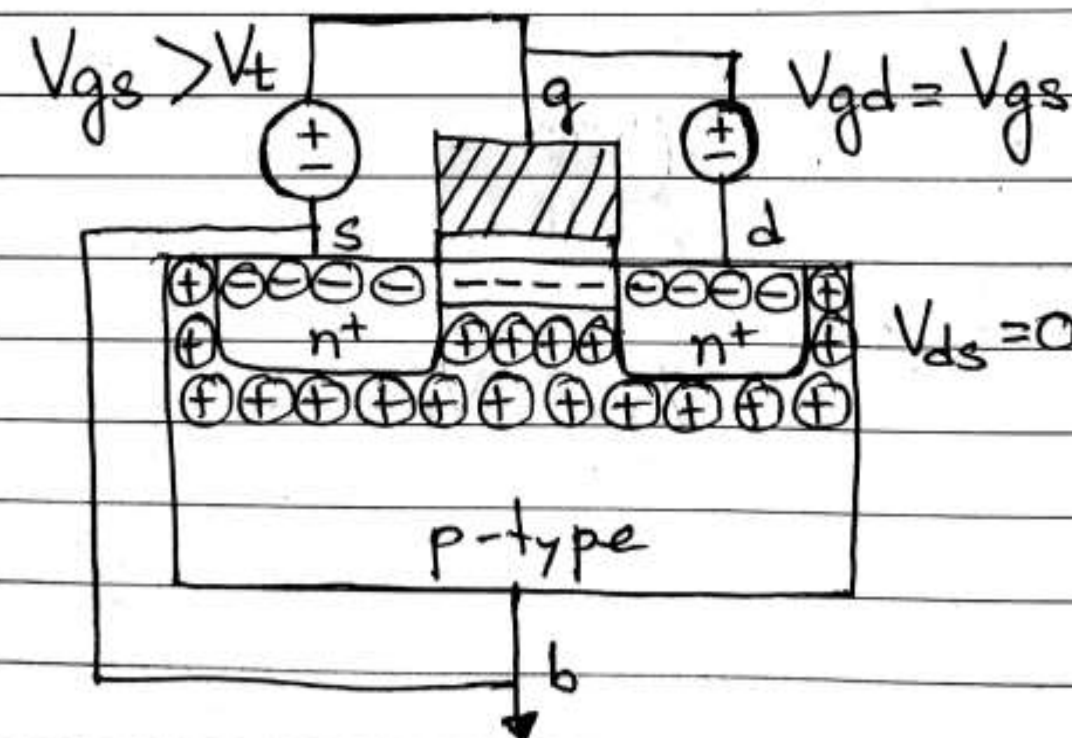
The potential difference between drain and source is

$$V_{ds} = V_{gs} - V_{gd}.$$

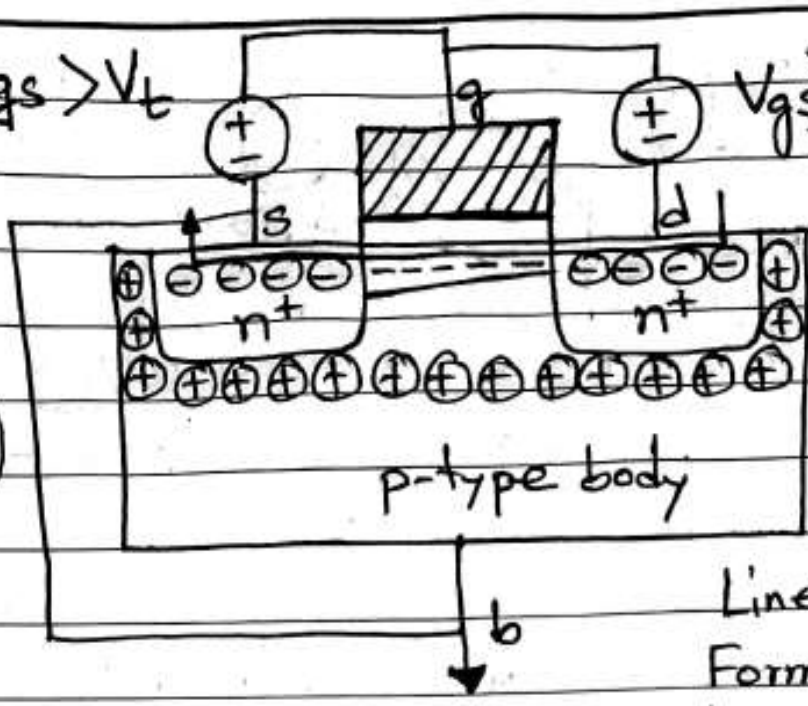
If $V_{ds} = 0$ (i.e $V_{gs} = V_{gd}$)

there is no electric field tending to push current from drain to source.

(b)



$V_{gs} > V_t$ $\quad$ $V_{gs} > V_{gd} > V_t$



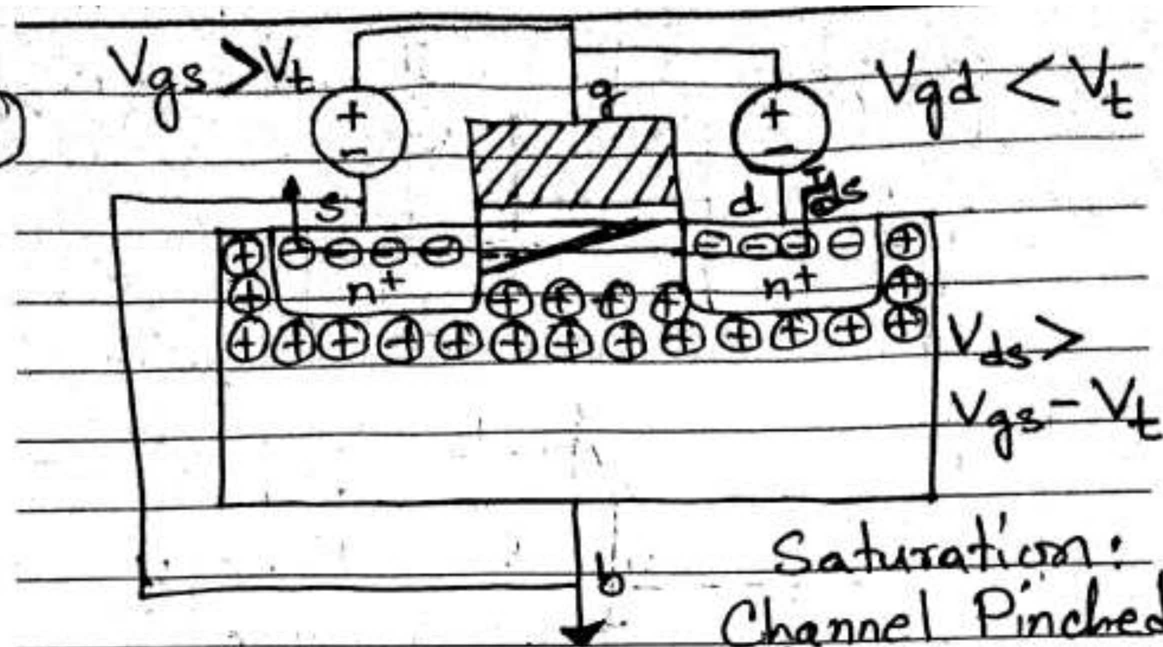
(c)

$0 < V_{ds} < V_{gs} - V_t$

Linear: channel Formed I_{ds} increases with V_{ds}

When a small positive potential V_{ds} is applied to the drain (Figure (c)), current I_{ds} flows through the channel from drain to source. This mode of operation is termed linear, resistive, nonsaturated or unsaturated, the current increases with both drain voltage and gate voltage.

(d)



Saturation: Channel Pinched off I_{ds} independent of V_{ds}.

If V_{ds} becomes sufficiently large that

$$V_{gd} < V_t$$

the channel is no longer inverted near the drain and becomes pinched off, figure (d).

However conduction is still brought about by the drift of electrons under the influence of the positive drain voltage.

As electrons reach the end of the channel, they are injected into the depletion region near the drain and accelerated toward the drain.

Above this drain voltage, the current I_{ds} is controlled only by gate voltage and ceases to be influenced by drain. This mode is called saturation