Analog Electronics

DIPLOMA WALLAH

EE/EEE

Jharkhand University Of Technology (JUT)

Unit 03

1. Types of FET & MOSFET: Definition, Symbols, N-type Enhancement Mode

1.1 Definition of MOSFET

- A MOSFET (Metal-Oxide-Semiconductor Field Effect Transistor) is a kind of field effect transistor (FET) in which a **gate electrode** is insulated from the semiconductor channel by a thin oxide (or dielectric) layer. cite☆turn0search10☆turn0search11☆turn0search0

- Because the gate draws virtually no current (insulated), it has a **very high input impedance**, and the gate-voltage controls the drain-to-source conduction.

- MOSFETs are widely used in digital logic (CMOS), power switching, analog circuits. cite☆turn0search10☆turn0search5

1.2 Classification: Channel Type & Mode

By channel polarity:

- N-channel MOSFET (NMOS)

- P-channel MOSFET (PMOS) cite☆turn0search9☆turn0search5

By mode of operation:

- **Enhancement mode**: The device is **normally off** when \(V_{GS}=0\); applying a gate voltage **enhances** conduction. cite☆turn0search2☆turn0search7☆turn0search9

- **Depletion mode**: The device is **normally on** at \(V_{GS}=0\); applying gate bias can **deplete** the channel and turn it off. citeturn0search19

Hence you can mix: N-channel enhancement, P-channel enhancement, N-channel depletion, P-channel depletion. But in most power and switching applications, N-channel enhancement mode is extremely common.

1.3 Symbols & Identification

image_group{"layout":"carousel","aspect_ratio":"1:1","query":["N-channel enhancement MOSFET symbol","P-channel enhancement MOSFET symbol","MOSFET symbol body substrate connection"],"num_per_query":2}

Key symbol features:

- Terminals: Gate (G), Drain (D), Source (S). Sometimes Body/Substrate (B) is shown.

- For enhancement mode, the symbol often shows a **broken/dashed line** for the channel under the gate (indicating the channel is **not present** until gate is biased) in the schematic symbol. citeturn0search7

- For N-channel, arrow in the body/ substrate may indicate direction of conventional current (or may not show arrow). For P-channel it's usually opposite polarity.

- In many discrete power MOSFETs, body/substrate is linked internally to source; so three terminals visible only.

1.4 Construction of N-Channel Enhancement Mode MOSFET

image_group{"layout":"carousel","aspect_ratio":"1:1","query":["N channel enhancement MOSFET cross section","MOSFET gate oxide layer SiO2 MOS capacitor structure","MOSFET substrate body region source drain doping diagram"],"num_per_query":2}

Detailed construction (N-channel, enhancement type):

- Substrate: A **P-type** semiconductor wafer (in the classic version). cite☆turn0search0☆turn0search11

- Two heavily doped **N+ regions** are diffused into the P-substrate: one becomes the **Source (S)**, the other the **Drain (D)**. cite☆turn0search9☆turn0search0

- On top of the region between source and drain, a thin layer of **insulating oxide** (e.g., silicon dioxide, SiO_2) is grown or deposited. Over this is fabricated the **Gate (G)** electrode (metal or polysilicon). cite☆turn0search11

- The source, drain, gate, and sometimes substrate body are bonded to external terminals. Often the body is tied to the source in discrete MOSFETs so you see only three terminals (G,D,S).

- At $V_{GS} = 0$ (no gate voltage) **no conduction channel** exists between drain and source (in enhancement type). The substrate region below the oxide remains P-type; the path from N+ source through P substrate to N+ drain is blocked by the P-N junction and/or lacks a continuous N-channel. cite☆turn0search6

- When V_{GS} is made sufficiently positive (for N-channel), it forms an **inversion layer** of electrons just below the gate oxide in the P-substrate, which acts as an **N-channel** connecting source and drain. This is why the device turns ON. cite☆turn0search9

1.5 Working Principle & Regions of Operation

Channel Formation & Conduction

- Step 1: Gate-to-source voltage V_{GS} is applied. If $V_{GS} < V_{TH}$ (threshold voltage) → **no channel**, device is OFF (only small leakage). cite☆turn0search6☆turn0search9

- Step 2: When $V_{GS} \geq V_{TH}$, electrons accumulate beneath the gate oxide; holes are repelled; eventually a sufficient density of electrons forms a conducting N-type channel between source and drain. The device starts to conduct. cite☆turn0search0☆turn0search11

- Step 3: A voltage between drain and source \(V_{DS}\) is applied; if enough \(V_{DS}\) is present (drain more positive than source for N-channel), current flows from drain to source (electrons flow source→drain, conventional current drain→source). The gate voltage modulates how many electrons are in the channel (so controls conductivity).

Regions of Operation

For N-channel enhancement mode MOSFET (classical model):

- **Cut-off region**: \(V_{GS} < V_{TH}\). Channel not formed. Very little current flows (just leakage).

- **Ohmic (or linear) region**: \(V_{GS} ≥ V_{TH}\) and \(V_{DS}\) is small (such that channel is continuous and not pinched off). The MOSFET acts like a voltage-controlled resistor between D and S.

- **Saturation (or active) region**: \(V_{GS} ≥ V_{TH}\) and \(V_{DS} ≥ (V_{GS} - V_{TH})\). The channel near the drain becomes pinched off (i.e., the channel narrows near the drain region), but current still flows; here the drain current \(I_D\) is mainly controlled by \(V_{GS}\), less dependent on \(V_{DS}\). cite☆turn0search10☆turn0search9

Graphically:

image_group☆{"layout":"carousel","aspect_ratio":"1:1","query":["MOSFET I-V characteristic curve N channel enhancement","MOSFET transfer characteristic ID vs VGS","MOSFET output characteristic ID vs VDS different VGS"],"num_per_query":2}

Key Equations (Simplified for Long-Channel MOSFETs)

Important Physical Effects

- **Inversion layer formation**: The P substrate under the gate is inverted to N-type when positive gate voltage accumulates electrons.

- **Pinch-off**: In saturation region, the channel near the drain end becomes depleted of carriers; the conduction path is “pinched off” though current still flows via drift of carriers in the depletion region.

- **Body-effect**: The threshold voltage can shift if the substrate (body) is not at same potential as source; a reverse bias between source and body increases V_{TH}.

- **Short-channel effects**: In modern MOSFETs with very short channel lengths, effects like **Drain-Induced Barrier Lowering (DIBL)**, velocity saturation, channel length modulation reduce ideal behaviour. cite☆turn0search27☆turn0search10

1.6 Summary of Section 1

You should now understand: what a MOSFET is, how it’s classified, its symbol, how an N-channel enhancement type is built and operates, what the important regions of operation are, and what the key physical equations/phenomena are.

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2. MOSFET as Switch & Ratings

2.1 MOSFET Used as a Switch

Because a MOSFET is **voltage-controlled**, has high input impedance, and (when ON) can have very low resistance between drain and source, it is an excellent device for switching applications. cite☆turn0search4☆turn0search16

Use case (N-channel enhancement):

- **OFF state**: $V_{GS} = 0$ (or below threshold) → no channel → $I_D \approx$ leakage only → transistor acts like an open switch.

- **ON state**: V_{GS} sufficiently above V_{TH} (e.g., 10-12 V for power MOSFETs, or 4.5-5 V for logic MOSFETs) → channel forms →

MOSFET acts like closed switch with low \(R_{DS(on)}\) → current flows from drain to source.

- Because gate requires little current (just to charge/discharge gate capacitances), switching losses can be low and thus MOSFETs are widely used in high efficiency power circuits.

Switching considerations:

- Gate capacitance means there is a finite time to turn ON/OFF (charging/discharging gate).

- When switching inductive loads, body diode or snubber may be required to handle reverse current or voltage spikes.

- Heat dissipation: even when ON, if current and voltage drop are nonzero, there is power loss → need to manage thermal performance.

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2. MOSFET as a Switch and Its Ratings

MOSFET as a Switch

- A MOSFET is a **voltage-controlled** device: you apply a gate-to-source voltage (V_{GS}) and you control the current between drain and source (I_D). (Electronics For You)
- When used as a switch:
    - **OFF state**: V_{GS} is below the threshold voltage (V_{TH}), so the channel is not formed (for an N-channel enhancement type). Very little I_D flows. (Circuit Digest)
    - **ON state**: V_{GS} is raised above V_{TH} sufficiently (for e.g., in power MOSFETs maybe 10 V or a logic-level gate of 4.5 V) so that the channel forms and the MOSFET acts like a low-resistance path between drain and source (low $R_{DS(on)}$). (Circuit Digest)
- Advantages of MOSFET in switching role:
    - Very high input (gate) impedance → minimal steady state gate current. (Basic Electronics Tutorials)

- Fast switching possible because it's majority-carrier device (no significant stored charge compared to BJTs) → faster turn-off. (Texas Instruments)

- Practical considerations when designing with a MOSFET as a switch:
    - Ensure gate drive can supply the required voltage quickly and handle the gate capacitance (charging/discharging delays). (Texas Instruments)
    - Account for conduction losses when ON: $I_{D} \times R_{DS(on)} \times$ whatever drop remains → heating. So thermal design matters.
    - Account for switching losses: during switching transitions, the MOSFET may be partially ON and partially OFF → higher dissipation.
    - For inductive loads, body-diode and recovery behavior may matter (voltage spikes, avalanche mode) when turning off. (toshiba.semicon-storage.com)

MOSFET Ratings

When selecting a MOSFET for switch applications, check key ratings in its datasheet:

- **$V_{DS(max)}$**: maximum allowable drain-to-source voltage in the OFF state (block voltage) without breakdown. (Circuit Digest)
- **$I_{D(max)}$**: maximum continuous (or pulsed) current the MOSFET can safely carry between drain and source under specified mounting/thermal conditions. (Circuit Digest)
- **$V_{GS(th)}$**: gate-to-source threshold voltage: the minimum V_{GS} at which the MOSFET begins to conduct (channel forms). Important to know whether logic level gate drive is enough. (Circuit Digest)
- **$R_{DS(on)}$**: on-state resistance between drain and source when fully ON (and specified V_{GS}, temperature). Lower $R_{DS(on)}$ reduces conduction losses and heating. (fuzetec.com)
- **$V_{GS(max)}$**: maximum gate-to-source voltage safe for the device (exceeding this may damage gate oxide).

- **Power dissipation (P_D)**: maximum power the device can lose (V_{DS} × I_D plus switching losses) while staying within safe junction temperature. Thermal resistance (junction-to-ambient) is often specified. (fuzetec.com)
- **Switching characteristics**: rise time, fall time, gate charge (Qg). These affect how fast you can switch and how much driver current/time is required. (Texas Instruments)
- **Safe Operating Area (SOA), avalanche rating**: For inductive switching and high-voltage turn-off situations, MOSFET may see voltage spikes; need to ensure device has appropriate ruggedness. (toshiba.semicon-storage.com)

Summary of Section

Using a MOSFET as a switch is about driving its gate properly, selecting it so that its blocking voltage, current capability, and loss characteristics match your load and switching frequency, and managing thermal/drive issues to ensure reliability.

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3. Applications of MOSFET & Differentiation Between BJT and MOSFET

Applications of MOSFET

MOSFETs are used in a wide variety of applications, especially where switching, power efficiency, or high-speed operation is needed. Some examples:

- In digital logic circuits: e.g., CMOS logic uses MOSFETs (n-channel & p-channel) as fundamental building blocks because of their high input impedance, low static power consumption. (Wikipedia)
- Power electronics: DC-DC converters, power supplies, motor drives, inverters: where efficient switching of current and voltage is key and fast switching helps reduce losses. (fuzetec.com)
- Load switches: For example high-side or low-side switches in battery or panel circuits, where MOSFET acts like an ideal switch with low loss. (Nexperia)
- Analog switches or variable resistors: In analog or mixed-signal circuits, MOSFET may be used in its linear region for switching, attenuation, resistor-like behavior. (Wikipedia)

- High frequency or fast switching where BJTs would suffer from charge storage delays: MOSFETs excel. (Texas Instruments)

Differentiation Between BJT and MOSFET

Here's a detailed comparison between the two, highlighting their main differences:

Feature	BJT (Bipolar Junction Transistor)	MOSFET (Metal-Oxide-Semiconductor FET)
Control mechanism	**Current-controlled device**: Base current controls collector current. (TutorialsPoint)	**Voltage-controlled device**: Gate voltage controls drain current; gate input current is basically negligible in steady state. (nextpcb.com)
Input impedance	Relatively low (because base current flows)	Very high input impedance due to insulated gate (almost no DC gate current) (Basic Electronics Tutorials)
Drive power	Requires base current to keep ON → consumes drive power	Requires gate charge initially, but steady state gate current is minimal → lower drive power
Switching speed	Slower compared to MOSFET because of minority-carrier storage and recombination times	Faster switching because majority carrier device, less stored charge → less delay in turn-off/turn-on. (Texas Instruments)
On-state loss	Has a saturation voltage drop ($V_{CE(sat)}$) when ON which causes power loss	Can have very low $R_{DS(on)}$ → therefore, lower conduction losses when properly driven. (ElProCus)
Thermal/ runaway behavior	BJTs are more prone to thermal runaway because increased temperature → increased leakage →	MOSFETs generally better in these respects (some designs may still have issues but less

	more current → more heat	severe for many cases) (Wikipedia)
Complexity of drive circuitry	Simpler in some low power analog uses	Often requires proper gate-drive design (especially for power MOSFETs) because of gate capacitance and rise/fall times and due to potential for high dv/dt switching
Usage domain	Good for linear amplification, moderate switching, analog circuits	Preferred for switching applications, high efficiency, digital logic, high current/high voltage switching
Cost / device size	Usually fewer parasitics for small amplifiers; may cost less in low-power analog	For equivalent blocking voltage and current a MOSFET might be more expensive but delivers better switching performance; in ICs MOSFET is dominant
Noise and linearity	Often better linearity in some analog amplifier applications	MOSFETs have advantages but sometimes BJTs are still used where matching and linear performance matter (Wikipedia)

Why You Use one vs the other

- If your circuit requires **very high switching speed**, or you want to minimize drive power, or you are doing **high power switching**, a MOSFET is often the better choice.
- If your circuit is more of an **analog amplifier**, where signal fidelity, linearity, or specific gain behaviour matter, a BJT may be preferred.
- Also, practical constraints matter: gate drive availability, cost, expected load currents/voltages, thermal environment, switching frequency, how many devices in parallel, etc.

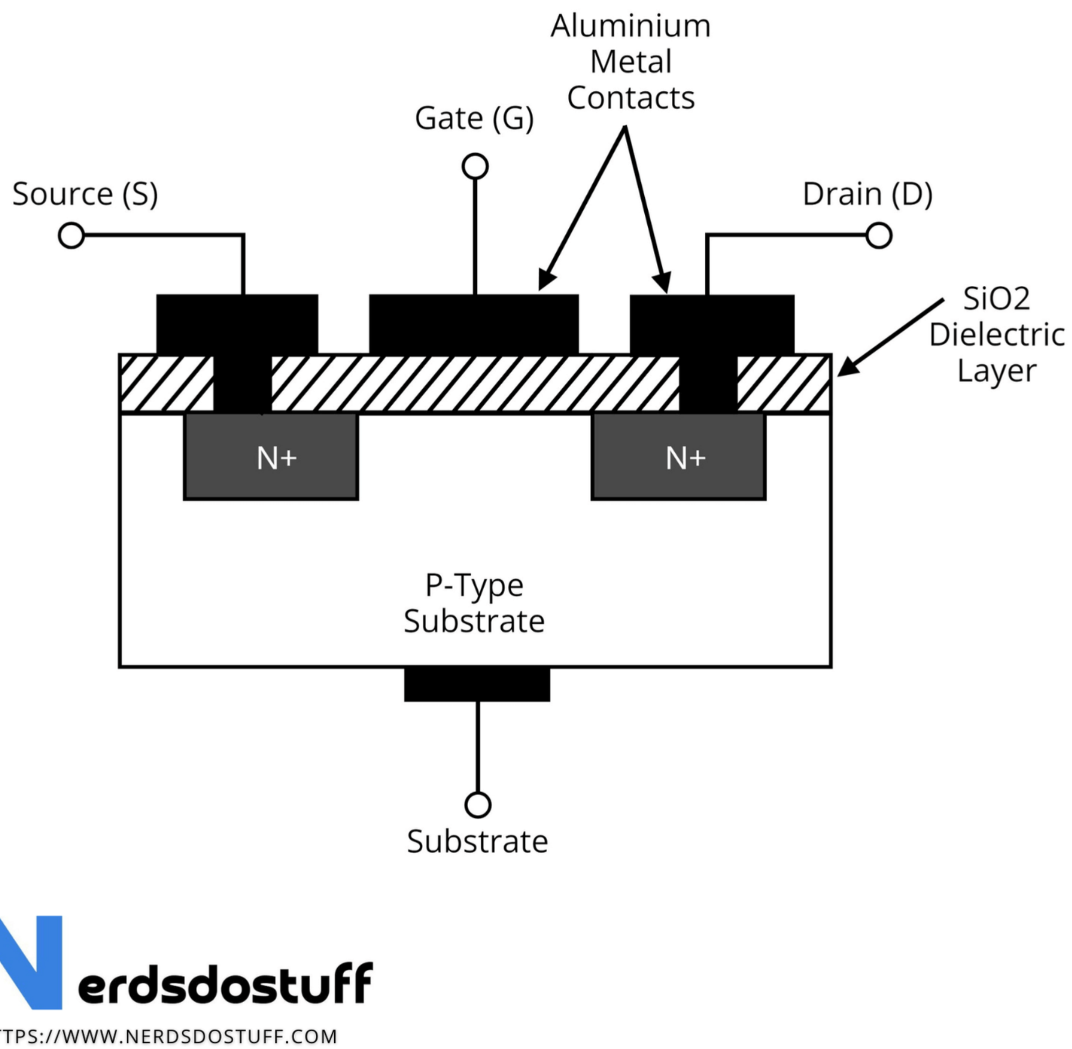
Final Wrap-Up

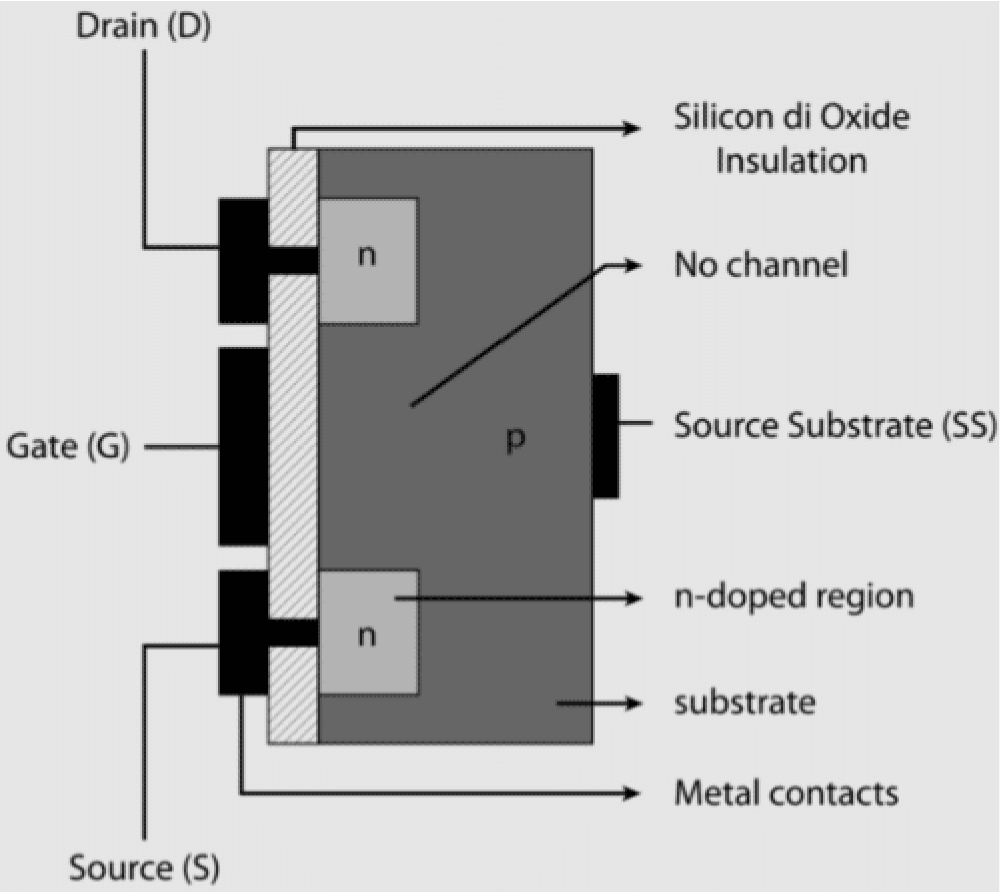
So to summarise:

- Using a MOSFET as a switch involves selecting the right device for your voltage/current/speed/thermal demands, driving its gate properly, and managing losses and thermal behaviour.
- MOSFETs are used in many modern electronics – from logic, switching power supplies, motor drivers, to load switches – because of their efficiency, speed and high input impedance.
- When comparing to BJTs: BJTs are current-controlled, lower input impedance, slower switching, but still good in many analog scenarios; MOSFETs are voltage-controlled, high input impedance, fast switching, low drive power, preferred for many switching tasks.

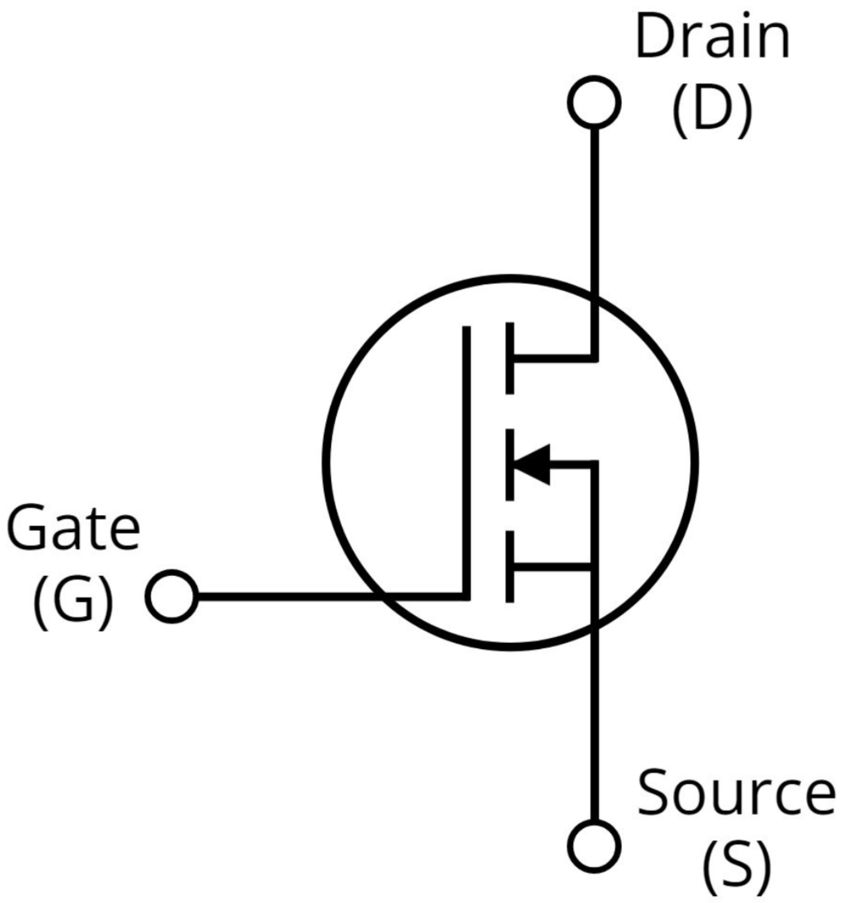
1. FET & MOSFET – Types, Definition, Symbols, N-type Enhancement Mode: Construction, Working, Characteristics

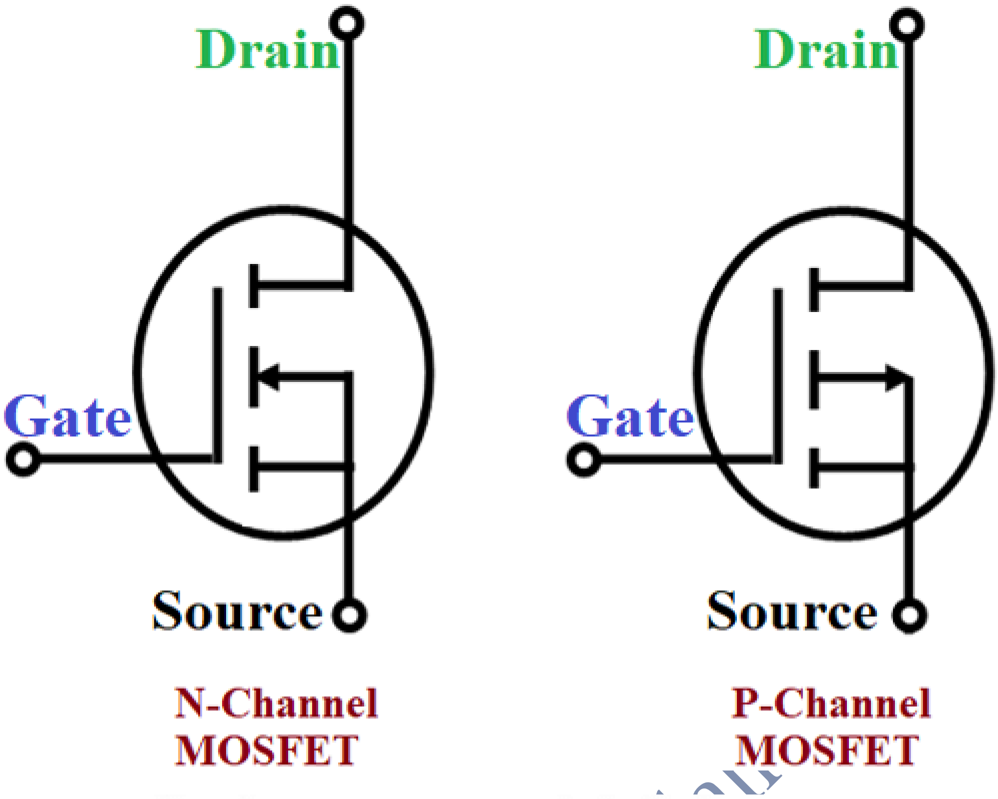
N-CHANNEL ENHANCEMENT MOSFET

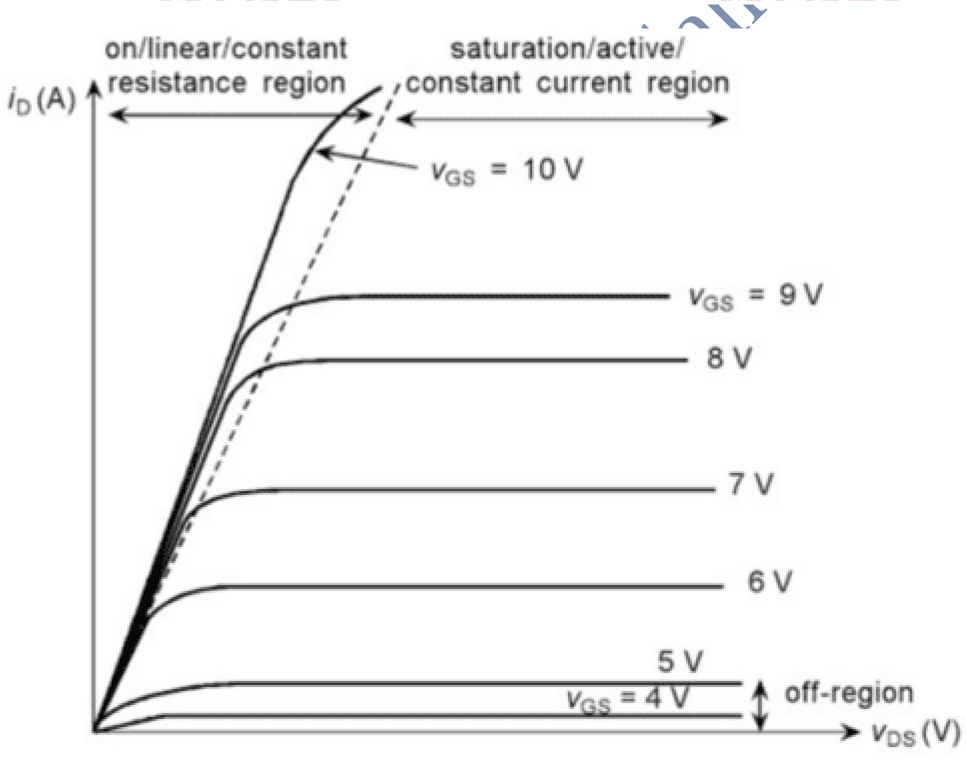


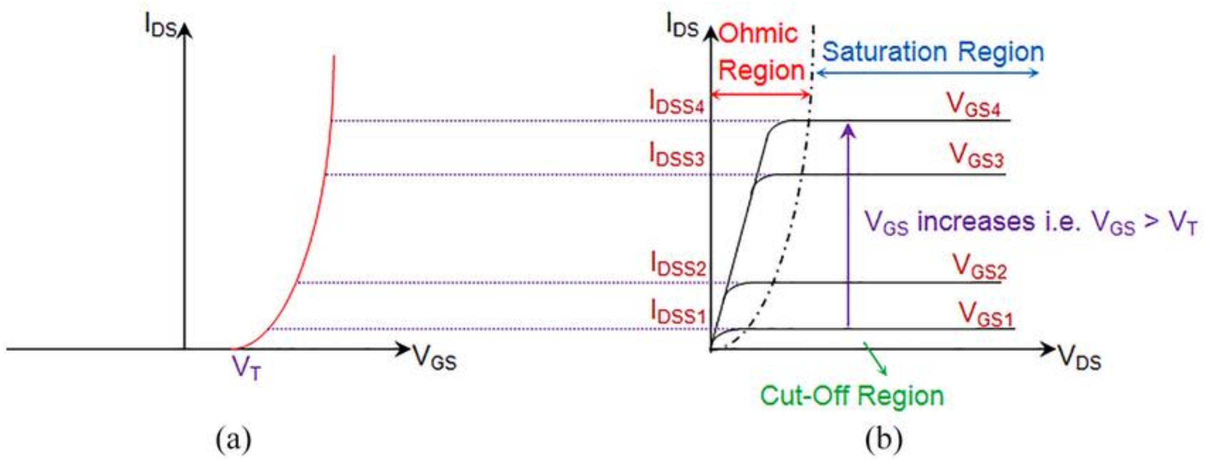

Drain (D)
Silicon di Oxide Insulation
n
No channel
Source Substrate (SS)
Gate (G)
p
n-doped region
n
substrate
Metal contacts
Source (S)

N-CHANNEL ENHANCEMENT MOSFET SYMBOL




Drain
Gate
Source
N-Channel MOSFET
Drain
Gate
Source
P-Channel MOSFET


on/linear/constant resistance region
saturation/active/ constant current region
i_D (A)
v_{GS} = 10 V
v_{GS} = 9 V
8 V
7 V
6 V
5 V
v_{GS} = 4 V
off-region
v_{DS} (V)



Explanation of the figures:

- The first figure shows the **construction** of an N-channel enhancement-mode MOSFET: P-type substrate, N+ source & drain regions, insulated gate over a thin oxide layer. (Electronics For You)
- The second figure shows the **symbol** for an enhancement-mode N-channel MOSFET, indicating gate (G), source (S), drain (D). (GeeksforGeeks)
- The third figure shows the **V-I characteristics** (output & transfer curves) of a MOSFET: how drain current (I_D) depends on gate voltage (V_{GS}) and drain-source voltage (V_{DS}). (TutorialsPoint)

These visuals help clarify the physical build, symbol schematic, and behaviour of the device under different voltages, which is vital for deep understanding.

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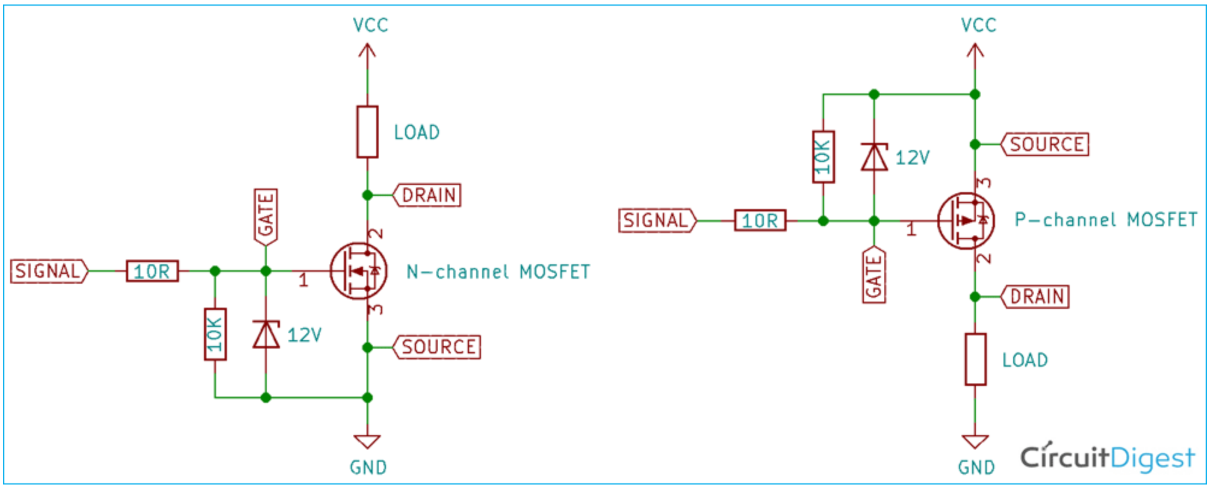
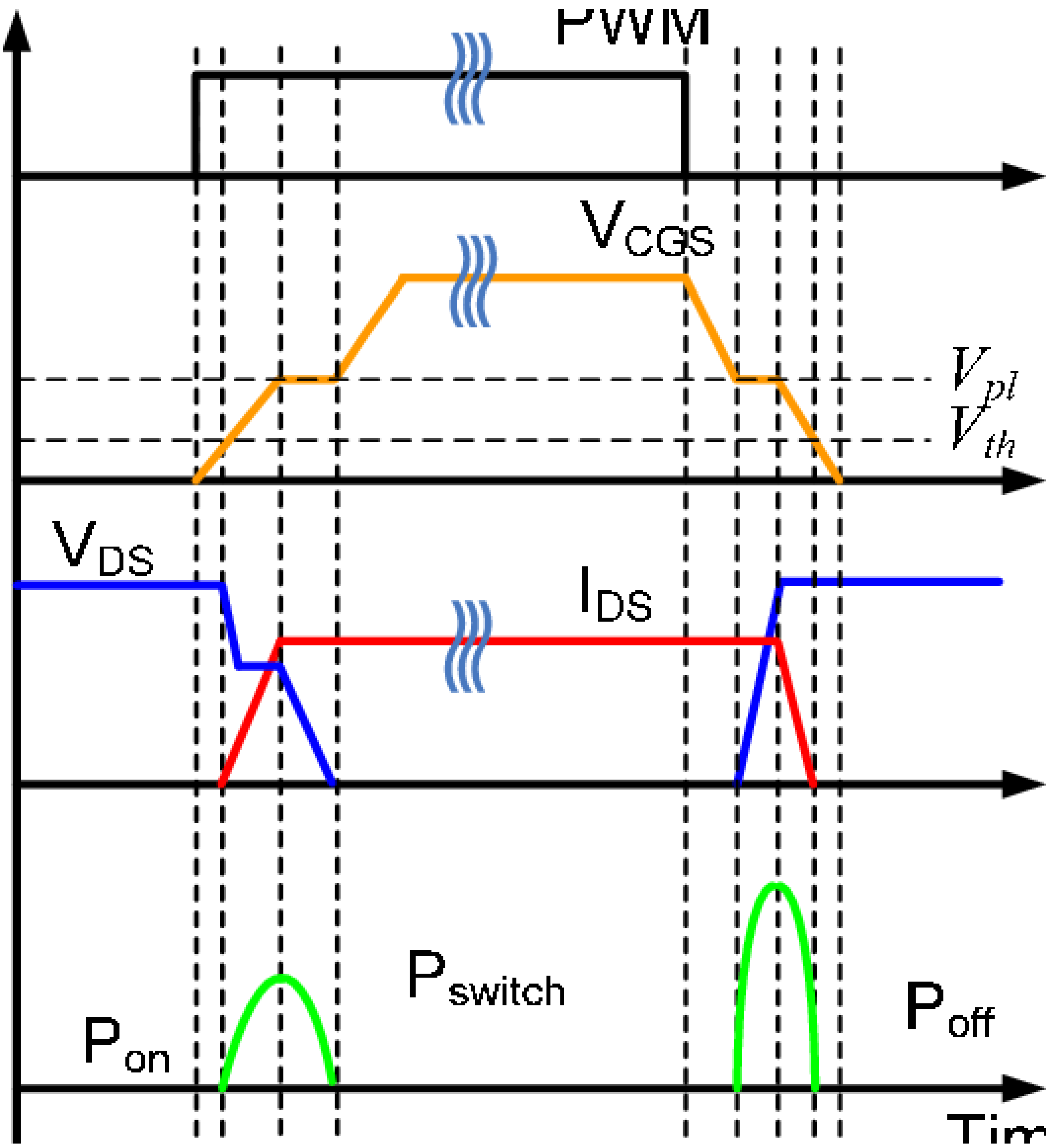
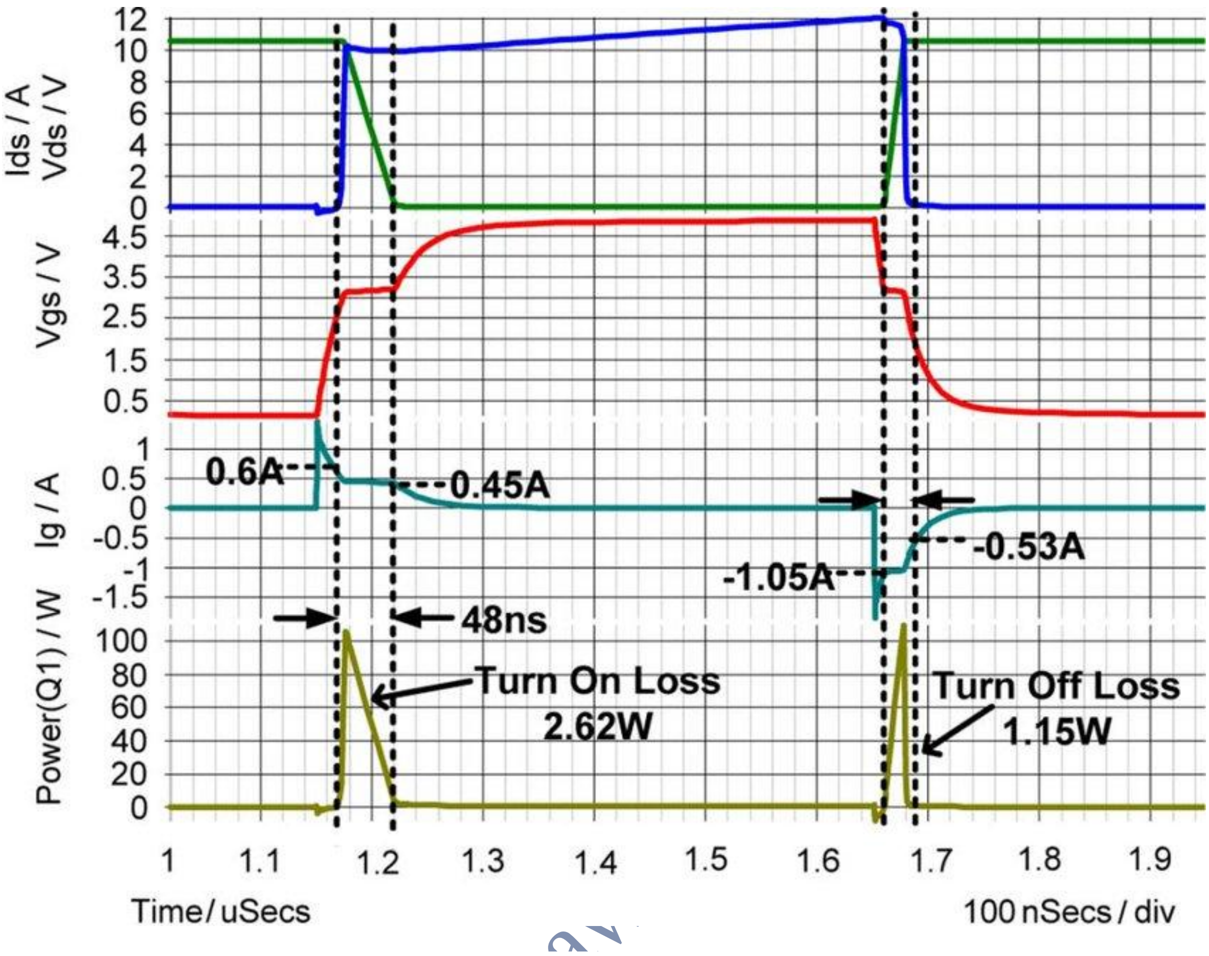
2. MOSFET as Switch & Ratings


VCC
LOAD
DRAIN
GATE
SIGNAL
10R
N-channel MOSFET
10K
12V
SOURCE
GND
VCC
SOURCE
10K
12V
SIGNAL
10R
P-channel MOSFET
GATE
DRAIN
LOAD
GND
CircuitDigest


PWM
VCGS
Vpl
Vth
VDS
IDS
Pon
Pswitch
Poff
Tim



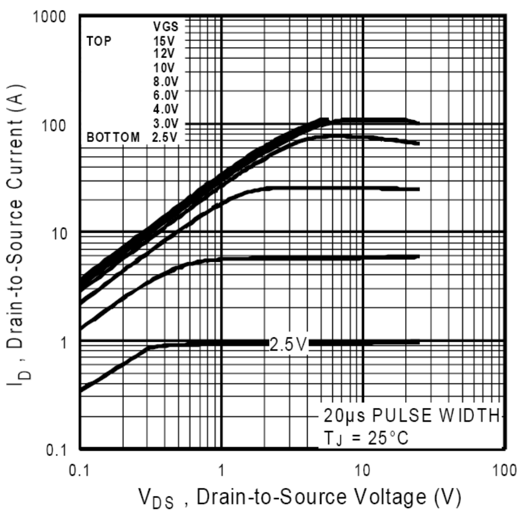


Fig 1. Typical Output Characteristics

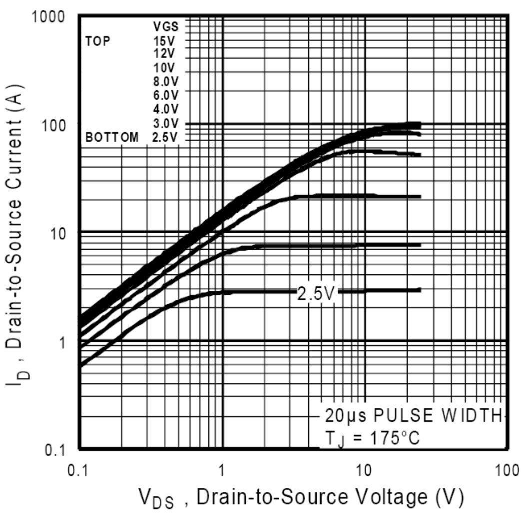


Fig 2. Typical Output Characteristics

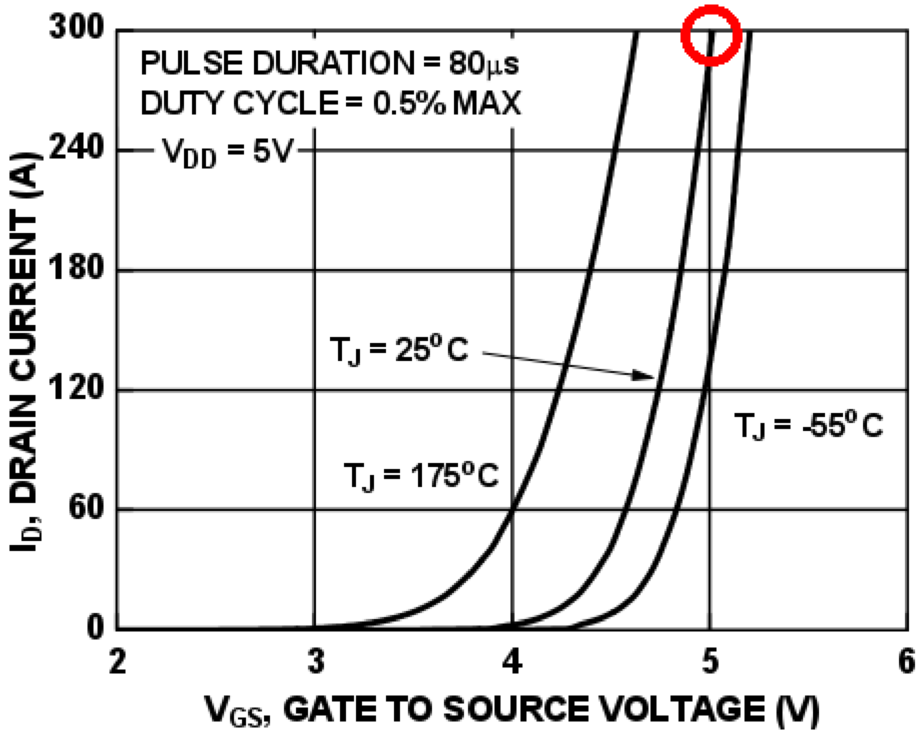


Figure 7. Transfer Characteristics

Explanation of the figures:

- The first image shows a typical circuit using a MOSFET as a **switch** (e.g., driving a load) showing gate drive, drain-source path when ON/OFF.
- The second image highlights the **switching behaviour**: gate charging/discharging, rise/fall times, the effect of gate capacitance on switching time.
- The third image is representative of a **datasheet rating table** (showing (V_{DS(max)}), (I_{D(max)}), (R_{DS(on)}), etc) that you must consult when selecting a MOSFET.

These help you connect the theory (how switching works, what ratings matter) with practical design considerations.

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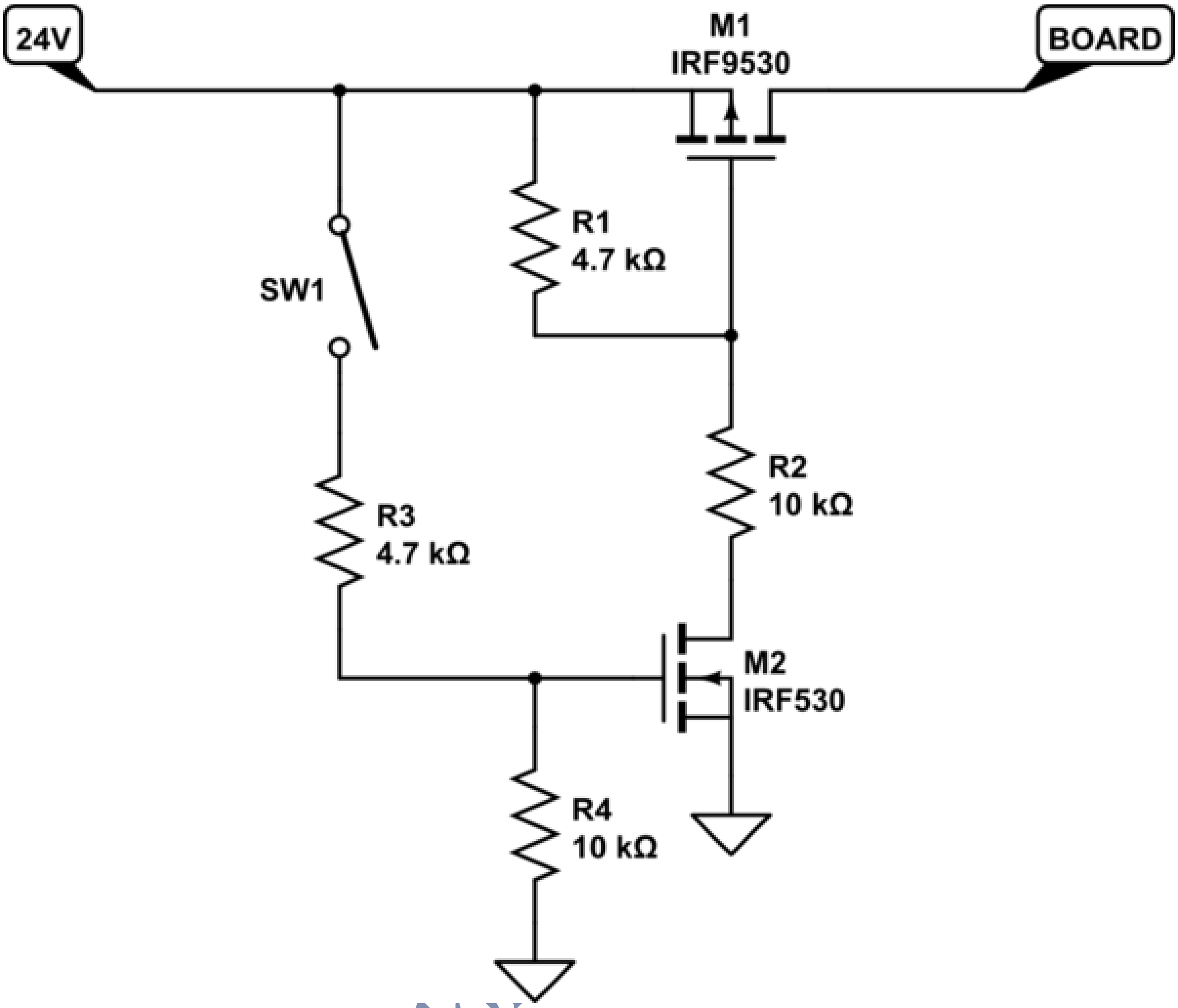
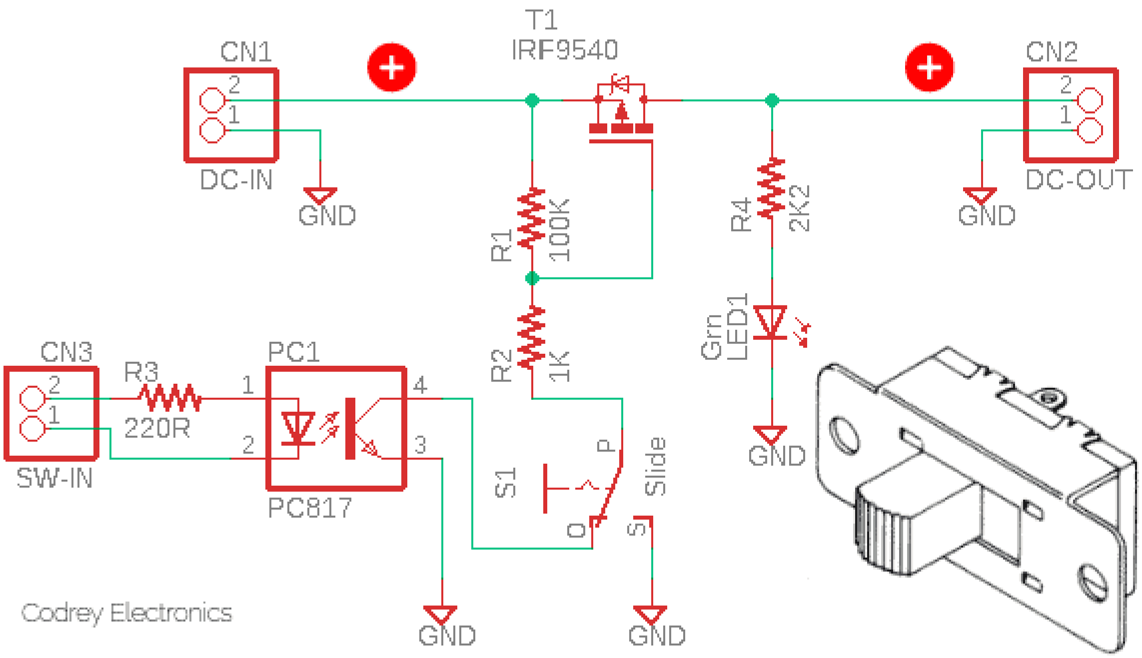
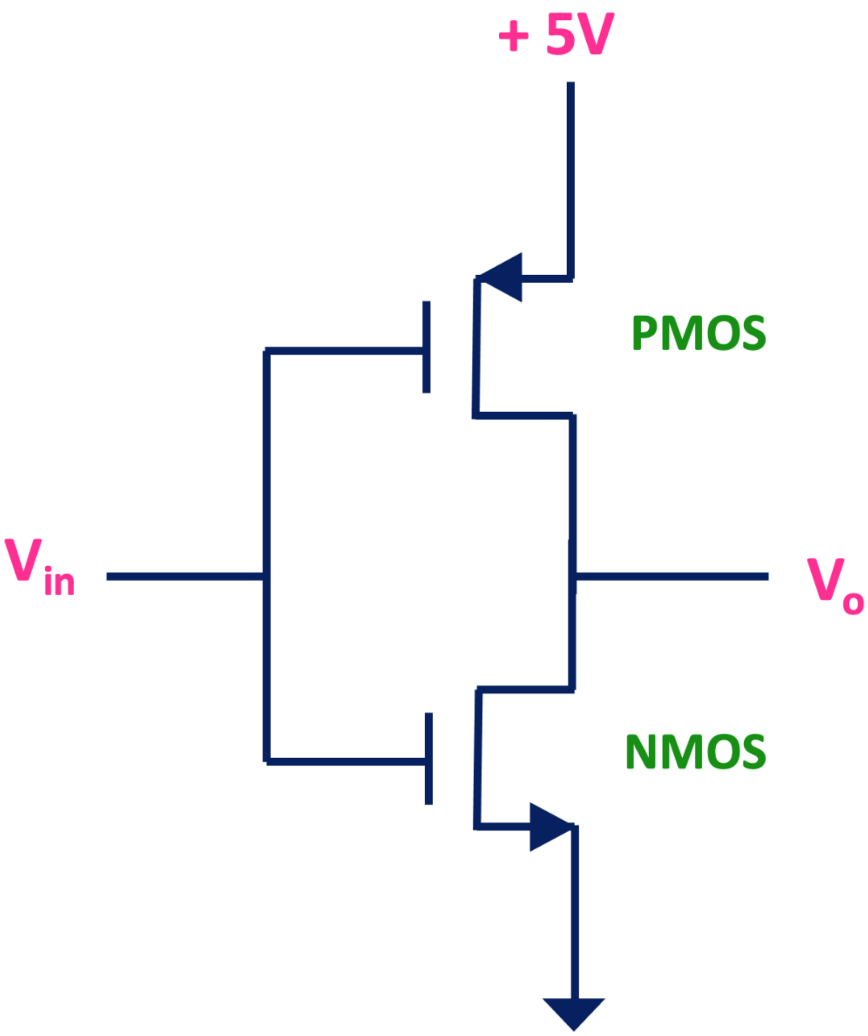
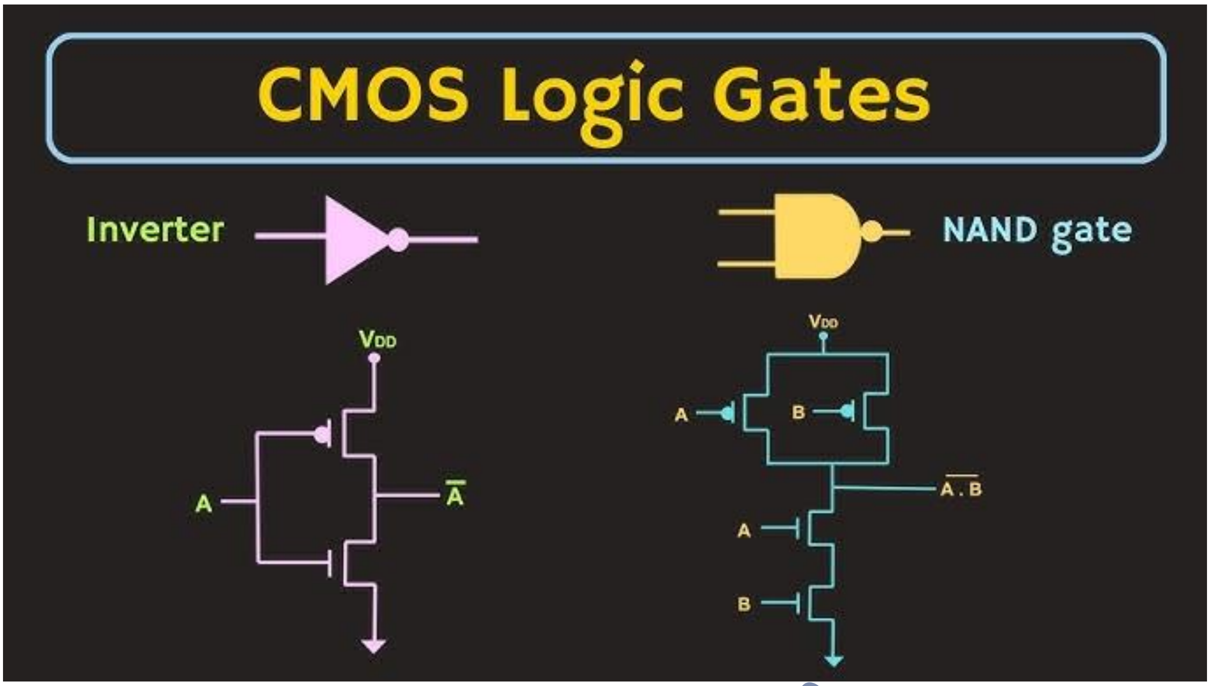
3. Applications of MOSFET & BJT vs MOSFET Comparison


24V
M1
IRF9530
BOARD
R1
4.7 kΩ
SW1
R2
10 kΩ
R3
4.7 kΩ
M2
IRF530
R4
10 kΩ


T1
IRF9540
CN1
DC-IN
GND
CN2
DC-OUT
GND
R1
100K
R4
2K2
Grn
LED1
R2
1K
CN3
SW-IN
R3
220R
PC1
PC817
S1
Slide
GND
GND
GND
Codrey Electronics

CMOS Inverter





TERMS	BJT	FET	MOSFET
Device Type	Current-Controlled	Voltage-Controlled	Voltage-Controlled
Current Flow	Bipolar	Unipolar	Unipolar
Terminals	Not Interchangeable	Interchangeable	Interchangeable
Operational Modes	No Modes	Depletion Mode Only	Both Modes*
Input Impedance	Low	High	Very High
Output Resistance	Moderate	Moderate	Low
Operational Speed	Low	Moderate	High
Noise	High	Low	Low
Thermal Stability	Low	Better	High

*Both Modes: Enhancement and Depletion Mode

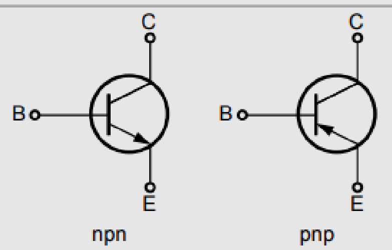
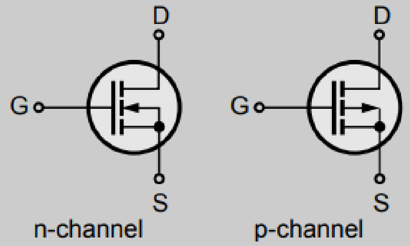
Sr. No.	BJT	MOSFET
1.	 Symbol	 Symbol
2.	This is bipolar device.	This is majority carrier device.
3.	Controlled by base.	Controlled by gate.
4.	Current controlled device.	Voltage controlled device.
5.	Input impedance less than MOSFET	Input impedance very high
6.	Negative temperature coefficient.	Positive temperature coefficient.
7.	Paralleling of BJTs is difficult.	Paralleling of MOSFETs is simple.
8.	Losses are low.	Losses are higher than BJTs.
9.	Drive circuit is complex.	Drive circuit is simple.
10.	Switching frequency is lower than MOSFET.	Switching frequency is high.
11.	More chances of thermal runaway and secondary breakdown.	The MOSFET is a majority carrier device. Majority carrier mobility decreases with temperature. This makes MOSFETs more immune to the thermal runaway and secondary breakdown.
12.	Lower packaging density.	Higher packaging density.
13.	BJTs are suitable for high power applications.	MOSFETs are suitable for low power application.
14.	BJTs are available with higher voltage and current ratings.	MOSFETs have less voltage and current ratings.

Table 4.7.1 Comparison of BJT and MOSFET

Explanation of the figures:

- One figure shows a MOSFET used in a **power-switching application** (for example a DC-DC converter or motor driver).
- Another shows MOSFETs in **logic/CMOS** circuits, highlighting their use in modern digital electronics.
- The comparison table shows key differences between a BJT and a MOSFET (control mechanism, drive requirements, etc) in a concise visual form.

These images support your understanding of *where* MOSFETs are used and *why* they might be chosen over BJTs in certain designs.

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