Block 13 — Transistor Fundamentals

Student Group

First Name	Surname	Matrikel Nr.

Table of Contents

TBD

1. Semiconductor components
   (approx. 4 blocks, based on previous lectures on Diodes and Transistors)

1. Bipolar transistor (structure, designations, characteristic curve, characteristic values)
2. Transistor as a switch (circuit, switching times and behavior)
3. MOSFET (structure, comparison with bipolar transistor)
4. Optional: Transistor as an amplifier

> A nice introduction to the bipolar transistor can be found in libretexts. Some of the following passages, videos and pictures are taken from this introduction.

Block 13 — Transistor Fundamentals

Learning objectives

> After this 90-minute block, you can
>
> - explain why a transistor can act as a controlled electronic valve.
> - distinguish bipolar junction transistors (BJTs) and field-effect transistors (FETs).
> - identify the terminals of a BJT: base B, collector C, and emitter E.
> - distinguish npn and pnp bipolar transistors from their layer structure and circuit symbols.
> - describe normal operation of an npn transistor using $U_{\rm BE}$, $U_{\rm CE}$, $U_{\rm CB}$, $I_{\rm B}$, $I_{\rm C}$, and $I_{\rm E}$.
> - use the current-gain approximation
>
> $$\begin{align*} I_{\rm C}\approx B I_{\rm B} \end{align*}$$ for simple operating-point estimates.
>
> - identify the basic BJT operating regions: cutoff, active region, and saturation.
> - explain why a saturated BJT is suitable as a closed switch, but not as a linear amplifier.
> - identify the terminals of a MOSFET: gate G, source S, drain D, and bulk B.
> - explain why a MOSFET is mainly voltage-controlled and why the stationary gate current is approximately zero.
> - compare BJTs and MOSFETs as switching elements at a basic level.

90-minute plan

- **Warm-up (10 min):**
  - Where do transistors occur in a robot controller?
  - Recall from Block 11: pn junctions and diode behavior.
  - Recall from Block 12: diodes are useful, but they cannot actively control a load current.
- **Core concepts (55 min):**
  - Introductory example: transistors inside logic circuits.

    - Transistor as controlled valve: control circuit and load circuit.
    - BJT terminals, npn/pnp structure, and sign conventions.
    - BJT current gain, characteristic curves, and operating regions.
    - Switching times as a bridge to transistor applications.
    - FET and MOSFET operating principle.
    - MOSFET channel formation, body diode, and MOSFET types.
    - BJT versus MOSFET as switching element.

- **Practice (20 min):**
    - Calculate collector current from base current and current gain.
    - Decide whether a BJT is likely in cutoff, active region, or saturation.
    - Estimate MOSFET conduction losses with $R_{\rm DS(on)}$.
    - Compare BJT and MOSFET control losses.

- **Wrap-up (5 min):**
    - Summary: BJT is current-controlled in the simple model; MOSFET is voltage-controlled in the simple model.
    - Preview: transistor applications such as low-side switches, high-side switches, PWM, relay drivers, and H-bridges are continued in Block 14.

Conceptual overview

- A transistor is a semiconductor component where a **small control signal** influences a **larger load current**.
- A BJT uses a base current $I_{\rm B}$ to control the collector current $I_{\rm C}$.
- A MOSFET uses a gate-source voltage $U_{\rm GS}$ to control the drain current $I_{\rm D}$.
- BJTs and MOSFETs are both used as switches and amplifiers, but their control principles are different.
- A transistor does not create energy. The load energy comes from the supply. The transistor only controls how much current may flow.
- This block explains the component behavior. Circuit dimensioning and applications are treated in Block 14.

Core content

Introductory Example

The electronics in personal computers, mobile phones, electric toothbrushes, industrial sensors, motor controllers, and almost all digital systems are based on transistor circuits.

In digital systems, logic gates such as NOT, NAND, and NOR are built from transistors. A microcontroller pin, for example, is not a tiny mechanical switch. It is an electronic switching network made from transistors.

A transistor is useful because a small control signal can decide whether a larger current path is

> open or closed.
>
> $$\begin{align*} \text{small control signal} \quad \Rightarrow \quad \text{large controlled current path} \end{align*}$$

In the following simulation, the internal transistor structure of a CMOS NAND gate is shown. The details of digital gates are not the focus of this block, but the example motivates why transistors are so important.

Simulation: CMOS NAND gate as motivation

Things to try:

- change the two input switches,
- observe the output voltage,
- identify that some transistors connect the output to $5~{\rm V}$, while others connect it to ground.

This chapter explains the two transistor families that are most important for the next blocks:

Type	Full name	Control quantity	Main current path
BJT	bipolar junction transistor	base current $I_{\rm B}$	collector-emitter path $C\rightarrow E$
MOSFET	metal-oxide-semiconductor field-effect transistor	gate-source voltage $U_{\rm GS}$	drain-source path $D\rightarrow S$

Tab. ##: Two important transistor families

From diode to transistor

A diode has two terminals and one pn junction. It can conduct or block depending on the applied voltage.

A transistor has at least three terminals. One terminal is used to control the current path between the other two terminals.

Analogy: controlled valve

Imagine a water valve.

- A small movement of the handle controls the main water flow.
- The handle does not supply the water energy.
- The pressure source supplies the water energy.

For a transistor:

- the control signal is the handle,

- the load current is the main water flow,
- the supply voltage provides the energy.

> A transistor is not simply “a stronger diode”. It is a controlled component: one electrical variable changes the current through another path.

Bipolar junction transistor: structure and terminals

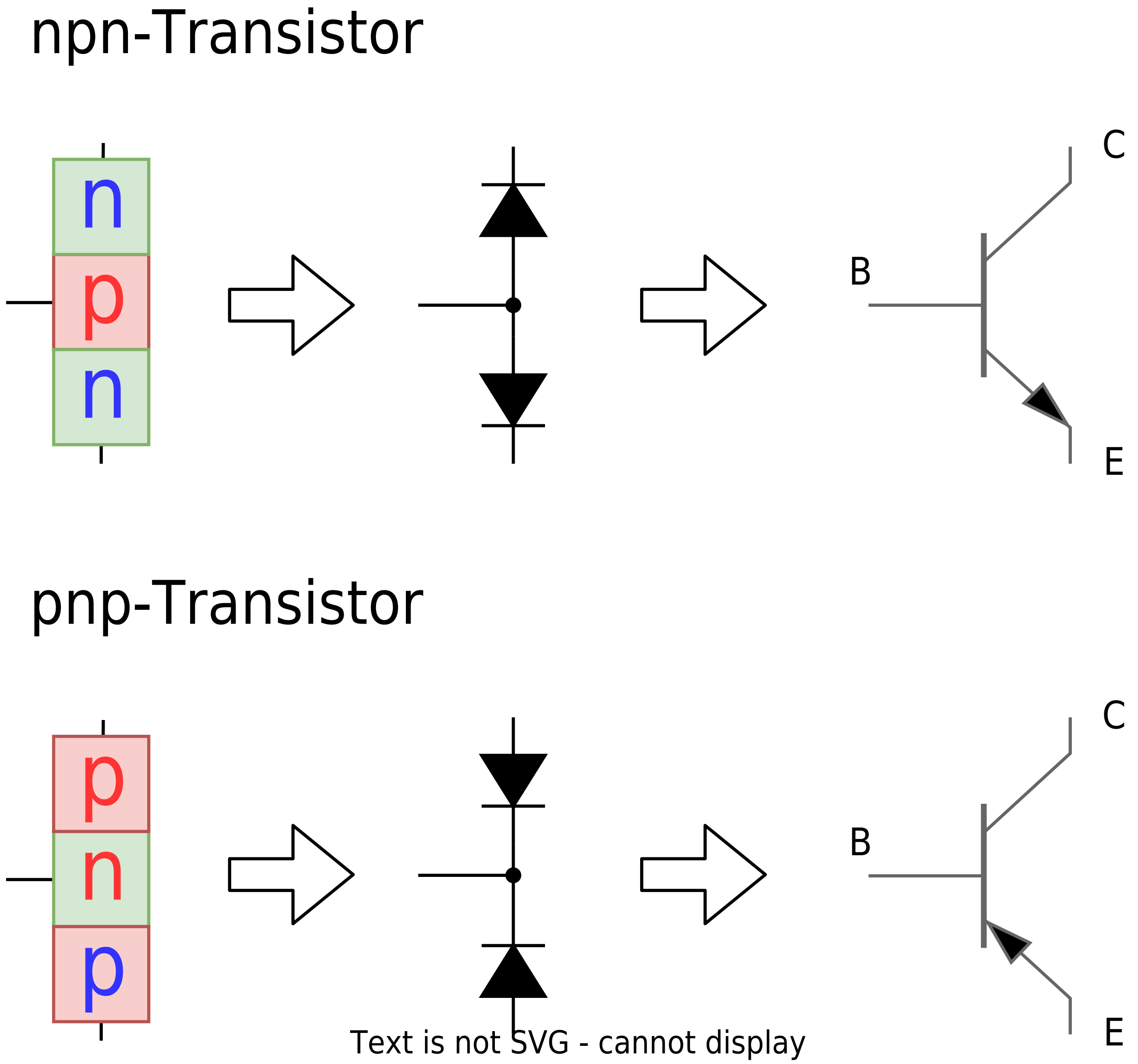
A bipolar junction transistor has three doped regions and three terminals.

- **Emitter E:** emits charge carriers into the transistor.
- **Base B:** thin control region.
- **Collector C:** collects charge carriers.

There are two basic BJT types:

- **npn transistor:** n-p-n layer sequence,
- **pnp transistor:** p-n-p layer sequence.

Fig. 1: Layer structure and circuit symbols of npn and pnp bipolar junction transistors.



> **Mnemonic for the emitter arrow**
>
> - **npn:** arrow **n**ot **p**ointing i**n**.
> - **pnp:** arrow **p**oints i**n**.
>
> The arrow indicates the technical current direction at the emitter in normal operation.

Important limitation of the diode picture

A BJT can be drawn as two pn junctions, but it is **not** simply two independent diodes.

The base region is very thin. This is essential: it allows charge carriers injected from the emitter to reach the collector.

Correct connection and normal operation of an npn transistor

For an npn transistor in normal active operation, the base-emitter junction is forward-biased and the collector-base junction is reverse-biased.

$$\begin{align*} U_{\rm BE} &> 0, & U_{\rm CE} &> 0, & U_{\rm CB} &> 0. \end{align*}$$

Fig. ##: Reference directions and voltages of an npn transistor in normal operation.

With the reference arrows commonly used in this course:

$$\begin{align*} I_{\rm B}>0, \qquad I_{\rm C}>0, \qquad I_{\rm E}<0. \end{align*}$$

Kirchhoff's current law gives

$$\begin{align*} I_{\rm B}+I_{\rm C}+I_{\rm E}=0. \end{align*}$$

Using current magnitudes:

$$\begin{align*} |I_{\rm E}|=I_{\rm B}+I_{\rm C}. \end{align*}$$

Type	**Voltage signs**	**Current signs with the shown reference arrows**
npn	$U_{\rm BE}>0$, $U_{\rm CE}>0$, $U_{\rm CB}>0$	$I_{\rm B}>0$, $I_{\rm C}>0$, $I_{\rm E}<0$
pnp	$U_{\rm BE}<0$, $U_{\rm CE}<0$, $U_{\rm CB}<0$	$I_{\rm B}<0$, $I_{\rm C}<0$, $I_{\rm E}>0$

Tab. 1: Sign conventions in normal operation

Simulation: correct transistor wiring

Things to try:

- compare npn and pnp polarity,
- observe which base-emitter voltage is needed,
- check the current direction through the collector-emitter path.

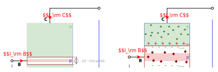
How the npn transistor controls current

The base-emitter junction behaves approximately like a diode. For a silicon transistor, noticeable base current often starts around

$$\begin{align*} U_{\rm BE}\approx 0.6\ldots0.7~{\rm V}. \end{align*}$$

When enough base current flows, the thin base region allows many carriers to pass from emitter to collector. Thus a small base current can control a larger collector current.

Fig. 2: Simplified function of an npn bipolar junction transistor: base current enables collector current.



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Analogy: narrow gate in a hallway

Imagine many people want to move from a large entrance hall to an exit hall, but a narrow gate is blocked.

- The emitter is the entrance side.
- The collector is the exit side.
- The base is the small gate control region.

A small action at the gate can allow many people to pass through the main hallway. This is only an analogy, but it helps to remember: the base controls a much larger collector-emitter current.

Because both electrons and holes contribute to the physical operation, the component is called **bipolar**.

> For the following explanations, npn transistors are used as the main example. For pnp transistors, polarities and current directions are reversed.

Current gain of the BJT

In the active region, a small base current controls a larger collector current.

\[\begin{align*} \boxed{ I_{\rm C}\approx B I_{\rm B} } \end{align*} \]

The factor \(B\) is the DC current gain:

\[\begin{align*} B=\frac{I_{\rm C}}{I_{\rm B}}. \end{align*} \]

For small changes around an operating point, the small-signal current gain is

\[\begin{align*} \beta = \frac{\Delta I_{\rm C}}{\Delta I_{\rm B}} = \frac{i_{\rm C}}{i_{\rm B}} \approx B. \end{align*} \]

Color scheme for the BJT control idea

$$ \begin{align*} {\color{blue}{I_{\rm B}}} &:\text{ small control current}, \\ {\color{green}{I_{\rm C}}} &:\text{ larger controlled current}, \\ {\color{red}{U_{\rm BE}I_{\rm B}}} &:\text{ input control power}. \end{align*} $$

The useful first approximation is

$$ \begin{align*} {\color{green}{I_{\rm C}}} \approx B\,{\color{blue}{I_{\rm B}}}. \end{align*} $$

> The current gain B is not a precise constant. It depends on transistor type, temperature, collector current, and manufacturing variation.
>
> For robust switch design, one usually does **not** rely on the typical value of B. This is treated in Block 14.

Simulation: input and current-gain characteristics

Things to try:

- change $U_{\rm BE}$,
- observe how $I_{\rm B}$ changes,
- observe how $I_{\rm C}$ changes with $I_{\rm B}$.

BJT characteristic curves and differential quantities

A transistor is nonlinear. Therefore we describe it by characteristic curves.

Important BJT characteristics are:

- **Input characteristic:** $I_{\rm B}(U_{\rm BE})$

The base-emitter path behaves approximately like a diode.

- **Control characteristic:** $I_{\rm C}(I_{\rm B})$

This shows the current gain.

- **Output characteristic:** $I_{\rm C}(U_{\rm CE})$ for different values of $I_{\rm B}$.

Fig. ##: Input, control, and output characteristics of an npn transistor.

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Important parameters around an operating point are

$$\begin{align*} r_{\rm BE} &= \frac{\Delta U_{\rm BE}}{\Delta I_{\rm B}} = \frac{u_{\rm BE}}{i_{\rm B}}, \\[4pt] r_{\rm CE} &= \frac{\Delta U_{\rm CE}}{\Delta I_{\rm C}} = \frac{u_{\rm CE}}{i_{\rm C}}. \end{align*}$$

Unit check

$$\begin{align*} [r_{\rm BE}] = \frac{{\rm V}}{{\rm A}} = \Omega, \qquad [r_{\rm CE}] = \frac{{\rm V}}{{\rm A}} = \Omega. \end{align*}$$

Simulation: BJT output characteristics

Things to try:

- change the input voltage $U_{\rm BE}$,
- observe the family of output curves,
- identify cutoff, active region, and saturation.

BJT operating regions

A BJT can operate in different regions.

Region	Approximate condition	Electrical behavior	Typical use
cutoff	$I_{\rm B}\approx 0$	$I_{\rm C}\approx 0$, transistor blocks	open switch
active region	$I_{\rm C}\approx B I_{\rm B}$	collector current controlled by base current	analog amplifier
saturation	$I_{\rm B}$ large enough, $U_{\rm CE}$ small	transistor conducts strongly	closed switch

Tab. 2: Basic operating regions of an npn transistor

Switching view

For a BJT used as a switch:

- **off:** cutoff region,
- **on:** saturation region.

In saturation, the collector-emitter voltage is small, often approximated by

$$\begin{align*} U_{\rm CE,sat}\approx 0.1\ldots 0.3~{\rm V}. \end{align*}$$

The conduction loss of a saturated BJT switch is approximately

$$\begin{align*} P_{\rm on,BJT} \approx U_{\rm CE,sat}I_{\rm C}. \end{align*}$$

The control loss at the base is approximately

$$\begin{align*} P_{\rm ctrl,BJT} \approx U_{\rm BE}I_{\rm B}. \end{align*}$$

> Detailed switch dimensioning, base resistor calculation, and switching inductive loads are continued in Block 14.

Switching times of a BJT

Real transistor switching is not instantaneous.

Typical time intervals are:

Symbol	**Meaning**
$t_{\rm d}$	delay time
$t_{\rm r}$	rise time
$t_{\rm on}$	total turn-on time
$t_{\rm s}$	storage time
$t_{\rm f}$	fall time
$t_{\rm off}$	total turn-off time

Tab. 3: BJT switching times

During switching, both current and voltage can be significant at the same time. Therefore switching losses occur during turn-on and turn-off.

$$\begin{align*} p(t)=u_{\rm CE}(t)i_{\rm C}(t). \end{align*}$$

Engineering interpretation

A BJT in saturation stores charge carriers in the base region. When switching off, this stored charge must be removed first. This contributes to the storage time $t_{\rm s}$.

Short preview: transistor switch and PWM

A transistor switch can connect and disconnect a load very quickly. If the switch is periodically on and off, the load sees an average voltage.

For an ideal switch with supply voltage $U_{\rm dc}$:

$$\begin{align*} \overline{u}_{\rm L} = \frac{1}{T}\int_0^T u_{\rm L}(t)\,{\rm d}t = \frac{T_{\rm on}}{T}U_{\rm dc}. \end{align*}$$

The duty cycle is

$$\begin{align*} d=\frac{T_{\rm on}}{T}. \end{align*}$$

Thus

$$\begin{align*} \boxed{ \overline{u}_{\rm L}=dU_{\rm dc} } \end{align*}$$

> This is the basic idea of pulse-width modulation (PWM). Applications to motor drivers and power stages are continued in Block 14.

Field-effect transistor: basic idea

A field-effect transistor controls current by an electric field.

For a MOSFET:

- **gate G:** control terminal,
- **source S:** reference terminal for $U_{\rm GS}$,
- **drain D:** load current terminal,
- **bulk B:** semiconductor body, often internally connected to source in discrete MOSFETs.

The name MOSFET means:

$$\begin{align*} \text{Metal-Oxide-Semiconductor Field-Effect Transistor}. \end{align*}$$

Key difference to the BJT

For a BJT:

$$\begin{align*} {\color{blue}{I_{\rm B}}} \quad \text{controls} \quad {\color{green}{I_{\rm C}}}. \end{align*}$$

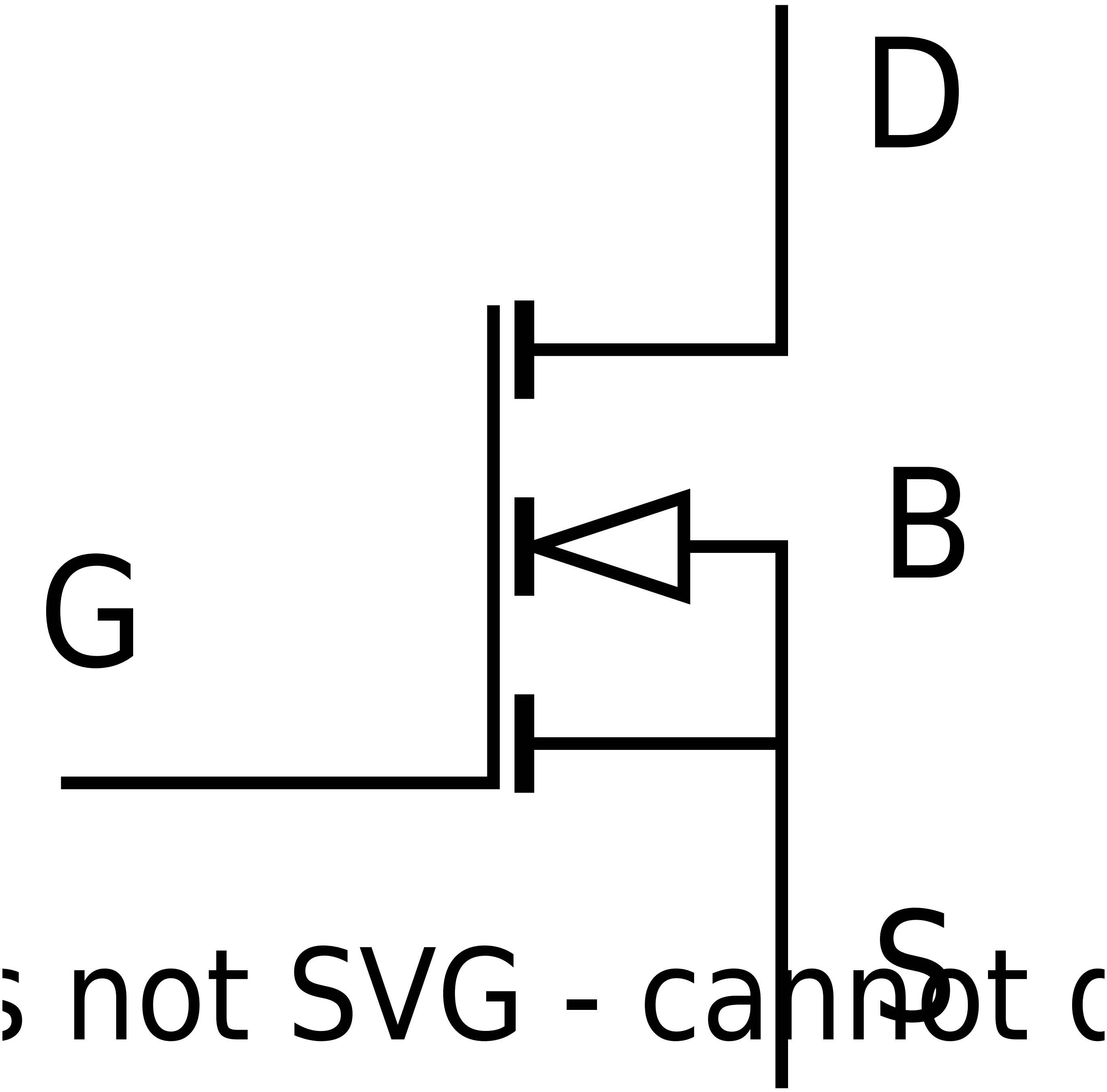
For a MOSFET:

$$\begin{align*} {\color{blue}{U_{\rm GS}}} \quad \text{controls} \quad {\color{green}{I_{\rm D}}}. \end{align*}$$

In stationary operation, the ideal gate current is approximately

$$\begin{align*} I_{\rm G}\approx 0. \end{align*}$$

Fig. 4: FET principle: a gate signal controls the drain-source current path.



Simulation: MOSFET as voltage-controlled switch

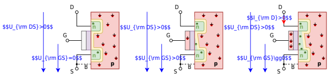
Things to try:

- change the gate voltage,
- observe that the gate draws no stationary current,
- observe how the drain-source path changes from blocking to conducting.

MOSFET structure and channel formation

The gate is separated from the semiconductor by a thin oxide layer. Therefore the gate behaves approximately like one plate of a capacitor.

Fig. 5: Simplified layer structure of an n-channel enhancement MOSFET.



For an n-channel enhancement MOSFET:

- at $U_{\rm GS}=0$, no conductive channel exists,
- when $U_{\rm GS}$ becomes large enough, electrons form a channel,
- then drain current $I_{\rm D}$ can flow.

The threshold voltage $U_{\rm GS(th)}$ indicates when a small channel just begins to form.

Important datasheet warning

$U_{\rm GS(th)}$ is **not** the voltage for a fully switched-on MOSFET.

For low conduction loss, use the gate voltage at which the datasheet specifies

$$\begin{align*} R_{\rm DS(on)}. \end{align*}$$

Body diode of a MOSFET

In a discrete power MOSFET, the bulk is often internally connected to the source. Together with the drain region, this creates an internal pn junction. This is the **body diode**.

> A real MOSFET is therefore not an ideal bidirectional switch. The body diode may conduct when the drain-source voltage has the reverse polarity.

Simulation: MOSFET channel and body diode

Things to try:

- increase $U_{\rm GS}$ and observe channel formation,
- reverse the drain-source polarity,
- observe when the body diode conducts.

MOSFET output characteristics

The drain current $I_{\rm D}$ depends on

- the drain-source voltage $U_{\rm DS}$,
- the gate-source voltage $U_{\rm GS}$.

Fig. ##: Qualitative output characteristics of an n-channel enhancement MOSFET.

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A MOSFET has several operating regions. Their names can be confusing because they are not identical to the BJT names.

Region	Approximate condition	Electrical behavior	Typical use
cutoff	$U_{\rm GS}<U_{\rm GS(th)}$	no useful channel, $I_{\rm D}\approx 0$	open switch
linear / ohmic region	$U_{\rm GS}$ high, $U_{\rm DS}$ small	behaves like a controlled resistor	closed switch
MOSFET saturation region	$U_{\rm GS}$ high, $U_{\rm DS}$ larger	current mainly controlled by $U_{\rm GS}$	analog operation, current-source-like behavior

Tab. 4: Basic regions of an n-channel enhancement MOSFET

The word **saturation** means different things for BJTs and MOSFETs.

- BJT saturation: good for a closed switch.
- MOSFET saturation: not the usual low-loss switch region.

A fully switched-on MOSFET is usually operated in the linear or ohmic region.

When a MOSFET is fully switched on, the drain-source path behaves approximately like a small resistance:

$$\begin{align*} U_{\rm DS}\approx R_{\rm DS(on)}I_{\rm D}. \end{align*}$$

The conduction loss is

$$\begin{align*} \boxed{ P_{\rm on,MOS} = R_{\rm DS(on)}I_{\rm D}^2 } \end{align*}$$

Unit check

\[\begin{align*} [P_{\rm on,MOS}] = \Omega\cdot{\rm A}^2 = \frac{{\rm V}}{{\rm

A}}\cdot{\rm A}^2 = {\rm V\,A} = {\rm W}. \end{align*}

Simulation: MOSFET output characteristics

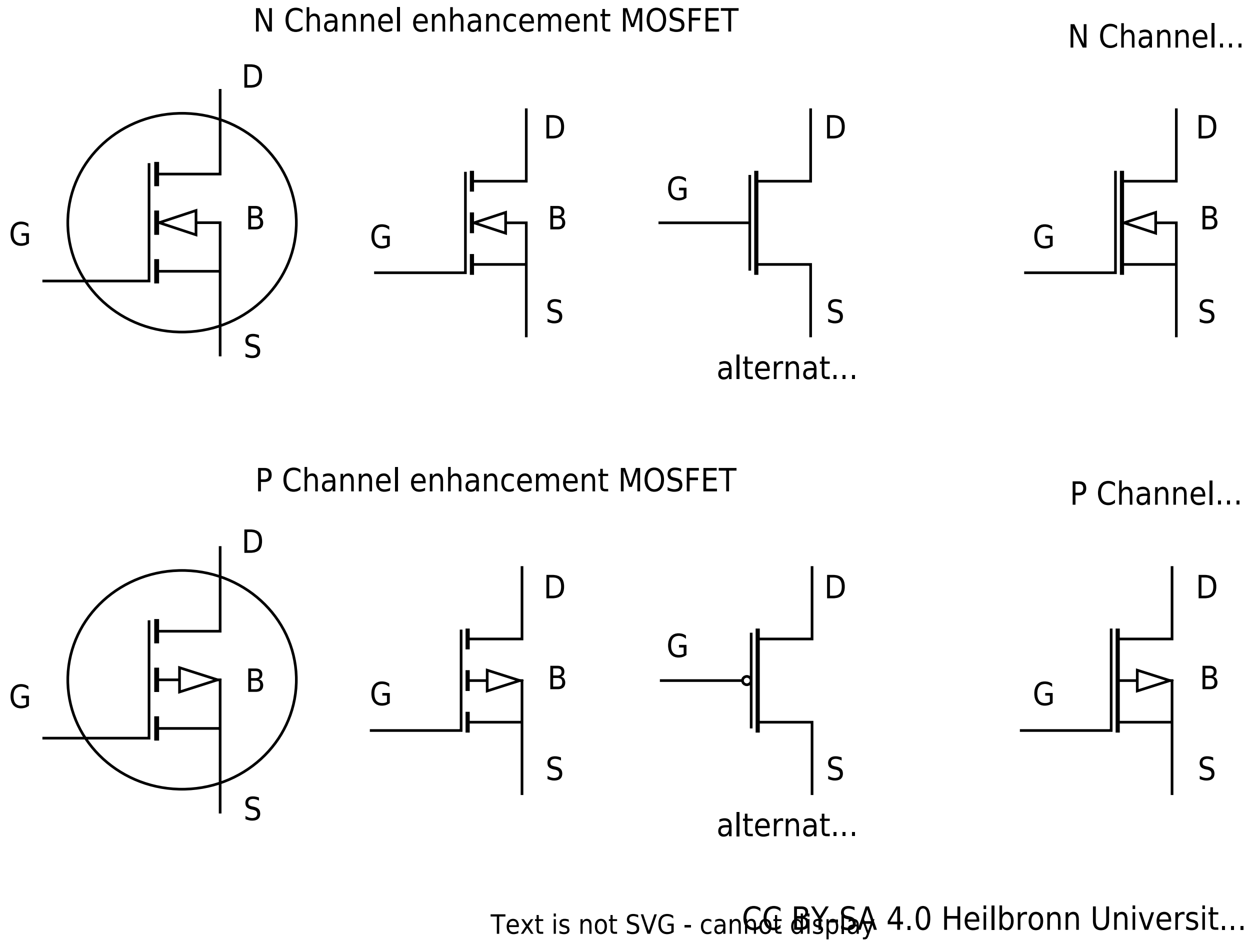
Things to try:

- change \(U_{\rm GS}\),
- observe the family of output curves,
- identify cutoff, linear/ohmic region, and MOSFET saturation region.

MOSFET types

MOSFETs can be classified by channel type and by whether they are normally off or normally on.

Fig. 7: Circuit symbols for common MOSFET types.



Channel type	Enhancement type / self-blocking	Depletion type / self-conducting
n-channel	off at \(U_{\rm GS}=0\), on for sufficiently positive \(U_{\rm GS}\)	on at \(U_{\rm GS}=0\), can be reduced by negative \(U_{\rm GS}\)
p-channel	off at \(U_{\rm GS}=0\), on for sufficiently negative \(U_{\rm GS}\)	on at \(U_{\rm GS}=0\), can be reduced by positive \(U_{\rm GS}\)

Tab. 5: Basic MOSFET types

In many mechatronic power circuits, the most common device is the **n-channel enhancement MOSFET**.

BJT versus MOSFET as a switch

Property	BJT	MOSFET
control quantity	base current $I_{\rm B}$	gate-source voltage $U_{\rm GS}$
stationary control current	required	approximately zero
stationary control loss	$P_{\rm ctrl}\approx U_{\rm BE}I_{\rm B}$	very small, but gate must be charged and discharged during switching
on-state loss	$P_{\rm on}\approx U_{\rm CE,sat}I_{\rm C}$	$P_{\rm on}=R_{\rm DS(on)}I_{\rm D}^2$
switching behavior	storage charge can slow turn-off	often faster, but gate capacitance matters
typical risk	current gain B varies strongly	gate oxide sensitive to overvoltage and ESD

Tab. 6: BJT and MOSFET as switching elements

> MOSFET gates are sensitive. A too large $|U_{\rm GS}|$ can destroy the thin gate oxide.

Engineering preview

In many modern digital and power-electronic circuits, MOSFETs are preferred as switches because they need almost no stationary gate current and can have very small $R_{\rm DS(on)}$.

However, the gate is capacitive. Fast switching requires charging and discharging this capacitance quickly. This is one reason why gate drivers are needed in power stages.

Exercises

Exercise E1.1 BJT terminals, signs, and current balance

An npn transistor is operated in normal active operation. The reference arrows are chosen as in the core content:

- $I_{\rm B}$ and $I_{\rm C}$ enter the transistor,
- $I_{\rm E}$ is also defined as entering the transistor.

For normal npn operation:

$$ \begin{align*} U_{\rm BE}>0, \qquad U_{\rm CE}>0, \qquad U_{\rm CB}>0. \end{align*} $$

1. State the meaning of the terminals B, C, and E.

SolutionResult

Use the terminal names of the bipolar junction transistor:

- B: control terminal,
- C: terminal of the main current path,
- E: terminal where carriers are emitted.

The names are not arbitrary. They describe the physical function of the regions.

$$\begin{align*} B&:\text{ base},\\ C&:\text{ collector},\\ E&:\text{ emitter}. \end{align*}$$

2. State the signs of $I_{\rm B}$, $I_{\rm C}$, and $I_{\rm E}$ in normal npn operation.

SolutionResult

For the reference arrows used here, base current and collector current enter the transistor.

The emitter current physically leaves the transistor. Since $I_{\rm E}$ is also defined as entering the transistor, its sign becomes negative.

$$\begin{align*} I_{\rm B}>0, \qquad I_{\rm C}>0, \qquad I_{\rm E}<0. \end{align*}$$

3. Calculate $I_{\rm E}$ for

$$\begin{align*} I_{\rm B}=50~\mu{\rm A}, \qquad I_{\rm C}=5.0~{\rm mA}. \end{align*}$$

SolutionResult

Apply Kirchhoff's current law at the transistor:

$$\begin{align*} I_{\rm B}+I_{\rm C}+I_{\rm E}=0. \end{align*}$$

Solve for $I_{\rm E}$:

$$\begin{align*} I_{\rm E}=-(I_{\rm B}+I_{\rm C}). \end{align*}$$

Insert both currents in the same unit:

$$\begin{align*} I_{\rm B}=50~\mu{\rm A}=0.050~{\rm mA}. \end{align*}$$

$$\begin{align*} I_{\rm E} &= -\left(0.050~{\rm mA}+5.0~{\rm mA}\right) \\ &= -5.05~{\rm mA}. \end{align*}$$

The emitter current magnitude is

$$\begin{align*} |I_{\rm E}|=5.05~{\rm mA}. \end{align*}$$

Exercise E2.1 BJT current gain and active-region estimate

An npn transistor is operated in the active region. The base current is

$$\begin{align*} I_{\rm B}=35~\mu{\rm A}. \end{align*}$$

The DC current gain is approximated by

$$\begin{align*} B=150. \end{align*}$$

1. Calculate the collector current $I_{\rm C}$.

SolutionResult

In the active region, use the current-gain approximation

$$I_{\rm C}\approx B$$

$$\begin{align*} I_{\rm C} &\approx B I_{\rm B} \\ &= 150\cdot 35~\mu{\rm A} \\ &= 5250~\mu{\rm A} = 5.25~{\rm mA}. \end{align*}$$

I_{\rm B}. \end{align*} \]

Insert the given current gain and base current.

2. Calculate the emitter current magnitude $|I_{\rm E}|$.

SolutionResult

Using magnitudes,

$$\begin{align*} |I_{\rm E}|=I_{\rm B}+I_{\rm C}. \end{align*}$$

Convert $I_{\rm B}$ to ${\rm mA}$:

$$\begin{align*} 35~\mu{\rm A}=0.035~{\rm mA}. \end{align*}$$

$$\begin{align*} |I_{\rm E}| &= 0.035~{\rm mA}+5.25~{\rm mA} \\ &= 5.285~{\rm mA} \approx 5.29~{\rm mA}. \end{align*}$$

3. Explain why the value of $I_{\rm C}$ is only an estimate.

SolutionResult

The formula

$$\begin{align*} I_{\rm C}\approx B I_{\rm B} \end{align*}$$

uses a simplified transistor model.

The current gain B is not an exact constant. It depends on transistor type, collector current, temperature, and manufacturing variation.

The collector current is only an estimate because B can vary strongly.

For robust circuit design, especially for switches, one should not rely only on a typical value of B.

Exercise E3.1 Cutoff, active region, or saturation?

An npn transistor is used with a resistive load. The supply voltage is

$$\begin{align*} U_{\rm dc}=12~{\rm V}. \end{align*}$$

The load resistance is

$$\begin{align*} R_{\rm L}=680~\Omega. \end{align*}$$

The base current is

$$\begin{align*} I_{\rm B}=0.15~{\rm mA}. \end{align*}$$

Assume a current gain

$$\begin{align*} B=100. \end{align*}$$

1. Calculate the collector current predicted by the active-region formula.

SolutionResult

If the transistor is in the active region, use

$$\begin{align*} I_{\rm C,active}\approx B I_{\rm B}. \end{align*}$$

This is the collector current the transistor would try to set.

$$\begin{align*} I_{\rm C,active} &\approx 100\cdot 0.15~{\rm mA} \\ &= 15~{\rm mA}. \end{align*}$$

2. Calculate the maximum load current set by the resistor.

SolutionResult

The load circuit limits the current. As a first estimate, neglect $U_{\rm CE,sat}$ and use Ohm's law:

$$\begin{align*} I_{\rm L,max}\approx \frac{U_{\rm dc}}{R_{\rm L}}. \end{align*}$$

$$\begin{align*} I_{\rm L,max} &\approx \frac{12~{\rm V}}{680~\Omega} \\ &= 17.6~{\rm mA}. \end{align*}$$

3. Decide whether the transistor is likely in the active region or in saturation.

SolutionResult

Compare the current predicted by the active-region formula with the maximum current allowed by the load circuit:

$$\begin{align*} I_{\rm C,active} \quad \text{versus} \quad I_{\rm L,max}. \end{align*}$$

If $I_{\rm C,active}$ is smaller than the load limit, the transistor can still be in the active region. If $I_{\rm C,active}$ is larger than the load limit, the transistor is driven into saturation.

$$\begin{align*} I_{\rm C,active}=15~{\rm mA} < I_{\rm L,max}=17.6~{\rm mA}. \end{align*}$$

The transistor is not forced into saturation by this base current. It is likely still in the active region.

4. What base current would approximately be required to reach the load-current limit in the active-region model?

SolutionResult

Set the active-region collector current equal to the maximum load current:

$$\begin{align*} I_{\rm L,max}=B I_{\rm B,limit}. \end{align*}$$

Solve for the base current:

$$\begin{align*} I_{\rm B,limit}=\frac{I_{\rm L,max}}{B}. \end{align*}$$

$$\begin{align*} I_{\rm B,limit} &= \frac{17.6~{\rm mA}}{100} \\ &= 0.176~{\rm mA}. \end{align*}$$

So a base current above about

$$\begin{align*} I_{\rm B}\approx 0.18~{\rm mA} \end{align*}$$

would begin to drive the transistor toward saturation.

Exercise E4.1 MOSFET threshold voltage versus fully switched-on operation

An n-channel enhancement MOSFET is used as a switch. The datasheet gives

$$\begin{align*} U_{\rm GS(th)}=2.0\ldots4.0~{\rm V}. \end{align*}$$

The datasheet also gives

$$\begin{align*} R_{\rm DS(on)}=80~{\rm m}\Omega \end{align*}$$

but only for

$$\begin{align*} U_{\rm GS}=10~{\rm V}. \end{align*}$$

The load current is

$$\begin{align*} I_{\rm D}=3.0~{\rm A}. \end{align*}$$

1. Explain why $U_{\rm GS(th)}$ is not the correct value for switching the MOSFET fully on.

SolutionResult

The threshold voltage only describes the beginning of channel formation. At $U_{\rm GS(th)}$, the datasheet usually defines only a very small drain

$U_{\rm GS(th)}$ means: the MOSFET just starts to conduct.

It does **not** mean: the MOSFET is a good low-resistance switch.

current.

For low-loss switching, the MOSFET must have a small $R_{\rm DS(on)}$. Therefore use the gate voltage for which $R_{\rm DS(on)}$ is specified.

For this datasheet value, low-loss operation is specified at

$$\begin{align*} U_{\rm GS}=10~{\rm V}. \end{align*}$$

2. Calculate the drain-source voltage $U_{\rm DS}$ when the MOSFET is fully switched on at $U_{\rm GS}=10~{\rm V}$.

SolutionResult

For a fully switched-on MOSFET, use the resistor approximation:

$$\begin{align*} U_{\rm DS}\approx R_{\rm DS(on)}I_{\rm D}. \end{align*}$$

Convert the resistance:

$$\begin{align*} 80~{\rm m}\Omega=0.080~\Omega. \end{align*}$$

$$\begin{align*} U_{\rm DS} &\approx 0.080~\Omega\cdot 3.0~{\rm A} \\ &= 0.24~{\rm V}. \end{align*}$$

3. Calculate the conduction loss $P_{\rm on,MOS}$.

SolutionResult

The conduction loss of a switched-on MOSFET is

$$\begin{align*} P_{\rm on,MOS}=R_{\rm DS(on)}I_{\rm$$

$$\begin{align*} P_{\rm on,MOS} &= 0.080~\Omega\cdot (3.0~{\rm A})^2 \\ &= 0.080~\Omega\cdot 9.0~{\rm A^2} \\ &= 0.72~{\rm W}. \end{align*}$$

D}^2. \end{align*} \]

Alternatively, you can use

$$\begin{align*} P_{\rm on,MOS}=U_{\rm DS}I_{\rm D}. \end{align*}$$

Exercise E5.1 BJT versus MOSFET as a switching element

A mechatronic actuator draws the load current

$$\begin{align*} I_{\rm L}=1.2~{\rm A}. \end{align*}$$

Two possible switching transistors are compared.

For the BJT, assume

$$\begin{align*} U_{\rm CE,sat}=0.25~{\rm V}, \qquad U_{\rm BE}=0.70~{\rm V}, \qquad I_{\rm B}=15~{\rm mA}. \end{align*}$$

For the MOSFET, assume

$$\begin{align*} R_{\rm DS(on)}=120~{\rm m}\Omega \end{align*}$$

at the available gate voltage.

1. Calculate the BJT conduction loss.

SolutionResult

For a saturated BJT switch, the conduction loss is approximated by

$$\begin{align*} P_{\rm on,BJT}\approx U_{\rm CE,sat}I_{\rm C}. \end{align*}$$

Here the collector current is the load current:

$$\begin{align*} P_{\rm on,BJT} &\approx 0.25~{\rm V}\cdot 1.2~{\rm A} \\ &= 0.30~{\rm W}. \end{align*}$$

$$\begin{align*} I_{\rm C}\approx I_{\rm L}. \end{align*}$$

2. Calculate the stationary BJT control loss at the base.

SolutionResult

The base-emitter path behaves approximately like a forward-biased diode.

The stationary control loss is

$$\begin{align*} P_{\rm ctrl,BJT}\approx U_{\rm BE}I_{\rm B}. \end{align*}$$

$$\begin{align*} P_{\rm ctrl,BJT} &\approx 0.70~{\rm V}\cdot 15~{\rm mA} \\ &= 10.5~{\rm mW}. \end{align*}$$

3. Calculate the MOSFET conduction loss.

SolutionResult

For a fully switched-on MOSFET, use

$$\begin{align*} P_{\rm on,MOS}=R_{\rm DS(on)}I_{\rm D}^2. \end{align*}$$

Here the drain current is the load current:

$$\begin{align*} I_{\rm D}\approx I_{\rm L}. \end{align*}$$

Convert

$$\begin{align*} P_{\rm on,MOS} &= 0.120~\Omega\cdot (1.2~{\rm A})^2 \\ &= 0.120~\Omega\cdot 1.44~{\rm A^2} \\ &= 0.173~{\rm W}. \end{align*}$$

$$\begin{align*} 120~{\rm m}\Omega=0.120~\Omega. \end{align*}$$

4. Which component has the lower on-state loss in this operating point?

SolutionResult

Compare the calculated conduction losses:

$$\begin{align*} P_{\rm on,BJT} \quad \text{and} \quad P_{\rm on,MOS}. \end{align*}$$

The lower value means lower heat generation in the switched-on state.

$$\begin{align*} P_{\rm on,MOS}=0.173~{\rm W} < P_{\rm on,BJT}=0.30~{\rm W}. \end{align*}$$

For this operating point, the MOSFET has the lower conduction loss.

5. State one important disadvantage or risk of each device.

SolutionResult

Use the qualitative comparison:

- BJT: controlled by base current.
- MOSFET: controlled by gate-source voltage.
- BJT switching can be affected by current gain and stored charge.
- MOSFET switching can be affected by gate oxide limits and gate charge.

Possible answer:

- **BJT:** needs continuous base current; current gain B varies strongly.
- **MOSFET:** gate oxide is sensitive to overvoltage and ESD; the gate capacitance must be charged and discharged during switching.

Both devices must be checked for power dissipation and temperature.

Exercise E6.1 MOSFET body diode and current direction

A discrete n-channel MOSFET is used as a low-side switch. The source is connected to ground, the drain is connected to a load, and the load is connected to $+24~{\rm V}$.

The MOSFET is off:

$$U_{\rm GS}=0.$$

1. Can the MOSFET channel conduct a useful load current?

SolutionResult

For an n-channel enhancement MOSFET:

- at $U_{\rm GS}=0$, no useful channel exists,
- a positive gate-source voltage is required to form the channel.

Therefore the drain-source path through the channel is off.

No. At

$$U_{\rm GS}=0$$

an n-channel enhancement MOSFET is normally off, so the channel does not conduct a useful load current.

2. Why is a real MOSFET still not an ideal bidirectional open switch?

SolutionResult

A discrete power MOSFET usually contains a body diode. This diode is caused by the internal pn junction between body and drain/source

A real MOSFET contains a body diode.

Therefore it can block well only in one polarity. In the opposite polarity, the body diode may become forwardregions.

Even when the MOSFET channel is off, the body diode can conduct for one drain-source polarity.

biased and conduct.

So a single MOSFET is not an ideal bidirectional open switch.

3. Why is the body diode important for motor-driver circuits?

SolutionResult

Motors and coils are inductive loads. Their current cannot change instantly.

When a transistor switches off, the current may continue through diodes or body diodes. This influences voltage spikes, current paths, losses, and braking behavior.

The body diode can provide a current path for inductive current.

This can be useful, but it also affects the behavior of H-bridges and motor drivers. The designer must know when the body diode conducts and whether its current and power limits are sufficient.

Common pitfalls

- **Thinking a BJT is just two diodes:** The thin base region makes transistor action possible. Two separate diodes do not behave like a transistor.
- **Forgetting the base-emitter diode:** The BJT input characteristic resembles a diode. For silicon, $U_{\rm BE}$ is often around $0.6\ldots0.7~{\rm V}$, depending on current and temperature.
- **Treating B as an exact constant:** The current gain can vary strongly. Robust switching circuits are not designed with a typical B only.
- **Confusing active region and saturation:** In the active region, $I_{\rm C}\approx B I_{\rm B}$. In saturation, the load circuit limits $I_{\rm C}$.
- **Using MOSFET threshold voltage as full-on voltage:** $U_{\rm GS(th)}$ is not sufficient for low conduction loss.
- **Confusing MOSFET saturation with BJT saturation:** A fully switched-on MOSFET is usually in the linear or ohmic region, not in the MOSFET saturation region.
- **Forgetting the MOSFET body diode:** A real power MOSFET is not an ideal bidirectional switch.

- **Ignoring MOSFET gate charge:** The stationary gate current is nearly zero, but fast switching still requires charging and discharging the gate capacitance.
- **Mixing voltage polarities for pnp and p-channel devices:** Their useful operating polarities are reversed compared with npn and n-channel devices.
- **Ignoring power dissipation:** Both BJTs and MOSFETs convert electrical energy into heat during conduction and switching.

Embedded resources

> The useful Falstad simulations are embedded directly in the relevant chapters above.