

# Block 13 — Transistor Fundamentals

## Student Group

| First Name | Surname | Matrikel Nr. |
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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  $(U_{BE})$ ,  $(U_{CE})$ ,  $(U_{CB})$ ,  $(I_B)$ ,  $(I_C)$ , and  $(I_E)$ .
- use the current-gain approximation

$$I_C \approx \beta I_B$$
 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  $(R_{DS(on)})$ .
    - 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  $(I_B)$  to control the collector current  $(I_C)$ .
- A MOSFET uses a gate-source voltage  $(U_{GS})$  to control the drain current  $(I_D)$ .
- 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, and like all other digital companions, are based on transistor circuits. All logic circuits can be traced back to NAND and NOR gates as building blocks. These logic gates consist of transistors. In the simulation below, the structure of a NAND gate is shown in the current CMOS structure. CMOS here indicates the structure of the circuit and semiconductor structure: **Complementary metal-oxide-semiconductor** - an oppositely complementary circuit of semiconductors of the metal-

oxide-semiconductor structure. The complementary structure is shown by the fact that.

- from the digital output (\$OUT2\$) to ground two transistors of one kind are connected in series and
- from the digital output (\$OUT2\$) to the  $5\text{~}\rm V$  supply, two transistors of a different type are connected in parallel.

These two different kinds of MOS-transistors and further used kinds shall be explained in this chapter.

## From diode to transistor

A variable resistor can be developed from the diode.

A diode has two terminals and one pn junction, as we have seen in [Block11](#). It can conduct or block depending on the applied voltage.

Therefore, there is only one path on which the current is dependent on the voltage on this path

With this controlled transition resistor ("transfer resistor" or better transistor) this gets a bit more extreenally controlled:

1. A transistor has at least three terminals.
2. 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 (BJT) has three doped regions and three terminals.

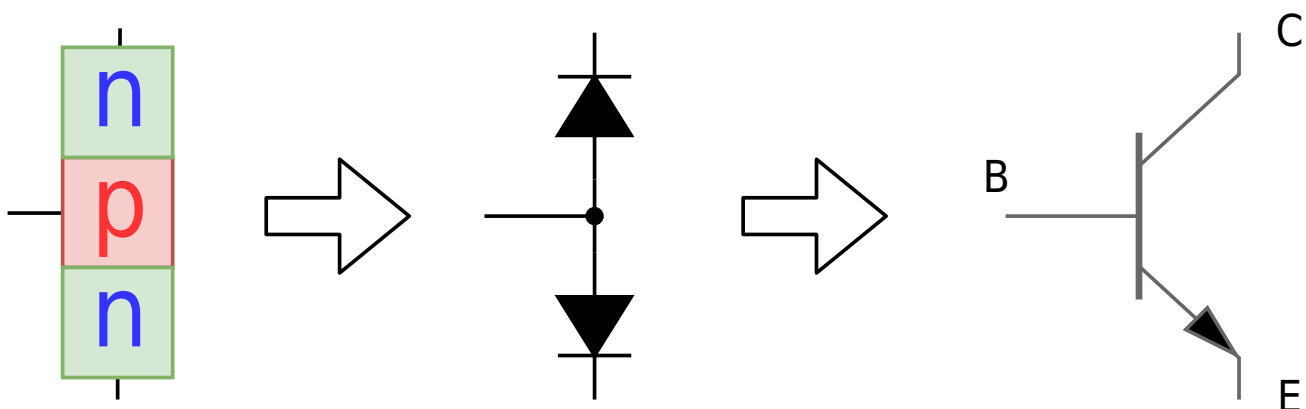
- **Emitter (E):** emits charge carriers (either holes or electrons) into the transistor.
- **Base (B):** thin control region.
- **Collector (C):** collects charge carriers.

There are two basic BJT types:

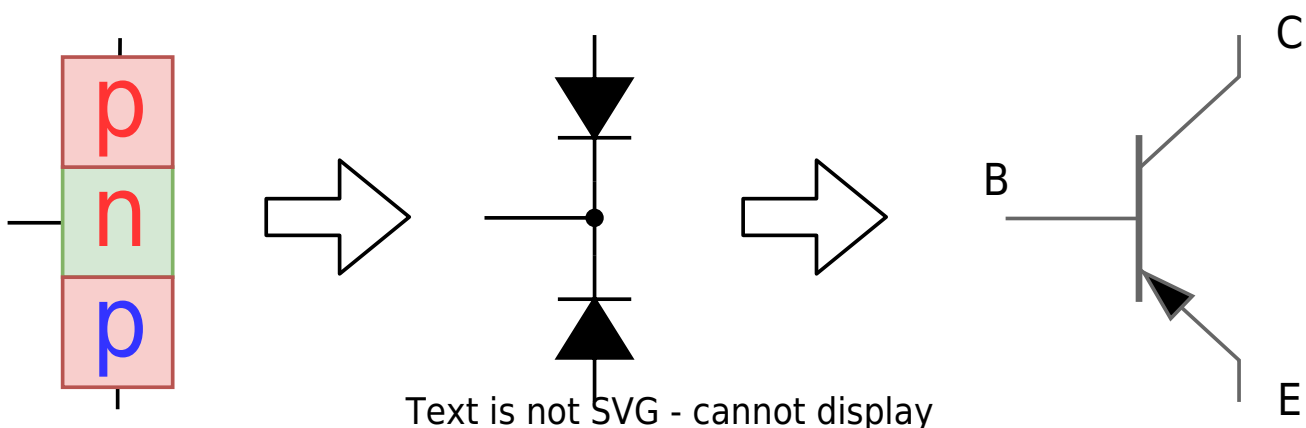
- **npn transistor:** n-p-n layer sequence,
- **pnp transistor:** p-n-p layer sequence.

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

## nnp-Transistor



## pnp-Transistor



Depending on the layer sequence (or “direction of the diodes”), PNP or NPN transistors result, represented by different circuit symbols with three terminals (see [figure 1](#)). In both transistor variants, charge carriers are emitted from the emitter terminal (E) toward the collector terminal (C) if a suitable current flows through the base terminal (B). In simplified terms, the negative charge carriers of the n-doped sides could represent a current through an NPN structure if negative charge carriers were also present in the P-doped layer. The current  $I_C$  flowing with it in the technical current direction is illustrated in the circuit symbol by the arrow direction at the emitter. In the NPN transistor, the current

$I_C$  flows from the collector to the emitter. Since positive charge carriers enable conductivity in the PNP transistor, the technical current direction here points from the emitter to the collector, and the arrow on the emitter points towards the collector. The direction of the arrow is similar to the direction of the diode or the PN junction.

### Mnemonic for the emitter arrow

- **nnp**: arrow **not** pointing in.
- **pnnp**: arrow **p**oints in.

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

#### 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.

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

$$U_{BE} > 0, \text{ \& } U_{CE} > 0, \text{ \& } U_{CB} > 0.$$

With the reference arrows commonly used in this course:

$$I_B > 0, \text{ \& } I_C > 0, \text{ \& } I_E < 0.$$

Kirchhoff's current law gives

$$I_B + I_C + I_E = 0.$$

Using current magnitudes:

$$|I_E| = I_B + I_C$$

| Type | Voltage signs                              | Current signs with the shown reference arrows |
|------|--------------------------------------------|-----------------------------------------------|
| npn  | $(U_{BE} > 0), (U_{CE} > 0), (U_{CB} > 0)$ | $(I_B > 0), (I_C > 0), (I_E < 0)$             |
| pnp  | $(U_{BE} < 0), (U_{CE} < 0), (U_{CB} < 0)$ | $(I_B < 0), (I_C < 0), (I_E > 0)$             |

Tab. 1: Sign conventions in normal operation

How the npn transistor controls current

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



Here, the figures in figure 2 shall be described:

- Figure: The physics of controlling the BJT takes place in the narrow P-layer in the middle. The following figures 2. - 6. refer to the highlighted section.
- Figure - Situation  $U_{CE} = 0 \text{ V}, U_{BE} = 0 \text{ V}$ :  
In this picture the unpowered transistor is shown. In it the free charge carriers (electrons in green, holes in red) and the junction layers between base and emitter, and base and collector in yellow. Only the junction layer shows the stationary charge carriers with their sign. As shown in the band model, the stationary charge carriers are present everywhere in both doped regions.
- Figure - Situation  $U_{CE} = 0 \text{ V}, 0 \text{ V} < U_{BE} < 0.6 \text{ V}$ :  
First, consider a small, positive voltage  $U_{BE}$ . This provides holes in the base with current  $I_B$ . This operates the PN junction between the base and emitter in the forward direction. In the figure, it is indicated with black circles that the injected holes compensate some stationary negative charge carriers in both junction layers. Electrons also flow through the emitter into the n-region, which attenuates the junction on the other side.
- Figure - Situation  $U_{CE} = 0 \text{ V}, U_{BE} > 0.6 \text{ V}$ :  
When the forward voltage of the PN junction between the base and emitter is exceeded, the injected holes and electrons cancel the bottom junction. In the simulation below, it can be seen that the circuitry of the transistor is such that in the diode circuit (which is not physically correct), the diode between the base and emitter becomes conductive.
- Figure - Situation  $U_{CE} > 0 \text{ V}, U_{BE} > 0.6 \text{ V}$ :  
Now with this voltage at the base, the working circuit, i.e. a voltage  $U_{BE} > 0$  should be present at the output. In the real system, the base is very small compared to the mean free path length of the electrons ("path to recombination with a hole"). This changes the situation at the upper PN junction. In a classical diode, no electrons are present in the P-doped region.

However, the electrons present here can cross the base and compensate for the stationary positive charge carriers in the upper junction. The holes injected into the base in turn compensate for the stationary negative charge carriers. Thus, this junction layer is also removed. This is possible as long as enough holes are injected into the base.

6. Figure - Situation  $U_{\text{CE}} > 0 \sim \text{V}$ ,  $U_{\text{BE}} > 0.6 \sim \text{V}$ :

Thus, in the NPN bipolar junction transistor, both holes (to remove the junction layers) and electrons (as the “main agents” responsible for charge transport, the so-called majority carrier charges) contribute to the conductivity. This is where the name bipolar junction transistor comes from.

## TLDR: How a transistor works

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

$$U_{\text{BE}} \approx 0.6 \text{ to } 0.7 \text{ V}.$$

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.

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. The base current flows over a diode between base and emitter (depicted as arrow in the symbol).

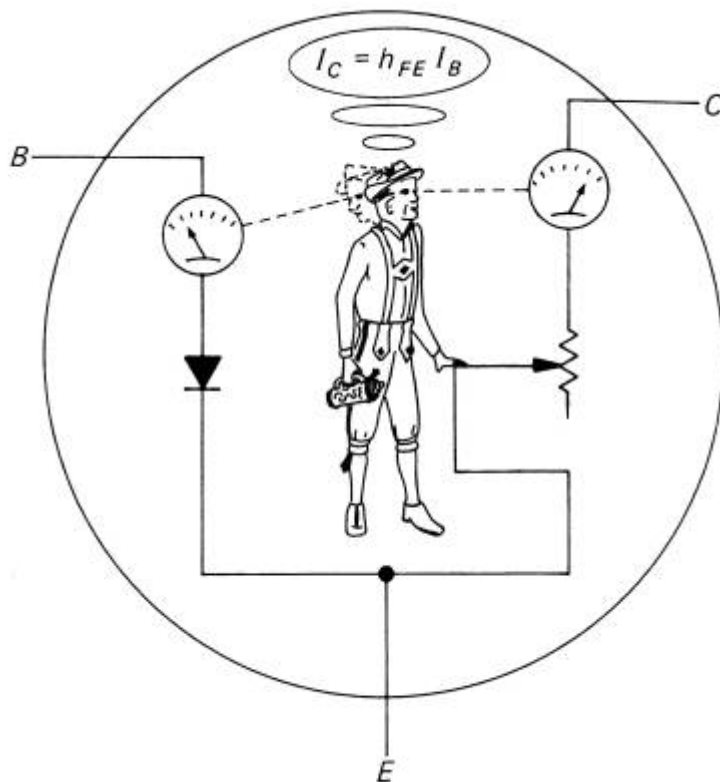


Fig. 3: function of NPN bipolar junction

transistor

$$I_C \approx \beta I_B$$

The factor  $\beta$  is the DC current gain:

$$\beta = \frac{I_C}{I_B}$$

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

$$h_{FE} = \beta = \frac{\Delta I_C}{\Delta I_B} \approx \frac{I_C}{I_B}$$

### Color scheme for the BJT control idea

$$\begin{aligned} & \text{small control current } I_B, \\ & \text{larger controlled current } I_C, \\ & \text{input control power } U_{BE} I_B \end{aligned}$$

The useful first approximation is

$$I_C \approx \beta I_B$$

The current gain  $\beta$  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  $\beta$ . This is treated

in [Block 14](#).

### BJT characteristic curves and differential quantities

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

Important BJT characteristics are:

- **Input characteristic:**  $(I_B(U_{BE}))$   
The base-emitter path behaves approximately like a diode.
- **Control characteristic:**  $(I_C(I_B))$   
This shows the current gain.
- **Output characteristic:**  $(I_C(U_{CE}))$  for different values of  $(I_B)$ .

Important parameters around an operating point are

$$\begin{aligned} r_{BE} &= \frac{\Delta U_{BE}}{\Delta I_B} = \frac{u_{BE}}{i_B}, \\ r_{CE} &= \frac{\Delta U_{CE}}{\Delta I_C} = \frac{u_{CE}}{i_C}. \end{aligned}$$

### BJT operating regions

A BJT operates mainly in three different regions.

| Region        | Approximate condition                  | Electrical behavior                          | Typical use      |
|---------------|----------------------------------------|----------------------------------------------|------------------|
| cutoff        | $(I_B \approx 0)$                      | $(I_C \approx 0)$ , transistor blocks        | open switch      |
| active region | $(I_C \approx \beta I_B)$              | collector current controlled by base current | analog amplifier |
| saturation    | $(I_B)$ large enough, $(U_{CE})$ 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

$$U_{CE,sat} \approx 0.1 \dots 0.3 \text{ V}.$$

The conduction loss of a saturated BJT switch is approximately

$$P_{\text{on,BJT}} \approx U_{\text{CE,sat}} I_{\text{C}}.$$

The control loss at the base is approximately

$$P_{\text{ctrl,BJT}} \approx U_{\text{BE}} I_{\text{B}}.$$

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             |
|------------------|---------------------|
| $t_{\text{d}}$   | delay time          |
| $t_{\text{r}}$   | rise time           |
| $t_{\text{on}}$  | total turn-on time  |
| $t_{\text{s}}$   | storage time        |
| $t_{\text{f}}$   | fall time           |
| $t_{\text{off}}$ | 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.

$$p(t) = u_{\text{CE}}(t) \cdot i_{\text{C}}(t).$$

## 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  $t_{\text{s}}$ .

## 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  $U_{\text{GS}}$ ,
- **drain (D):** load current terminal,
- **bulk (B):** semiconductor body, often internally connected to source in discrete MOSFETs.

The name MOSFET means:

$$\text{Metal-Oxide-Semiconductor Field-Effect Transistor}.$$

## Key difference to the BJT

For a BJT:

$$\{I_{\text{B}}\} \quad \text{controls} \quad \{I_{\text{C}}\}.$$

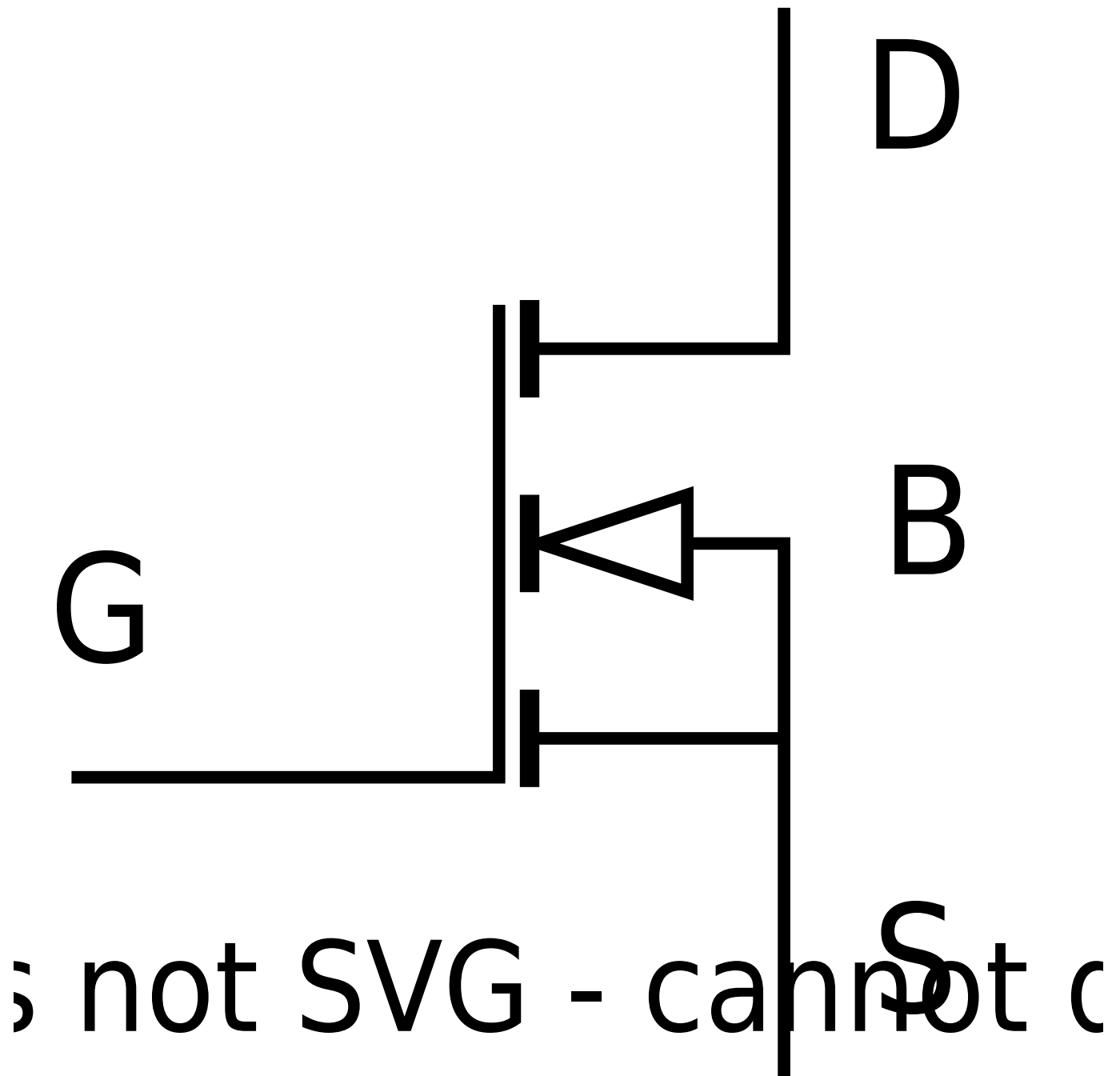
For a MOSFET:

$$\{U_{\text{GS}}\} \quad \text{controls} \quad \{I_{\text{D}}\}.$$

In stationary operation, the ideal gate current is approximately

$$I_{\text{G}} \approx 0.$$

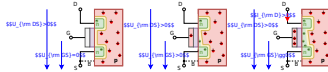
Fig. 4: FET principle: a gate signal controls the drain-source current path.



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

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

### Important datasheet warning

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

For low conduction loss, use the gate voltage at which the datasheet specifies  $R_{\text{DS(on)}}$ .

### 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  $(U_{\text{GS}})$  and observe channel formation,
- reverse the drain-source polarity,
- observe when the body diode conducts.

### MOSFET output characteristics

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

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

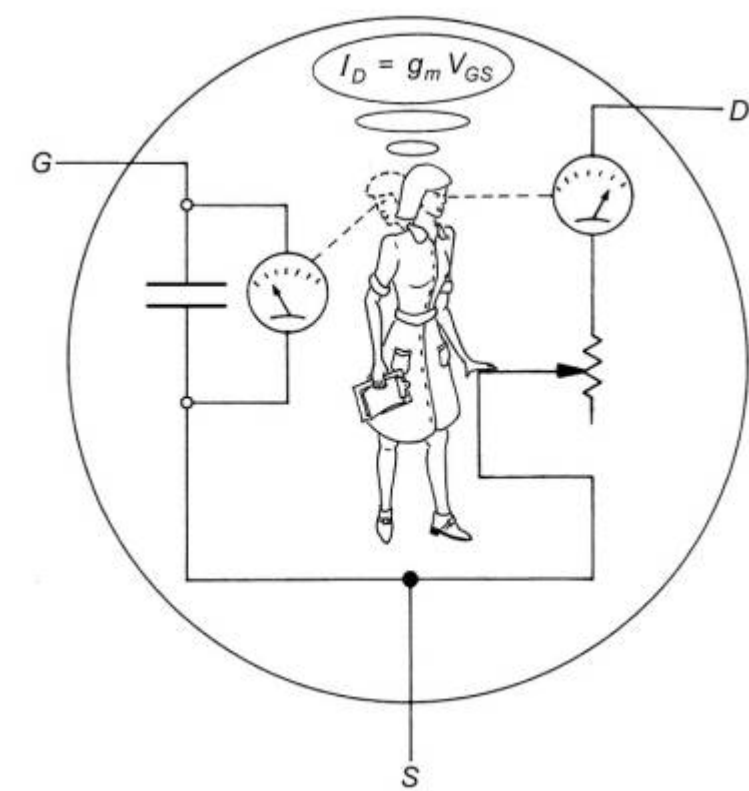


Fig. 6: Function of the MOSFET

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,<br>$(I_{\rm D} \approx 0)$ | 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:

$$U_{\rm DS} \approx R_{\rm DS(on)} \cdot I_{\rm D}.$$

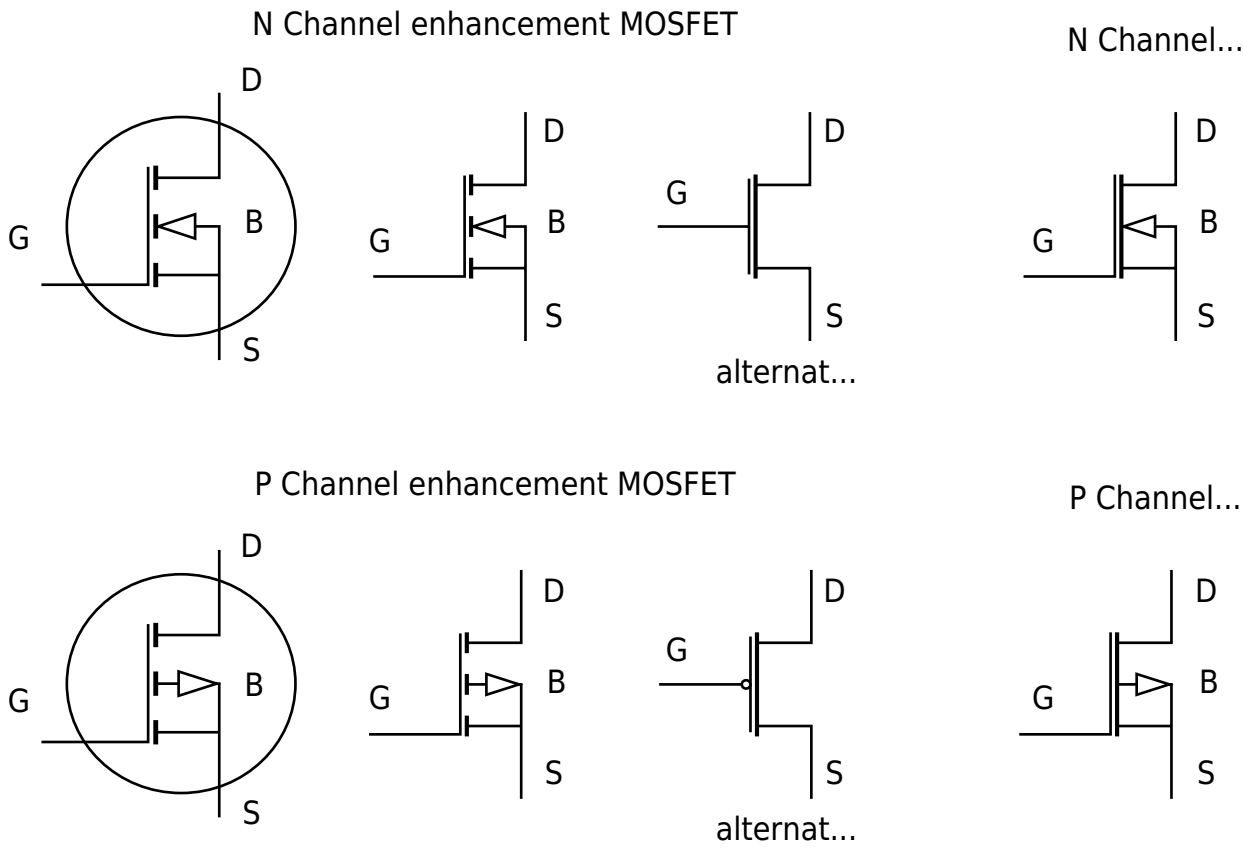
The conduction loss is

$$P_{\rm on,MOS} = R_{\rm DS(on)} \cdot I_{\rm D}^2$$

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.



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

Tab. 6: BJT and MOSFET as switching elements

MOSFET gates are sensitive. A too large  $(|U_{GS}|)$  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  $(R_{DS(on)})$ . 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:

- $(I_B)$  and  $(I_C)$  enter the transistor,
- $(I_E)$  is also defined as entering the transistor.

For normal npn operation:

$$U_{BE} > 0, \quad U_{CE} > 0, \quad U_{CB} > 0.$$

- 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  $(I_B)$ ,  $(I_C)$ , and  $(I_E)$  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  $(I_E)$  is also defined as entering the transistor, its sign becomes negative.

```
\[ \begin{align*} I_B > 0, \quad I_C > 0, \quad I_E < 0. \end{align*} \]
```

3. Calculate  $(I_E)$  for

```
\[ \begin{align*} I_B = 50 \mu\text{A}, \quad I_C = 5.0 \text{ mA}. \end{align*} \]
```

## SolutionResult

Apply Kirchhoff's current law at the transistor:

$$I_{\text{B}} + I_{\text{C}} + I_{\text{E}} = 0.$$

Solve for  $I_{\text{E}}$ :

$$I_{\text{E}} = -(I_{\text{B}} + I_{\text{C}}).$$

Insert both currents in the same unit:

$$I_{\text{B}} = 50 \mu\text{A} = 0.050 \text{ mA}.$$

$$I_{\text{E}} = -\left(0.050 \text{ mA} + 5.0 \text{ mA}\right) = -5.05 \text{ mA}.$$

The emitter current magnitude is

$$|I_{\text{E}}| = 5.05 \text{ mA}.$$

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

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

$$I_{\text{B}} = 35 \mu\text{A}.$$

The DC current gain is approximated by

$$\beta = 150.$$

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

SolutionResult

In the active region, use the current-gain approximation

$$I_{\text{C}} \approx \beta I_{\text{B}}.$$

Insert the given current gain and base

$$I_{\text{C}} \approx \beta I_{\text{B}} = 150 \cdot 35 \mu\text{A} = 5.25 \text{ mA}.$$

current.

2. Calculate the emitter current magnitude  $|I_E|$ .

#### SolutionResult

Using magnitudes,

$$|I_E| = I_B + I_C$$

Convert  $I_B$  to mA:

$$35 \mu\text{A} = 0.035 \text{ mA}$$

$$\begin{aligned} |I_E| &= 0.035 \text{ mA} + 5.25 \text{ mA} \\ &= 5.285 \text{ mA} \approx 5.29 \text{ mA} \end{aligned}$$

3. Explain why the value of  $I_C$  is only an estimate.

#### SolutionResult

The formula

$$I_C \approx \beta I_B$$

uses a simplified transistor model.

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

The collector current is only an estimate because  $\beta$  can vary strongly.

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

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

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

$$U_{\text{dc}} = 12 \text{ V}.$$

The load resistance is

$$R_{\text{L}} = 680 \, \Omega.$$

The base current is

$$I_{\text{B}} = 0.15 \text{ mA}.$$

Assume a current gain

$$\beta = 100.$$

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

## SolutionResult

If the transistor is in the active region, use

$$I_{\text{C,active}} \approx \beta I_{\text{B}}.$$

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

$$I_{\text{C,active}} \approx 100 \cdot 0.15 \text{ mA} \\ = 15 \text{ mA}.$$

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

## SolutionResult

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

$$I_{\text{L,max}} \approx \frac{12 \text{ V}}{680 \, \Omega} \\ = 17.6 \text{ mA}.$$

$$I_{L,\max} \approx \frac{U_{dc}}{R_L}.$$

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:

$$I_{C,\text{active}} \quad \text{versus} \quad I_{L,\max}.$$

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

$$I_{C,\text{active}} = 15 \text{ mA} < I_{L,\max} = 17.6 \text{ mA}.$$

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:

$$I_{L,\max} = I_{B,\text{limit}}.$$

$$I_{B,\text{limit}} = \frac{17.6 \text{ mA}}{100} = 0.176 \text{ mA}.$$

So a base current above about

Solve for the base current:

$$I_{B,limit} = \frac{I_{L,max}}{\beta}.$$

$$I_{B} \approx 0.18 \text{ mA}$$

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

$$U_{GS(th)} = 2.0 \sim 4.0 \text{ V}.$$

The datasheet also gives

$$R_{DS(on)} = 80 \text{ m}\Omega$$

but only for

$$U_{GS} = 10 \text{ V}.$$

The load current is

$$I_D = 3.0 \text{ A}.$$

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

#### SolutionResult

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

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

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

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

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

$$U_{GS} = 10 \text{ V}.$$

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

#### SolutionResult

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

$$U_{\text{DS}} \approx R_{\text{DS(on)}} I_{\text{D}}.$$

Convert the resistance:

$$80\text{ m}\Omega = 0.080\text{ }\Omega.$$

$$U_{\text{DS}} \approx 0.080\text{ }\Omega \cdot 3.0\text{ A} = 0.24\text{ V}.$$

3. Calculate the conduction loss  $(P_{\text{on,MOS}})$ .

#### SolutionResult

The conduction loss of a switched-on MOSFET is

$$P_{\text{on,MOS}} = R_{\text{DS(on)}} I_{\text{D}}^2.$$

Alternatively, you can use

$$P_{\text{on,MOS}} = U_{\text{DS}} I_{\text{D}}.$$

$$P_{\text{on,MOS}} = 0.080\text{ }\Omega \cdot (3.0\text{ A})^2 = 0.080\text{ }\Omega \cdot 9.0\text{ A}^2 = 0.72\text{ W}.$$

### Exercise E5.1 BJT versus MOSFET as a switching element

A mechatronic actuator draws the load current

$$I_{\text{L}} = 1.2 \text{ A}.$$

Two possible switching transistors are compared.

For the BJT, assume

$$U_{\text{CE,sat}} = 0.25 \text{ V}, \quad U_{\text{BE}} = 0.70 \text{ V}, \quad I_{\text{B}} = 15 \text{ mA}.$$

For the MOSFET, assume

$$R_{\text{DS(on)}} = 120 \text{ m}\Omega$$

at the available gate voltage.

1. Calculate the BJT conduction loss.

#### SolutionResult

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

$$P_{\text{on,BJT}} \approx U_{\text{CE,sat}} I_{\text{C}}.$$

Here the collector current is the load current:

$$I_{\text{C}} \approx I_{\text{L}}.$$

$$P_{\text{on,BJT}} \approx 0.25 \text{ V} \cdot 1.2 \text{ A} = 0.30 \text{ W}.$$

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

$$P_{\text{ctrl,BJT}} \approx U_{\text{BE}} I_{\text{B}}.$$

$$P_{\text{ctrl,BJT}} \approx 0.70 \text{ V} \cdot 15 \text{ mA} = 10.5 \text{ mW}.$$

3. Calculate the MOSFET conduction loss.

## SolutionResult

For a fully switched-on MOSFET, use

$$P_{\text{on,MOS}} = R_{\text{DS(on)}} I_{\text{D}}^2.$$

Here the drain current is the load current:

$$I_{\text{D}} \approx I_{\text{L}}.$$

Convert

$$120 \text{ mA} = 0.120 \text{ A}.$$

$$P_{\text{on,MOS}} = 0.120 \text{ A} \cdot (1.2 \text{ A})^2 = 0.120 \text{ A} \cdot 1.44 \text{ A}^2 = 0.173 \text{ W}.$$

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

## SolutionResult

Compare the calculated conduction losses:

$$\begin{aligned} P_{\text{on,BJT}} \\ \quad \text{and} \quad P_{\text{on,MOS}}. \end{aligned}$$

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

$$P_{\text{on,MOS}} = 0.173 \text{ W} < P_{\text{on,BJT}} = 0.30 \text{ W}.$$

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  $\beta$  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  $(+24\text{ V})$ .

The MOSFET is off:

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

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

#### SolutionResult

For an n-channel enhancement MOSFET:

- at  $(U_{\text{GS}} = 0)$ , 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

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

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 regions.

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

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 forward-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,  $(U_{\text{BE}})$  is often around  $(0.6 \text{ to } 0.7 \text{ V})$ , depending on current and temperature.
- **Treating  $(\beta)$  as an exact constant:** The current gain can vary strongly. Robust switching circuits are not designed with a typical  $(\beta)$  only.
- **Confusing active region and saturation:** In the active region,  $(I_{\text{C}}) \approx \beta I_{\text{B}}$ . In saturation, the load circuit limits  $(I_{\text{C}})$ .
- **Using MOSFET threshold voltage as full-on voltage:**  $(U_{\text{GS(th)}})$  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



## Functional Principle of a Transistor

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