

# Block 11 — Semiconductor Fundamentals and Diodes

## Student Group

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## Table of Contents

- Block 11 — Semiconductor Fundamentals and Diodes** ..... 3
- Learning objectives* ..... 3
- 90-minute plan* ..... 3
- Conceptual overview* ..... 4
  - Scope of this block ..... 4
- Core content** ..... 5
  - Conductors, semiconductors, and insulators ..... 5
    - Physical picture ..... 5
  - Intrinsic conduction, electrons, and holes ..... 5
    - Analogy: empty seat in a lecture hall ..... 6
  - Doping: n-type and p-type semiconductors ..... 6
  - The pn junction ..... 6
    - Analogy: a door with a spring ..... 8
  - Forward and reverse operation ..... 8
  - Ideal diode model ..... 9
    - Engineering meaning ..... 9
  - Real diode characteristic ..... 9
  - Practical diode models for circuit calculation ..... 10
  - Operating point with a series resistor ..... 11
  - Z-diodes and LEDs as diode types ..... 11
    - Z-diode preview ..... 12
- Exercises** ..... 12
  - Exercise E1.1 Quick check: doping and charge carriers ..... 12
  - Exercise E2.1 Quick check: diode polarity ..... 13
  - Exercise E3.1 Quick check: current with the constant-voltage model ..... 14
  - Exercise E4.1 Quick check: differential diode resistance ..... 14
  - Exercise E5.1 Longer exercise: operating point with a piecewise-linear diode ..... 15

- Common pitfalls** ..... 16
- Embedded resources** ..... 16
  - PhET: Semiconductors ..... 16
  - Falstad: Diode I/V curve ..... 16

TBD

## 1. Semiconductor components

(approx. 4 blocks, based on previous lectures on [Diodes](#) and [Transistors](#) )

1. Fundamentals (conductors, semiconductors, insulators, doping, band model, intrinsic conductivity)
2. Diodes (real characteristic curve, operating point, equivalent circuit)
3. Zener diode
4. LED
5. Protective circuit with diodes
6. Rectifier circuits (single-phase rectifier, center tap circuit, bridge rectifier, smoothing capacitor)
7. Bipolar transistor (structure, designations, characteristic curve, characteristic values)
8. Transistor as a switch (circuit, switching times and behavior)
9. MOSFET (structure, comparison with bipolar transistor)
10. Optional: Transistor as an amplifier

# Block 11 — Semiconductor Fundamentals and Diodes

## Learning objectives

After this 90-minute block, you can

- distinguish conductors, semiconductors, and insulators using the band model.
- explain intrinsic conduction, electron conduction, and hole conduction.
- explain how n-doping and p-doping change the number of mobile charge carriers.
- describe the formation of a pn junction and the depletion region.
- decide whether a diode is forward-biased or reverse-biased from  $(u_{\text{AK}})$ .
- compare the ideal diode model, the constant-voltage model, and the piecewise-linear diode model.
- use the diode equation

$$i_{\text{D}} = I_{\text{S}}(T) \left( e^{\frac{u_{\text{AK}}}{mU_{\text{T}}}} - 1 \right)$$
 at a qualitative level.

- calculate simple diode operating points with a series resistor.
- identify basic diode types such as universal diodes, Z-diodes, and LEDs.

## 90-minute plan

- **Warm-up (10 min):**

- Why does a diode conduct in one direction but not in the other?
- Recall from EEE1: voltage, current direction, power, and resistors.
- Recall from EEE2: transient overvoltages at inductive loads will later need diode protection.

- **Core concepts (55 min):**

- Conductors, semiconductors, insulators, and the band gap.
- Intrinsic conduction, electron conduction, hole conduction.
- Doping: n-type and p-type material.
- pn junction, depletion region, diffusion voltage.
- Diode operation in forward and reverse direction.
- Ideal and real diode characteristics.
- Practical diode models for circuit calculations.

- **Practice (20 min):**

- Determine diode polarity and conduction state.
- Calculate current with a constant-voltage diode model.
- Estimate differential resistance at a given operating point.
- Compare ideal and real diode assumptions.

- **Wrap-up (5 min):**

- Key messages: pn junction, forward/reverse bias, current limiting, diode models.
- Preview: rectifiers, smoothing, protection circuits, LEDs, and Z-diode stabilizers in [Block 12](#).

## Conceptual overview

- A semiconductor is neither a good conductor nor a perfect insulator. Its conductivity can be controlled by material, temperature, light, and doping.
- A diode is a pn junction with two terminals:
  - **anode A** on the p-side,
  - **cathode K** on the n-side.
- In forward direction, the external voltage reduces the depletion region and current can flow.
- In reverse direction, the depletion region becomes wider and only a very small leakage current flows, until breakdown occurs.
- A diode is nonlinear. It is not a resistor.
- In circuits, diode current must usually be limited by another component, often a resistor.

### Scope of this block

This block explains **why** diodes behave as they do and how we model them.

Diode applications such as

- rectifiers,
- smoothing capacitors,
- freewheeling diodes,
- input protection circuits,
- LED circuits,
- Z-diode voltage stabilizers

are continued in [Block 12](#).

## Core content

### Conductors, semiconductors, and insulators

Materials differ strongly in their specific resistance ( $\rho$ ).

Fig. ##: Band model for conductors, semiconductors, and insulators.



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In the band model, two energy ranges are especially important:

- the **valence band**, where electrons are bound,
- the **conduction band**, where electrons can move through the crystal.

The energy gap between them is called the **band gap** ( $E_{\text{g}}$ ).

<tabcaption tab\_band\_gap|Qualitative band model>

Material type	Band model	Electrical behavior
conductor	conduction band available or overlapping	many mobile charge carriers
semiconductor	small band gap, typically a few ( $\text{eV}$ )	conductivity can be controlled
insulator	large band gap	almost no mobile charge carriers

### Physical picture

A semiconductor can be imagined as a parking garage with two floors.

- The lower floor is almost full: the valence band.
- The upper floor allows movement: the conduction band.
- The band gap is the energy needed to move an electron to the upper floor.

Doping adds useful “parking spots” or “missing spots” so that charge transport becomes much easier.

### Intrinsic conduction, electrons, and holes

In a pure semiconductor, some electrons can gain enough energy to leave their bonds. Then

- the electron becomes mobile in the conduction band,
- a missing electron remains in the valence band,
- this missing electron behaves like a positive mobile charge carrier.

The missing electron is called a **hole**.

There are two types of mobile charge carriers in semiconductors:

- **electrons** with negative charge,
- **holes** with positive effective charge.

### Analogy: empty seat in a lecture hall

Imagine a fully occupied row of seats. If one student moves to the right into an empty seat, the empty seat appears to move to the left.

The empty seat is not a real object, but it behaves as if it moves. A hole in a semiconductor is similar: it is a missing electron, but it behaves like a positive moving charge carrier.

### Doping: n-type and p-type semiconductors

Doping means adding a very small amount of foreign atoms to the semiconductor crystal.

Fig. 3: N-doping: donor atoms provide additional mobile electrons.

Fig. ##: P-doping: acceptor atoms create additional holes.



<tabcaption tab\_doping|Doping of silicon>

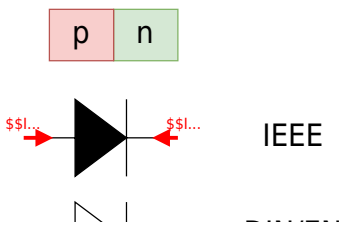
Doping type	Typical dopant atoms	Main mobile charge carriers	Name of dopant
n-type	phosphorus, arsenic, antimony	electrons	donors
p-type	boron, aluminium, indium	holes	acceptors

Doping does **not** mean that the semiconductor becomes strongly charged as a whole. The crystal is still approximately electrically neutral. Doping mainly changes how many mobile charge carriers are available.

### The pn junction

A diode is formed when p-doped and n-doped regions meet.

Fig. 4: Diode symbol and pn junction with anode A and cathode K.



At the junction:

- electrons diffuse from the n-side into the p-side,
- holes diffuse from the p-side into the n-side,
- electrons and holes recombine,
- a region with almost no mobile charge carriers forms.

This region is called the **depletion region** or **space-charge region**.

Fig. 5: Formation of the depletion region at a pn junction.

n Doped                      n Doped

The depletion region behaves like an internal barrier. Without an external voltage, it prevents a large current.

### Analogy: a door with a spring

The depletion region is like a spring-loaded door.

- In one direction, you push against the spring and can open the door.
- In the other direction, the spring pushes the door more firmly closed.

The diode behaves similarly: one polarity reduces the barrier, the other polarity increases it.

### Forward and reverse operation

We define the diode voltage

$$\left[ \begin{array}{l} u_{\text{AK}} = u_{\text{A}} - u_{\text{K}} \end{array} \right]$$

- $(u_{\text{AK}} > 0)$ : anode is more positive than cathode.
- $(u_{\text{AK}} < 0)$ : anode is more negative than cathode.

<tabcaption tab\_diode\_bias|Diode operation depending on  $(u_{AK})$ >

Condition	Name	Effect on depletion region	Current
$(u_{AK}) > 0$	forward bias	depletion region becomes smaller	large current possible
$(u_{AK}) < 0$	reverse bias	depletion region becomes larger	only small leakage current, until breakdown

### Mnemonic

$\text{\[ \begin{align*} \text{Positive Anode, Negative Is Cathode} \end{align*} \]}$

This helps to remember the forward direction of a diode.

## Ideal diode model

The simplest model is the ideal diode.

$\text{\[ \begin{align*} \text{forward direction: } u_{AK}=0, \quad i_D > 0 \end{align*} \]}$

$\text{\[ \begin{align*} \text{reverse direction: } i_D = 0, \quad u_{AK} < 0 \end{align*} \]}$



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Fig. ##: Ideal diode characteristic.

## Engineering meaning

The ideal diode is useful for a first decision:

- Is the diode conducting?
- Is the diode blocking?
- Which path can current take?

It is too simple for accurate voltage and current calculations.

## Real diode characteristic

A real diode has an exponential current-voltage characteristic.

$\text{\[ \begin{align*} \boxed{ i_D = \color{red}{I_S(T)} \left( \color{blue}{e^{\frac{u_{AK}}{mU_T}}} - 1 \right) } \end{align*} \]}$

with

$$U_{\text{T}} = \frac{kT}{e}$$

<tabcaption tab\_diode\_equation\_symbols|Symbols in the diode equation>

Symbol	Meaning
$I_{\text{S}}(T)$	reverse saturation current, strongly temperature-dependent
$m$	emission coefficient, typically $(1 \dots 2)$
$U_{\text{T}}$	thermal voltage
$k$	Boltzmann constant
$e$	elementary charge
$T$	absolute temperature in $(\text{K})$

At room temperature,  $U_{\text{T}}$  is approximately

$$U_{\text{T}} \approx 26 \text{ mV}$$

Typical values at  $(25^\circ \text{C})$ :

<tabcaption tab\_typical\_diode\_values|Typical diode values>

Diode material	Approximate threshold voltage $(U_{\text{TO}})$	Reverse saturation current $(I_{\text{S}})$
silicon	$(\approx 0.7 \text{ V})$	some $(\text{pA})$
germanium	$(\approx 0.3 \text{ V})$	some $(\mu\text{A})$

The value  $(0.7 \text{ V})$  for a silicon diode is not a physical constant. It is a useful approximation for typical currents in small signal and basic power circuits.

### Practical diode models for circuit calculation

For hand calculations we usually do not use the full exponential equation.

Fig. ##: Comparison of ideal, constant-voltage, and piecewise-linear diode models.



<tabcaption tab\_diode\_models|Diode models for circuit calculations>

Model	Forward direction	Reverse direction	Use
ideal diode	$(u_{\text{AK}} = 0)$	$(i_{\text{D}} = 0)$	switching logic, first estimate

Model	Forward direction	Reverse direction	Use
constant-voltage model	$(u_{AK} \approx U_{TO})$	$(i_D \approx 0)$	quick current calculations
piecewise-linear model	$(u_{AK} \approx U_{TO} + r_F i_D)$	$(i_D \approx 0)$	more accurate operating point

The differential forward resistance is

$$r_F = \frac{\Delta U_F}{\Delta I_F}$$

For large forward voltages compared with  $(U_T)$ , the diode equation leads approximately to

$$r_D = \frac{du_D}{di_D} \approx \frac{mU_T}{I_D}$$

### Unit check

$$[r_D] = \frac{[U_T]}{[I_D]} = \frac{[V]}{[A]} = \Omega$$

## Operating point with a series resistor

A diode must usually be operated with a current-limiting element.

For the circuit

$$U_E \rightarrow R \rightarrow D$$

the loop equation is

$$U_E = U_R + U_D$$

With the constant-voltage model,

$$U_D \approx U_{TO}$$

Therefore

$$I_D \approx \frac{U_E - U_{TO}}{R}$$

Never connect a normal diode or LED directly to an ideal voltage source in forward direction. The diode current must be limited.

## Z-diodes and LEDs as diode types

A Z-diode is operated in reverse breakdown. In its operating range, the diode voltage is approximately constant:

$$u_{\text{Z}} \approx U_{\text{Z}}$$

The piecewise-linear model is

$$u_{\text{Z}} \approx U_{\text{Z}} + r_{\text{Z}} i_{\text{Z}}$$

### Z-diode preview

Z-diodes are useful for voltage limitation and voltage stabilization. The practical circuits are treated in [Block 12](#).

An LED is a diode that emits light in forward direction. The required forward voltage depends on the semiconductor material and therefore on the color.

<tabcaption tab\_led\_forward\_voltage|Typical LED forward voltages>

LED color	Typical $(U_{\text{TO}})$
infrared	$\approx 1.3 \text{ V}$
red	$\approx 1.6 \text{ V}$
yellow	$\approx 1.7 \text{ V}$
green	$\approx 1.8 \text{ V}$
blue	$\approx 3.2 \text{ V}$

LEDs usually tolerate only small reverse voltages. Do not operate an LED in reverse direction unless the datasheet explicitly allows it.

## Exercises

### Exercise E1.1 Quick check: doping and charge carriers

Complete the table.

Doping type	Typical dopant atom	Main mobile charge carrier	Dopant name
n-type	?	?	?
p-type	?	?	?

Result

Doping type	Typical dopant atom	Main mobile charge carrier	Dopant name

Doping type	Typical dopant atom	Main mobile charge carrier	Dopant name
n-type	phosphorus, arsenic, or antimony	electrons	donor
p-type	boron, aluminium, or indium	holes	acceptor

N-type material has additional mobile electrons. P-type material has additional mobile holes.

The semiconductor as a whole remains approximately electrically neutral.

### Exercise E2.1 Quick check: diode polarity

A diode has the anode voltage

$$U_{\text{A}} = 4.8 \text{ V}$$

and the cathode voltage

$$U_{\text{K}} = 4.1 \text{ V}.$$

- Calculate  $u_{\text{AK}}$ .
- Is the diode forward-biased or reverse-biased?
- For a silicon diode, is a noticeable current likely?

Result

$$u_{\text{AK}} = U_{\text{A}} - U_{\text{K}} = 4.8 \text{ V} - 4.1 \text{ V} = 0.7 \text{ V}.$$

Since

$$u_{\text{AK}} > 0,$$

the diode is forward-biased.

For a silicon diode,  $(0.7 \text{ V})$  is a typical forward voltage in the mA range. Therefore a noticeable current is likely.

**Exercise E3.1 Quick check: current with the constant-voltage model**

A silicon diode is connected in series with a resistor.

$$U_{\text{E}} = 5.0 \text{ V}, \quad R = 1.0 \text{ k}\Omega.$$

Use the constant-voltage model

$$U_{\text{D}} \approx 0.7 \text{ V}.$$

Calculate the diode current  $I_{\text{D}}$ .

Result

The voltage across the resistor is

$$U_{\text{R}} = U_{\text{E}} - U_{\text{D}} = 5.0 \text{ V} - 0.7 \text{ V} = 4.3 \text{ V}.$$

Therefore

$$I_{\text{D}} = \frac{U_{\text{R}}}{R} = \frac{4.3 \text{ V}}{1.0 \text{ k}\Omega} = 4.3 \text{ mA}.$$

**Exercise E4.1 Quick check: differential diode resistance**

A diode operates at

$$I_{\text{D}} = 10 \text{ mA}.$$

Assume

$$m = 1, \quad U_{\text{T}} = 26 \text{ mV}.$$

Estimate the differential diode resistance

$$r_{\text{D}} \approx \frac{m U_{\text{T}}}{I_{\text{D}}}.$$

Result

$$r_{\text{D}} \approx \frac{mU_{\text{T}}}{I_{\text{D}}} \approx \frac{1 \cdot 26 \text{ mV}}{10 \text{ mA}} \approx 2.6 \Omega.$$

This is a small-signal resistance around the operating point. It is not the same as the large-signal ratio  $(\frac{U_{\text{D}}}{I_{\text{D}}})$ .

### Exercise E5.1 Longer exercise: operating point with a piecewise-linear diode

A diode is connected in series with a resistor.

$$U_{\text{E}} = 12 \text{ V}, \quad R = 560 \Omega.$$

For the diode, use the piecewise-linear forward model

$$U_{\text{D}} = U_{\text{TO}} + r_{\text{F}} I_{\text{D}}$$

with

$$U_{\text{TO}} = 0.65 \text{ V}, \quad r_{\text{F}} = 5.0 \Omega.$$

- Draw the loop equation.
- Calculate  $(I_{\text{D}})$ .
- Calculate  $(U_{\text{D}})$ .
- Calculate the diode power  $(P_{\text{D}})$ .
- Compare briefly with the constant-voltage model  $(U_{\text{D}} = 0.65 \text{ V})$ .

Result

The loop equation is

$$U_{\text{E}} = R I_{\text{D}} + U_{\text{D}}.$$

Insert the piecewise-linear diode model:

$$U_{\text{E}} = R I_{\text{D}} + U_{\text{TO}} + r_{\text{F}} I_{\text{D}}.$$

Thus

$$I_{\text{D}} = \frac{U_{\text{E}} - U_{\text{TO}}}{R + r_{\text{F}}}.$$

Insert the values:

$$I_{\text{D}} = \frac{12\text{ V} - 0.65\text{ V}}{560\ \Omega + 5.0\ \Omega} = \frac{11.35\text{ V}}{565\ \Omega} = 20.1\text{ mA}$$

The diode voltage is

$$U_{\text{D}} = U_{\text{TO}} + r_{\text{F}} I_{\text{D}} = 0.65\text{ V} + 5.0\ \Omega \cdot 20.1\text{ mA} = 0.65\text{ V} + 0.101\text{ V} = 0.751\text{ V}$$

The diode power is

$$P_{\text{D}} = U_{\text{D}} I_{\text{D}} = 0.751\text{ V} \cdot 20.1\text{ mA} = 15.1\text{ mW}$$

With the constant-voltage model,

$$I_{\text{D}} = \frac{12\text{ V} - 0.65\text{ V}}{560\ \Omega} = 20.3\text{ mA}$$

The difference is small here because  $(r_{\text{F}} \ll R)$ .

## Common pitfalls

- **Thinking a diode is just a resistor:** A diode is nonlinear. The ratio  $(U/I)$  is not constant.
- **Forgetting current limitation:** A forward-biased diode needs a current-limiting component.
- **Treating  $(0.7\text{ V})$  as exact:** The forward voltage depends on current, temperature, and semiconductor material.
- **Mixing anode and cathode:** Current flows easily from anode to cathode when the diode is forward-biased.
- **Ignoring reverse limits:** Real diodes have maximum reverse voltage. LEDs often tolerate only small reverse voltages.
- **Confusing hole movement with electron movement:** Holes are missing electrons, but they behave like positive mobile charge carriers.
- **Using the exponential diode equation without unit care:**  $(U_{\text{T}})$  must be in volts and  $(T)$  in kelvin.

## Embedded resources

### PhET: Semiconductors

Use this simulation to explore doping and the formation of a diode.

### Falstad: Diode I/V curve

Use this simulation to compare a resistor characteristic with the nonlinear diode characteristic.

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