Electronics for Physicists

Analog Electronics

Chapter 2; Lecture 05

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14.11.2023

Karlsruhe Institute of Technology

KIT, Winter 2023/24

Institute for Data Processing and Electronics

Chapter 2

Circuits with R, C, L

- AC behavior of R, C, L
- Complex Voltages & Currents
- Filters
- Oscillators

Overview

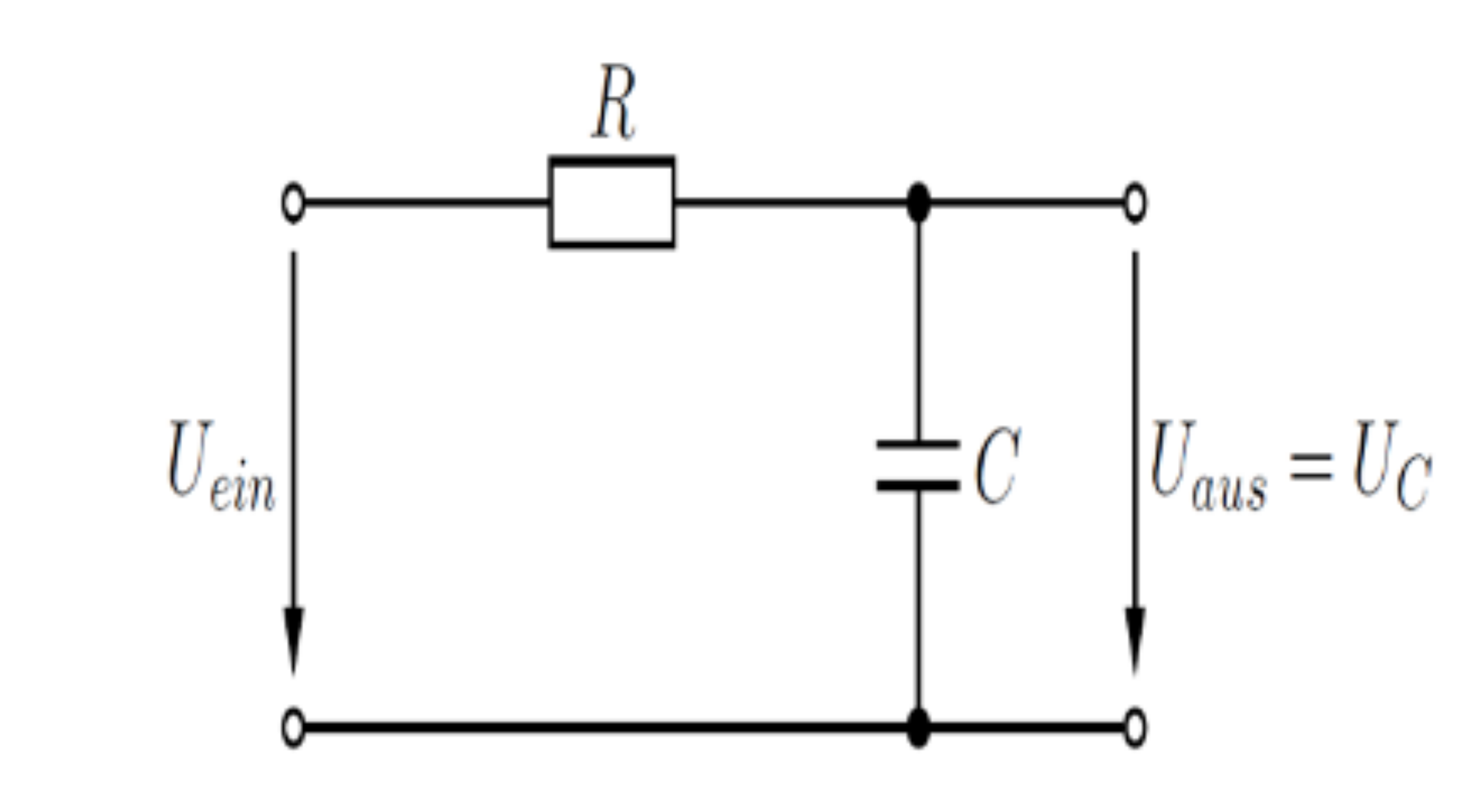
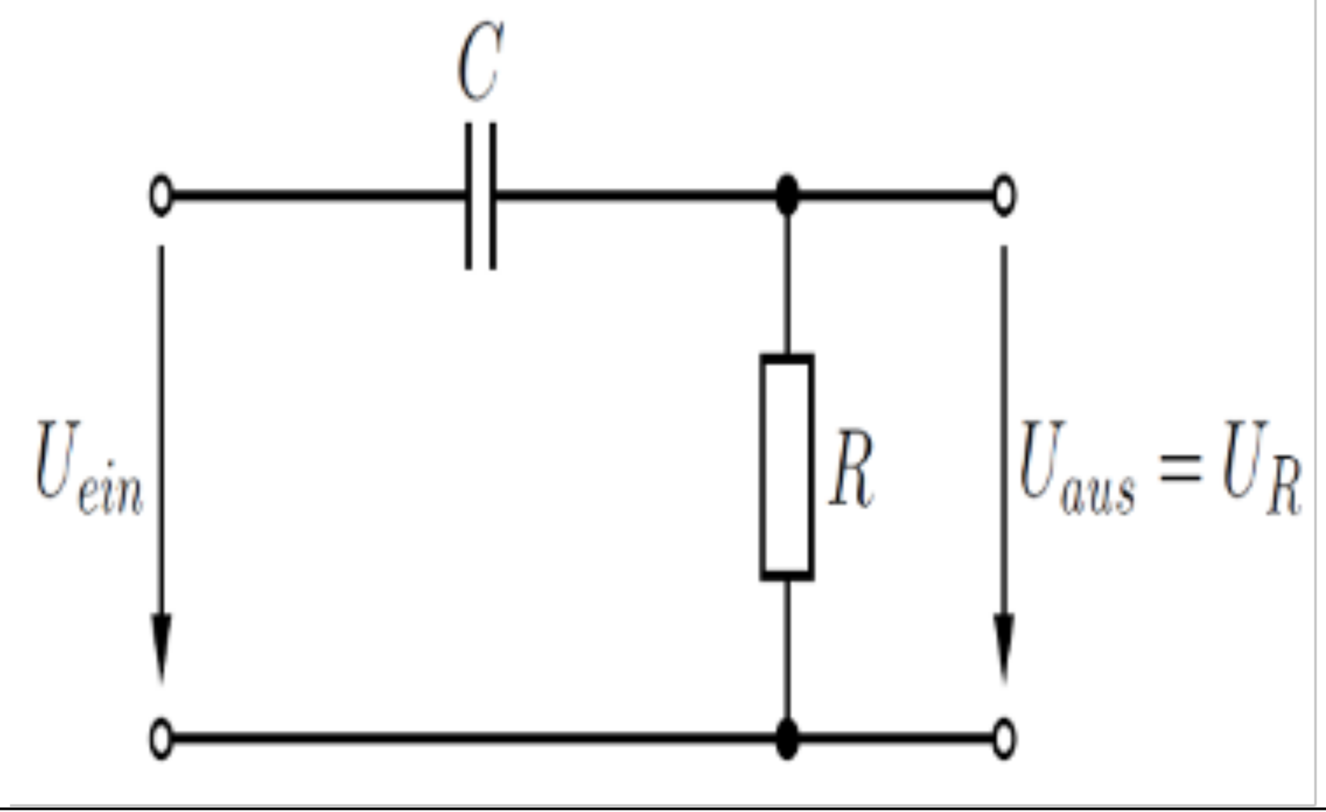
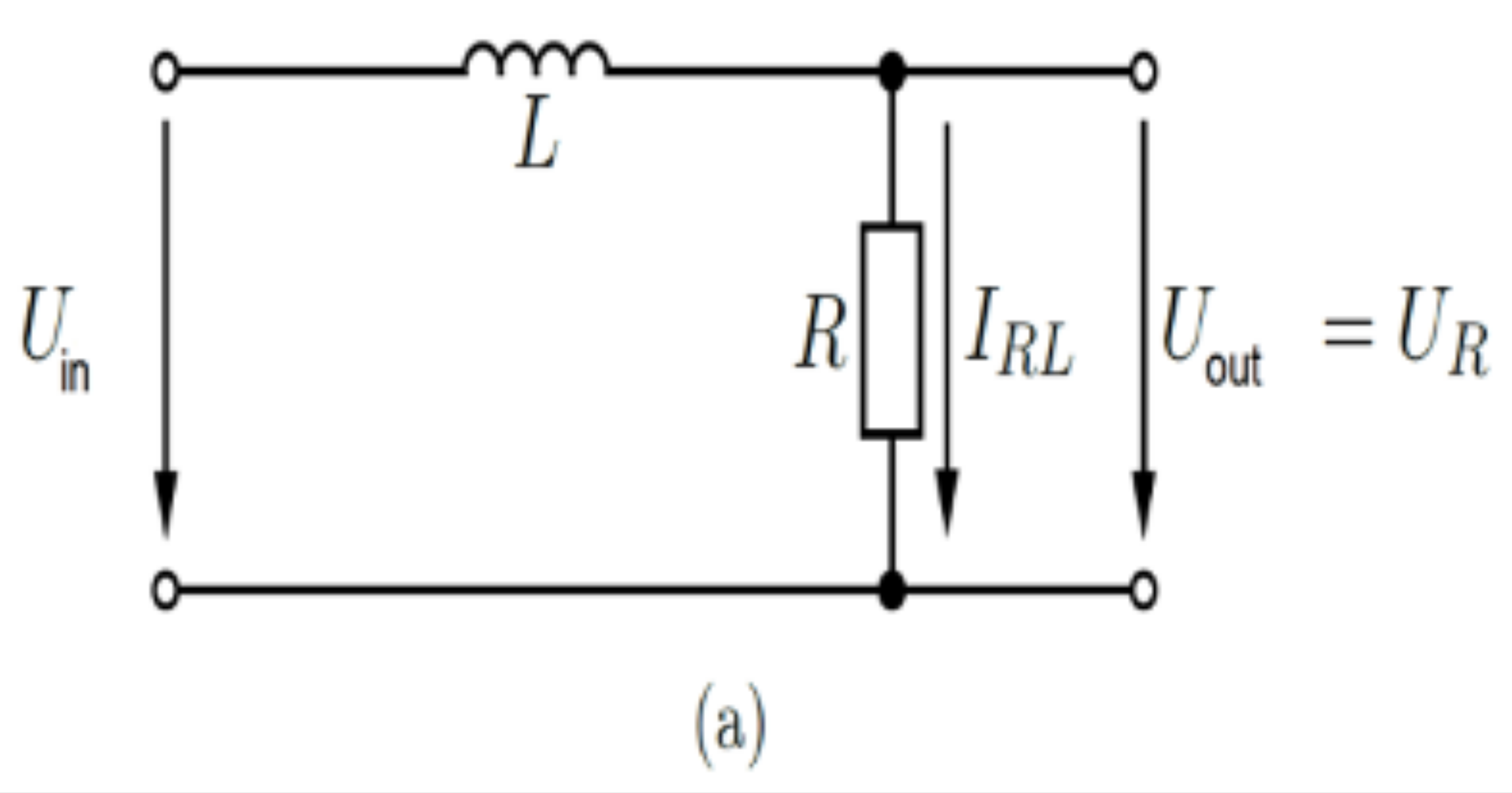
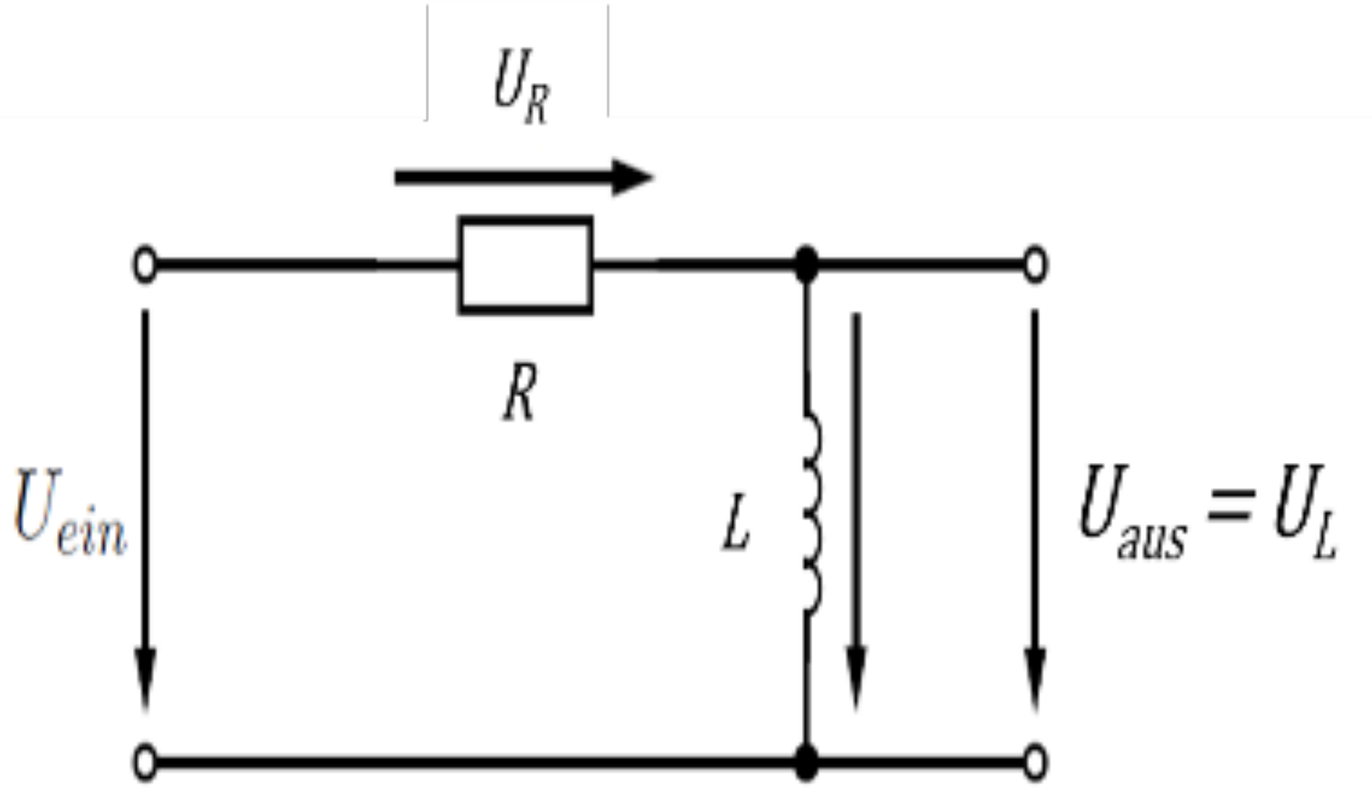
Chapter 2

Filters

In: Circuits with R, C, L

High- and Low Pass Filters

Reminder / Summary

Type	low pass	high pass
RC		
RL		

Low Pass

Tiefpass

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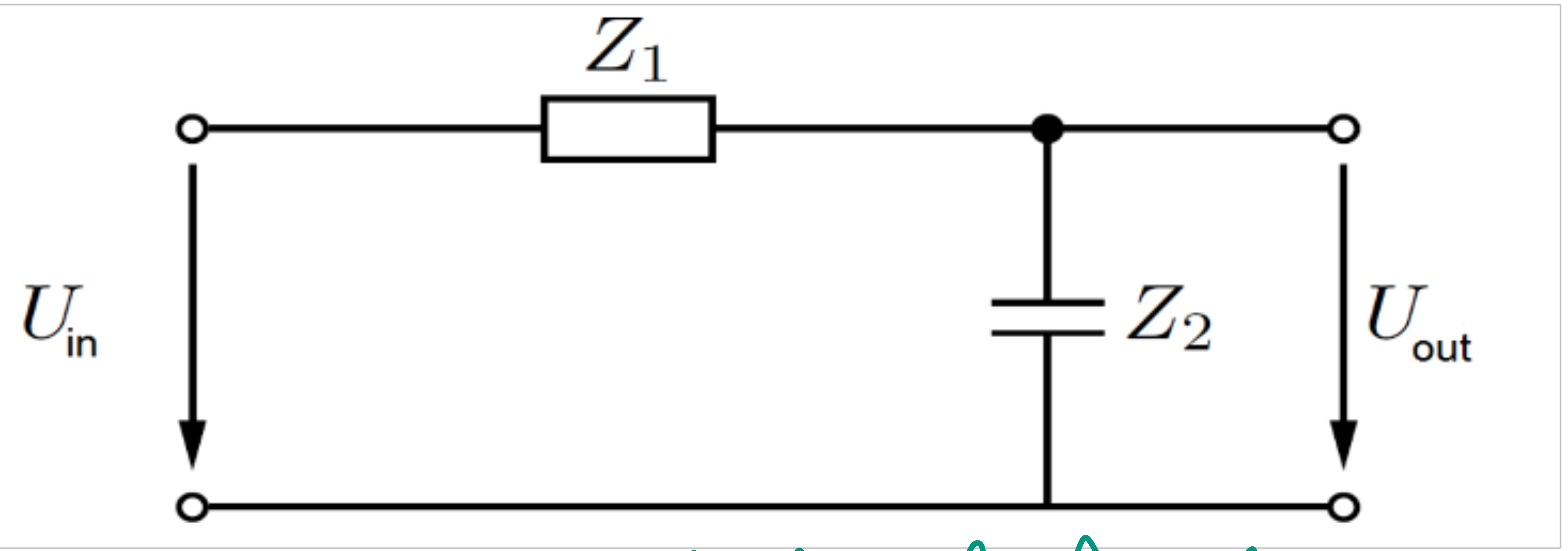


Integrator / low pass filter

$$\underline{U}_{out} = \underline{U}_{in} \frac{\underline{Z}_2}{\underline{Z}_1 + \underline{Z}_2}$$ (voltage divider!)

complex transfer function

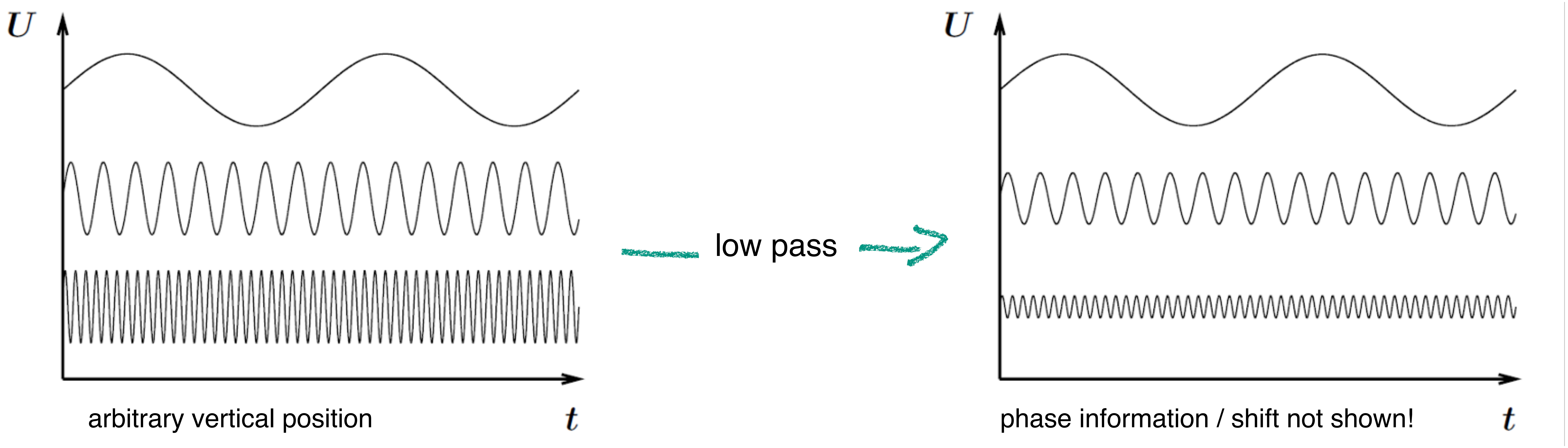
$$\frac{\underline{U}_{out}}{\underline{U}_{in}} = \underline{Z} = \frac{\underline{Z}_2}{\underline{Z}_1 + \underline{Z}_2} = \frac{\frac{1}{j\omega C}}{\frac{1}{j\omega C} + R} = \frac{1}{1 + j\omega RC} = \frac{1 - j\omega RC}{1 + (\omega RC)^2}$$

with $\underline{Z} = Z e^{j\varphi}$: $Z = \frac{1}{\sqrt{1 + (\omega RC)^2}}$ and $\tan\varphi = \frac{\mathrm{Im}(\underline{Z})}{\mathrm{Re}(\underline{Z})} = -\omega RC$

$Z \approx 1$ for $\omega \approx 0$ and $Z \approx 0$ for $\omega >> 1/(RC)$

Low Pass

Impact on Signals

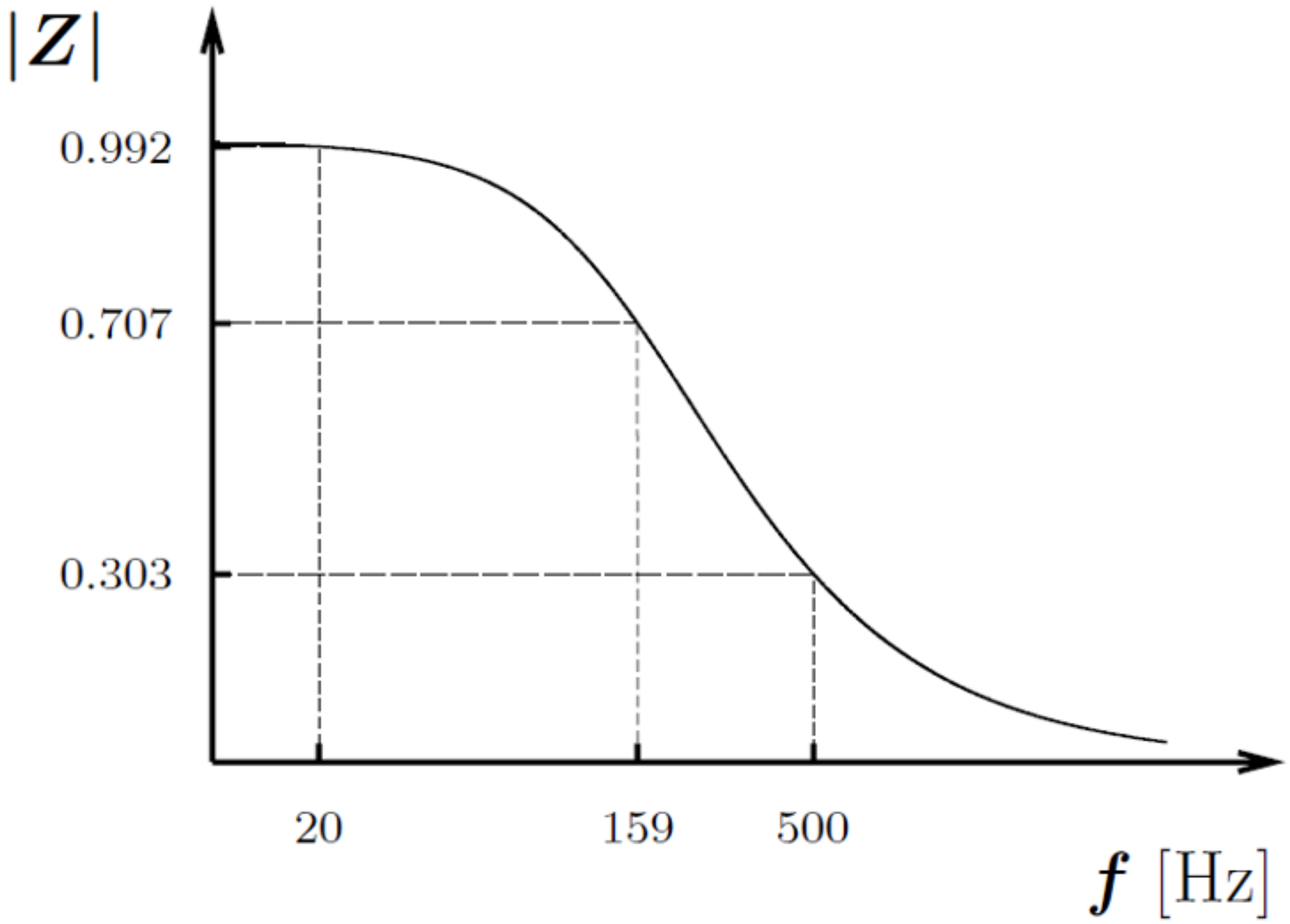


- Low frequency signals pass unchanged
- High frequency signals are damped
- For high frequencies the output signal is delayed in time with respect to the input signal

Low Pass

Frequence Dependence

- Amplitude of output signal depends on frequency.
- Phase depends on frequency.
- The frequency of input and output signal is identical.



$$Z = \frac{1}{\sqrt{1 + (\omega RC)^2}}$$

Brief Excursion: Decibel

Characterizing Filter Properties

Definitions: $10\ log \frac{P_{in}}{P_{out}}$ for power $20\ log \frac{U_{in}}{U_{out}}$ or $20\ log \frac{I_{in}}{I_{out}}$ for current / voltage

dB	voltage ratio $20 \log \frac{U_{aus}}{U_{ein}}$	power ratio $10 \log \frac{P_{aus}}{P_{ein}}$
100	10^5	10^{10}
40	100	10^4
20	10	100
6,02	2	4
3,01	$\sqrt{2}$	2
0	1	1
− 3,01	$\frac{1}{\sqrt{2}}$	$\frac{1}{2}$
− 6,02	$\frac{1}{2}$	$\frac{1}{4}$
− 20	0,1	10^{-2}
− 40	0,01	10^{-4}
− 100	10^{-5}	10^{-10}

NB: log = base 10 logarithm

Reminder:

log(ab) = log(a) + log(b):

dB values can be added!

Additional terms:

dBm: dB relative to 1 mW: $10\ log \frac{P[\mathrm{W}]}{1\ \mathrm{mW}}$

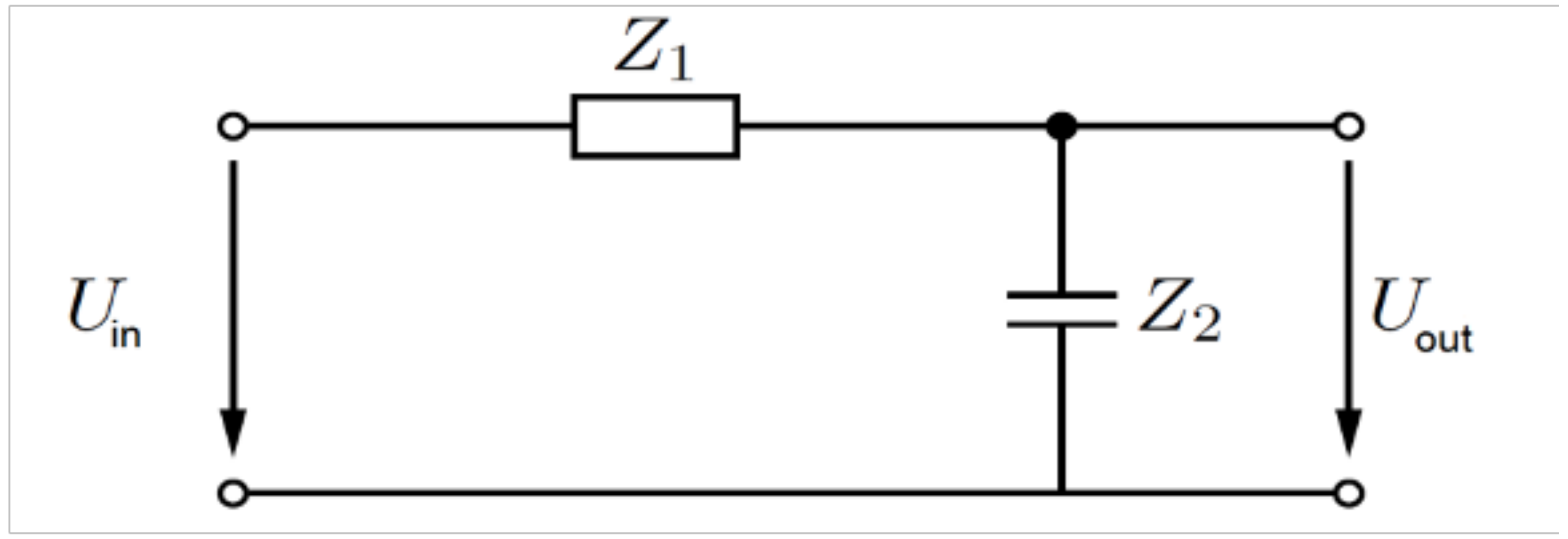
dBmA: dB relative to 1 mA: $20\ log \frac{I[\mathrm{A}]}{1\ \mathrm{mA}}$

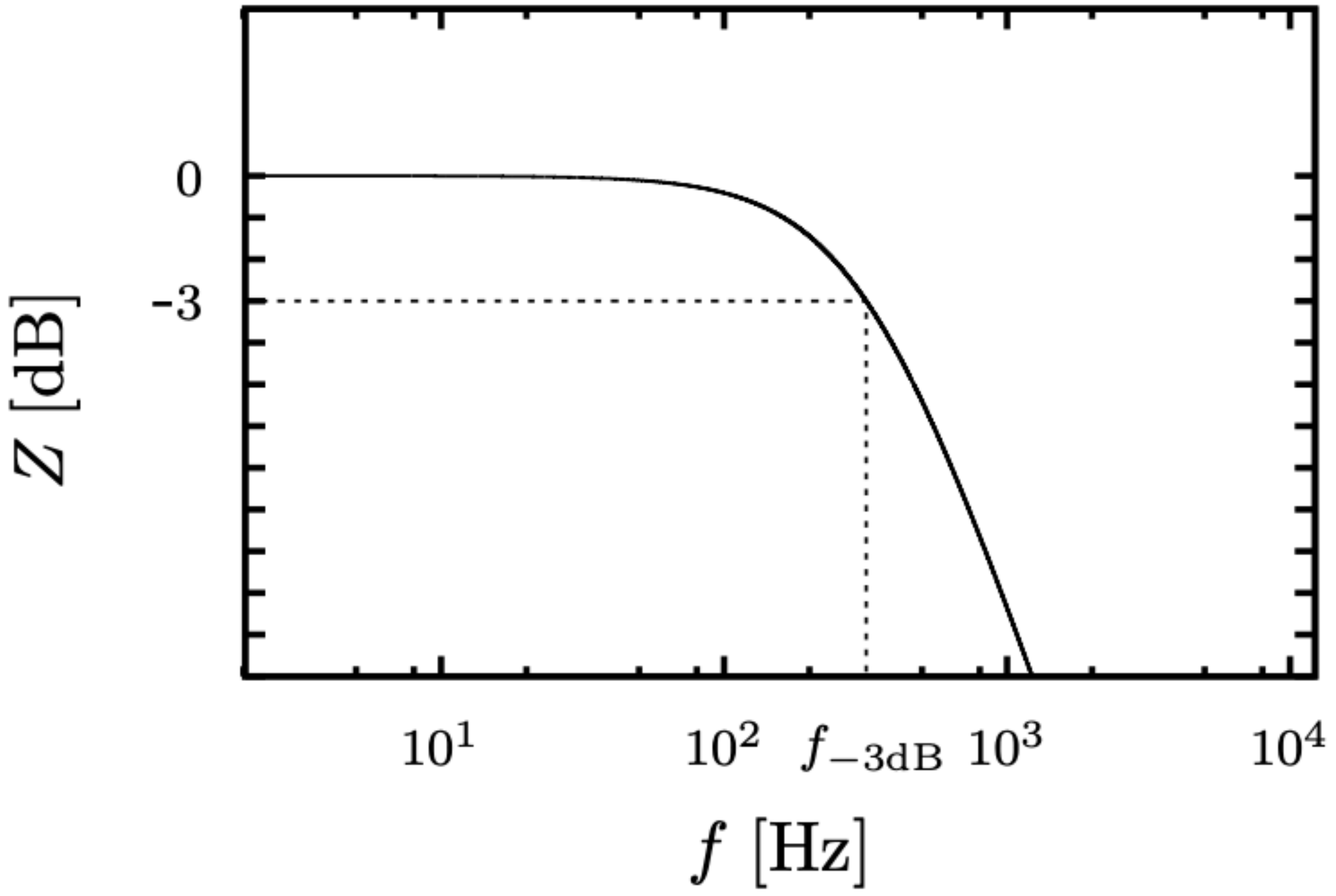
Bode Plot: Introduction, Low Pass

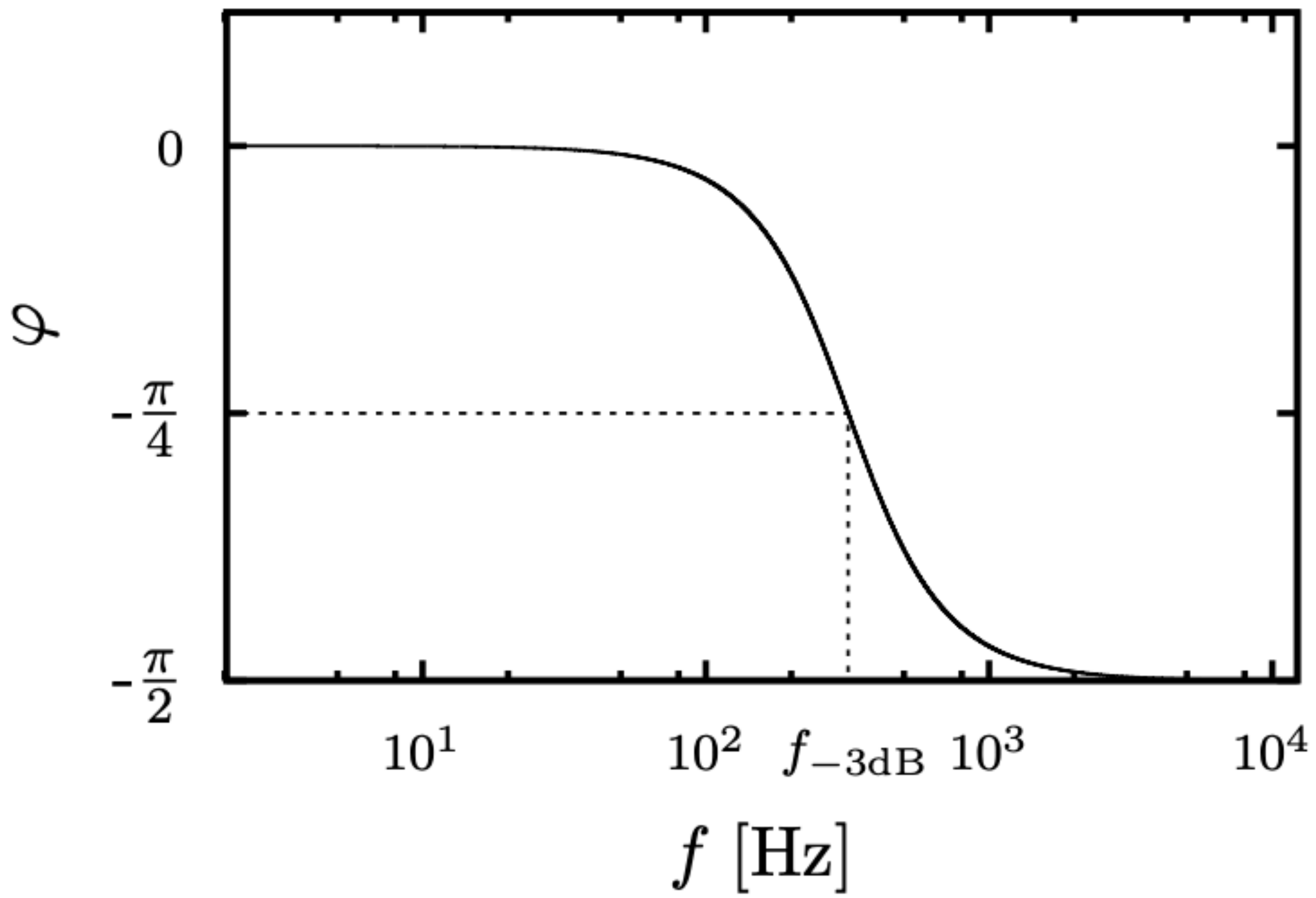
Bodediagramm

- A commonly used representation of the transfer function (*komplexe Übertragungsfunktion*) $Z\,e^{j\varphi}$
- Two plots:
  - Amplitude of transfer function ***Z*** in dB vs log(f)
  - Phase **ϕ** vs log(f)

$$f = \frac{\omega}{2\pi}$$







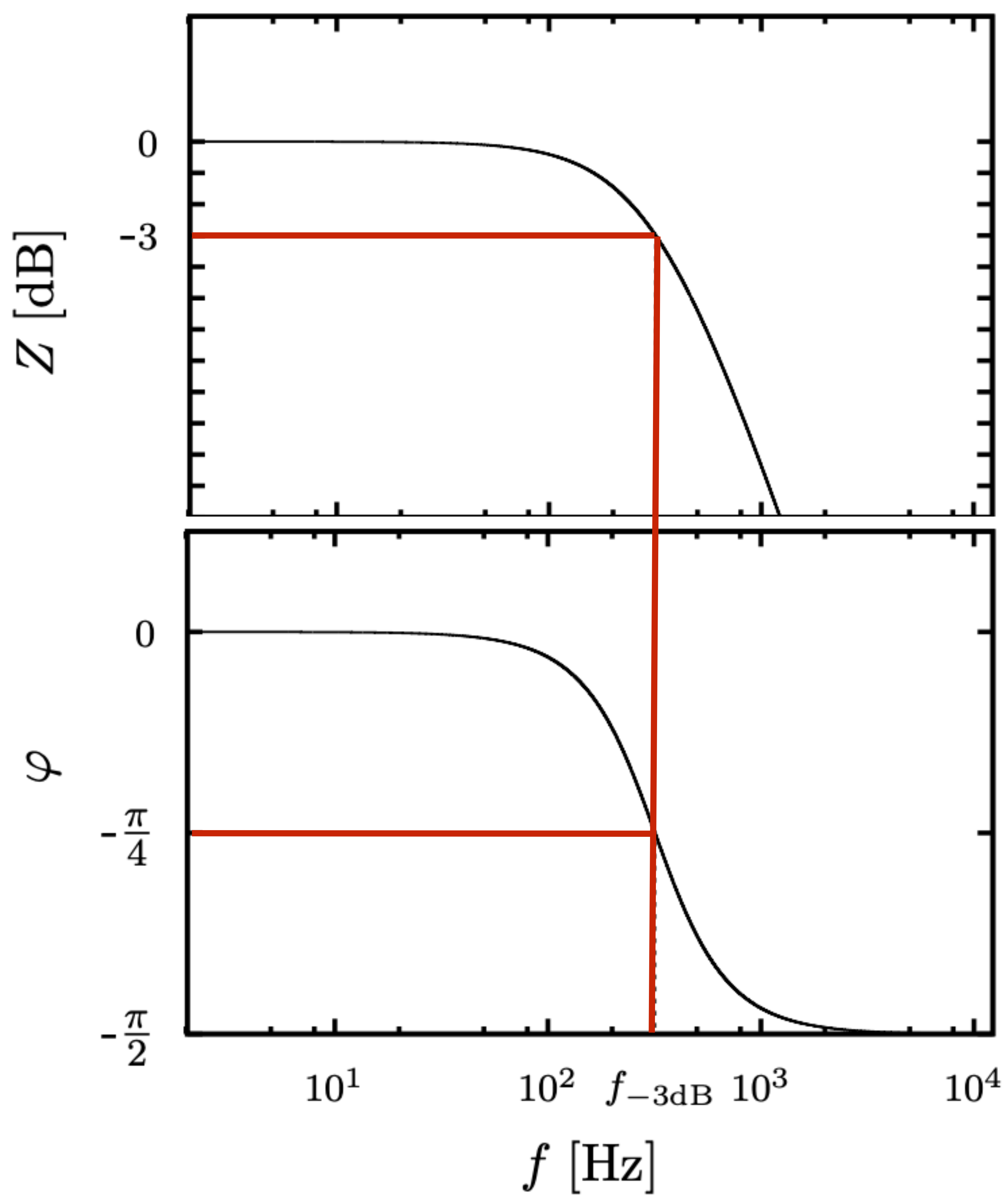
$$Z = \frac{1}{\sqrt{1 + (\omega RC)^2}}$$

$$\tan\varphi = -\,\omega RC$$

here:
R = 10 kΩ
C = 100 nF

Bode Plot: Low Pass

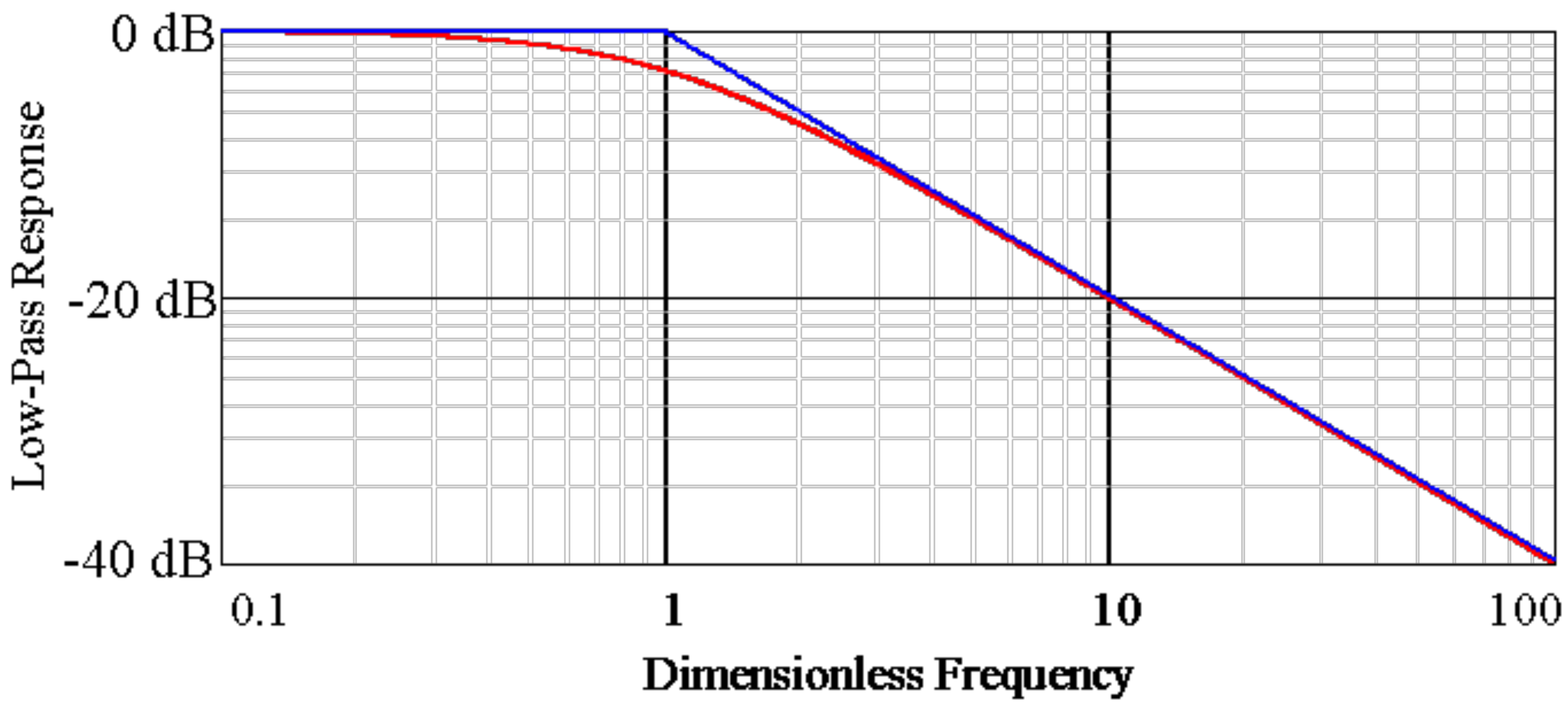
Closer Look



Cutoff frequency: Z has dropped by 1/√2 (-3 dB)

$$f_{-3\,\text{dB}} = \frac{1}{2\pi RC} \qquad \omega_{-3\,\text{dB}} = \frac{1}{RC}$$

Since $\tan\varphi = -\omega RC$: for critical frequency: -1; -> ϕ = - π/4



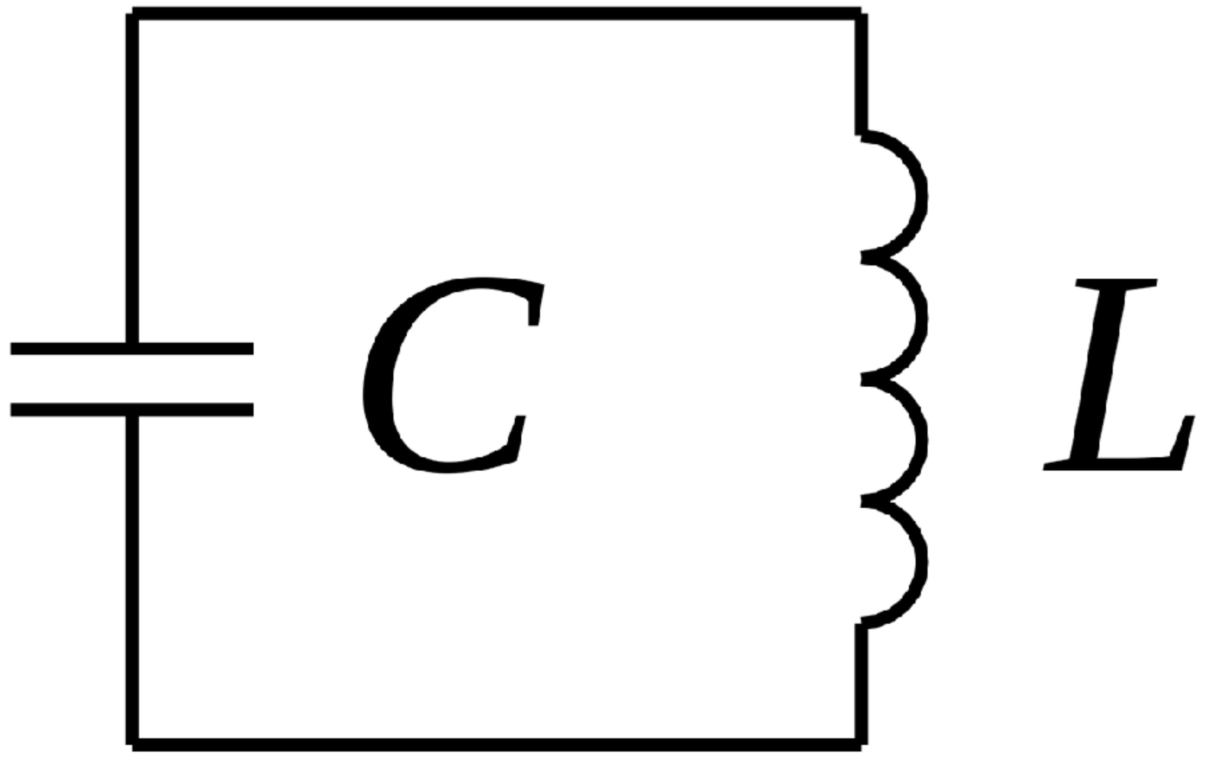
At high frequencies Z drops by 20 dB per frequency decade.

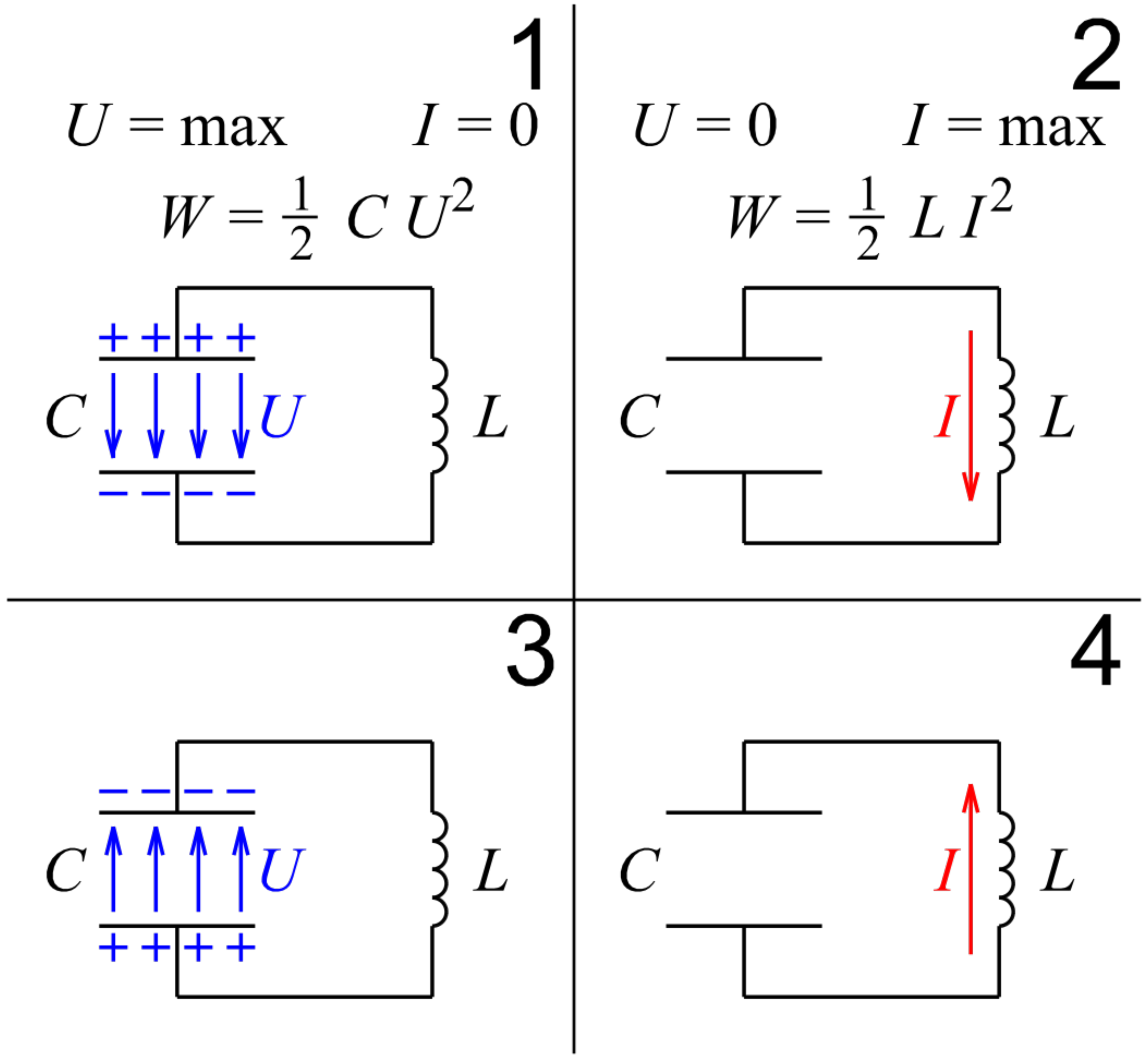
Corresponds to 6 dB / Octave (frequency doubling / halving)

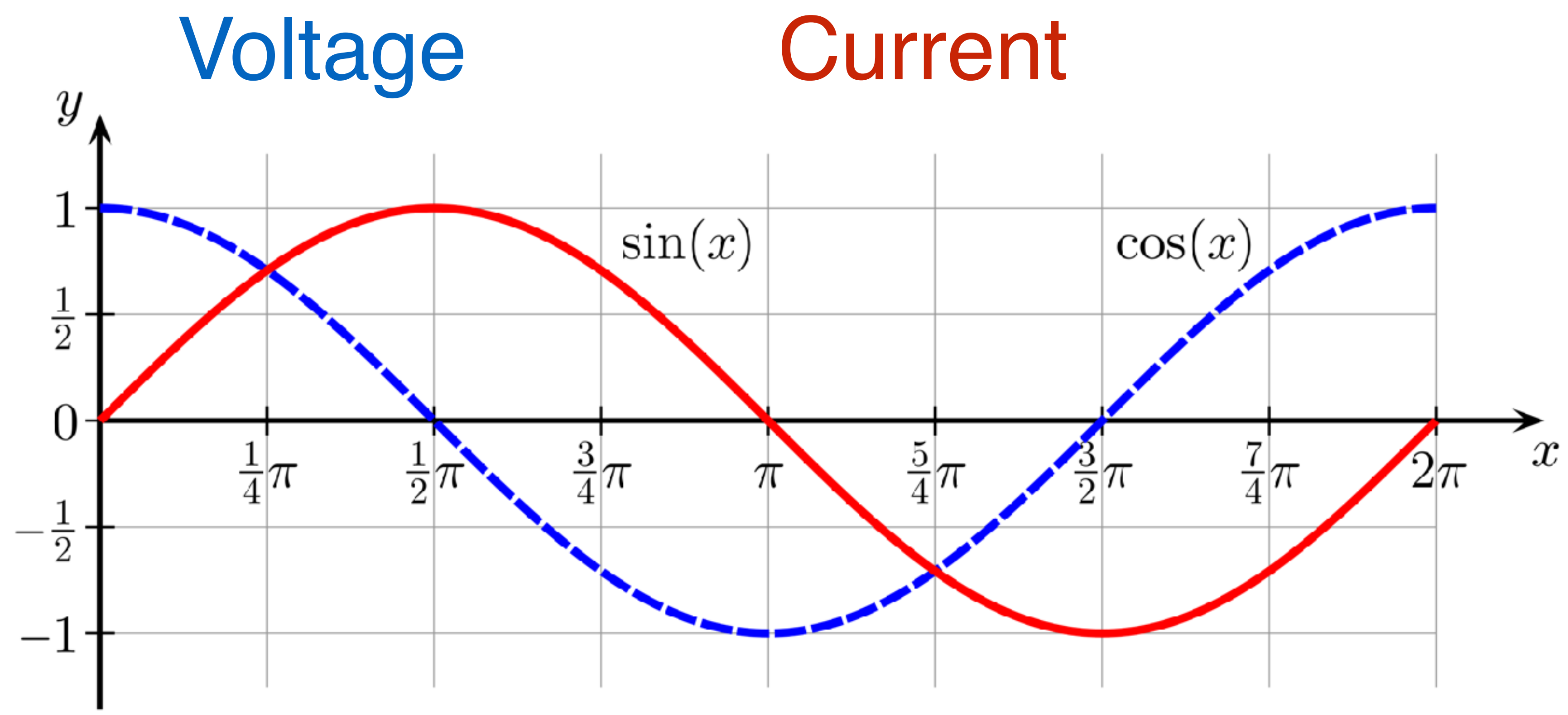
Chapter 2

Oscillators

In: Circuits with R, C, L







Resonance:
Z is maximal, the imaginary part of $\underline{Z}$ is 0 (Phase ϕ = 0)

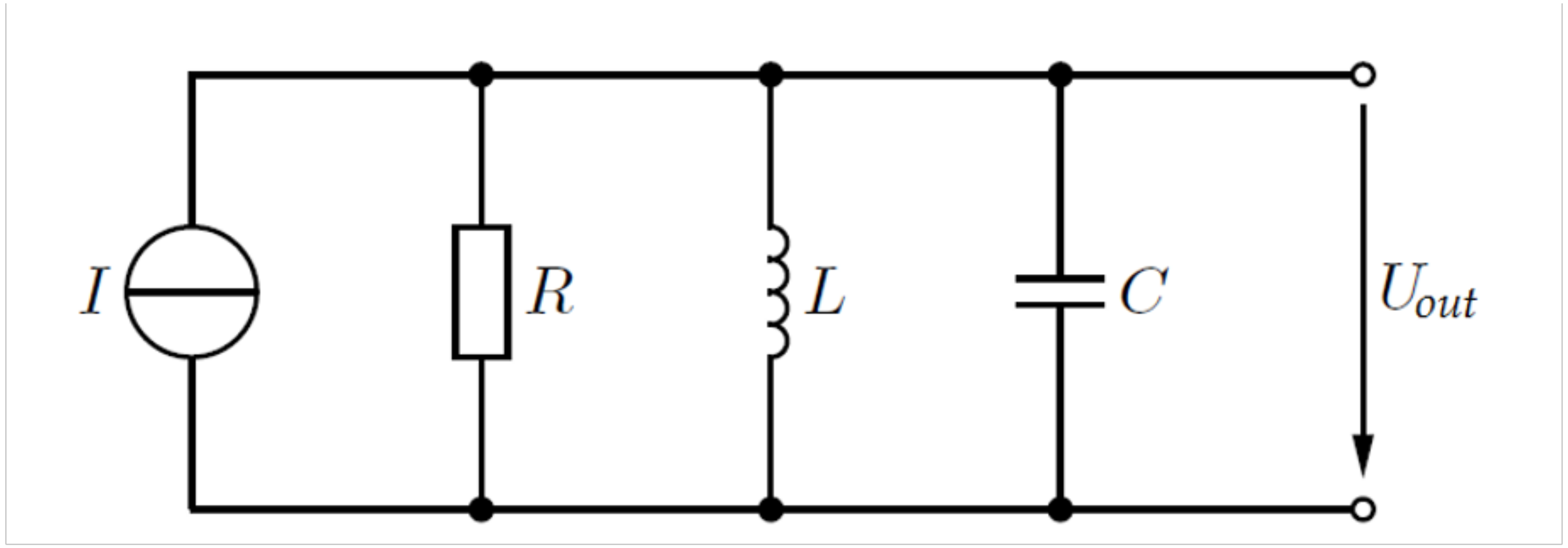
$$\underline{Z} = \frac{1}{\frac{1}{Z_C} + \frac{1}{Z_L}} = \frac{1}{j\omega C - j\frac{1}{\omega L}}$$

$$= \frac{-j\left(\omega C - \frac{1}{\omega L}\right)}{\left(\omega C - \frac{1}{\omega L}\right)^2}$$

$\underline{Z}$ is real for $\omega C = \frac{1}{\omega L}$ => $\omega_0 = \frac{1}{\sqrt{LC}}$ resonance frequency

RLC Oscillator: Extension with Resistor

Schwingkreis



- Parallel oscillator with R:
  - "Driven" by current from current source

$$\underline{Z} = \frac{1}{\frac{1}{\underline{Z}_R} + \frac{1}{\underline{Z}_C} + \frac{1}{\underline{Z}_L}} = \frac{1}{\frac{1}{R} + \mathrm{j}\,\omega\, C - \mathrm{j}\,\frac{1}{\omega\, L}} = \frac{\frac{1}{R} - \mathrm{j}\left(\omega\, C - \frac{1}{\omega\, L}\right)}{\frac{1}{R^2} + \left(\omega\, C - \frac{1}{\omega\, L}\right)^2}$$

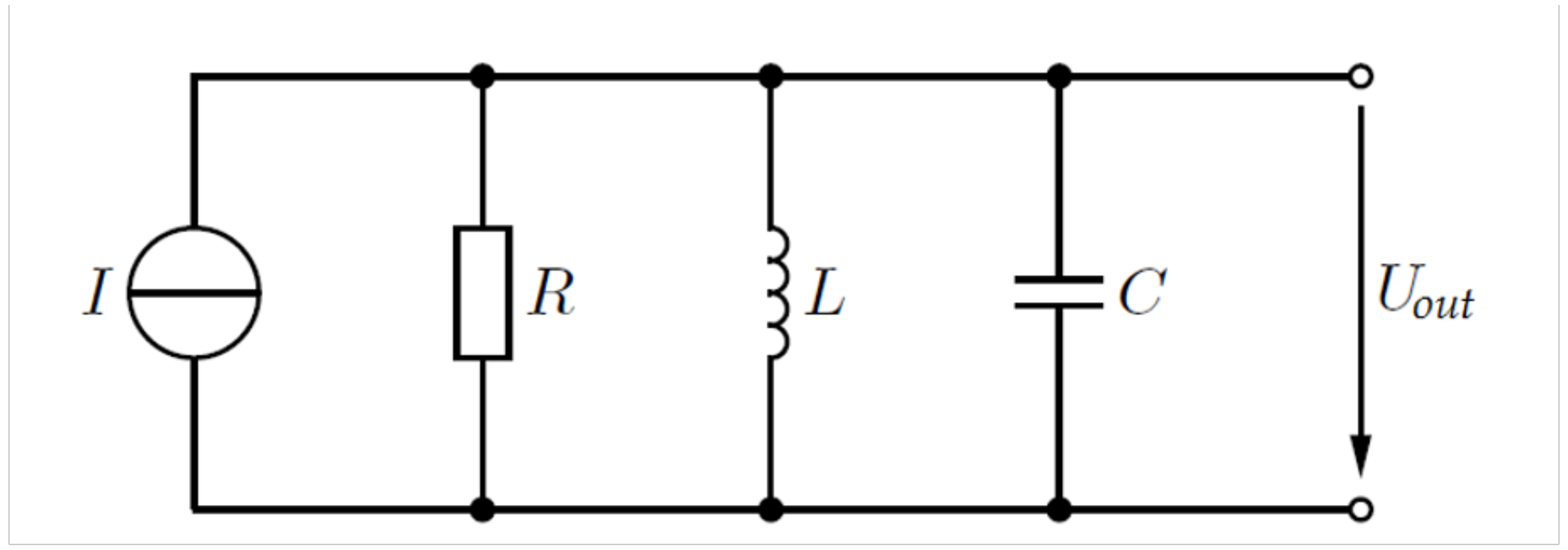
$$Z = \frac{1}{\sqrt{\frac{1}{R^2} + \left(\omega\, C - \frac{1}{\omega\, L}\right)^2}}$$

$$\tan\varphi = \left(\frac{1}{\omega\, L} - \omega\, C\right) R$$

=> Resonance frequency identical to idealized pure LC circuit!

RLC Oscillator

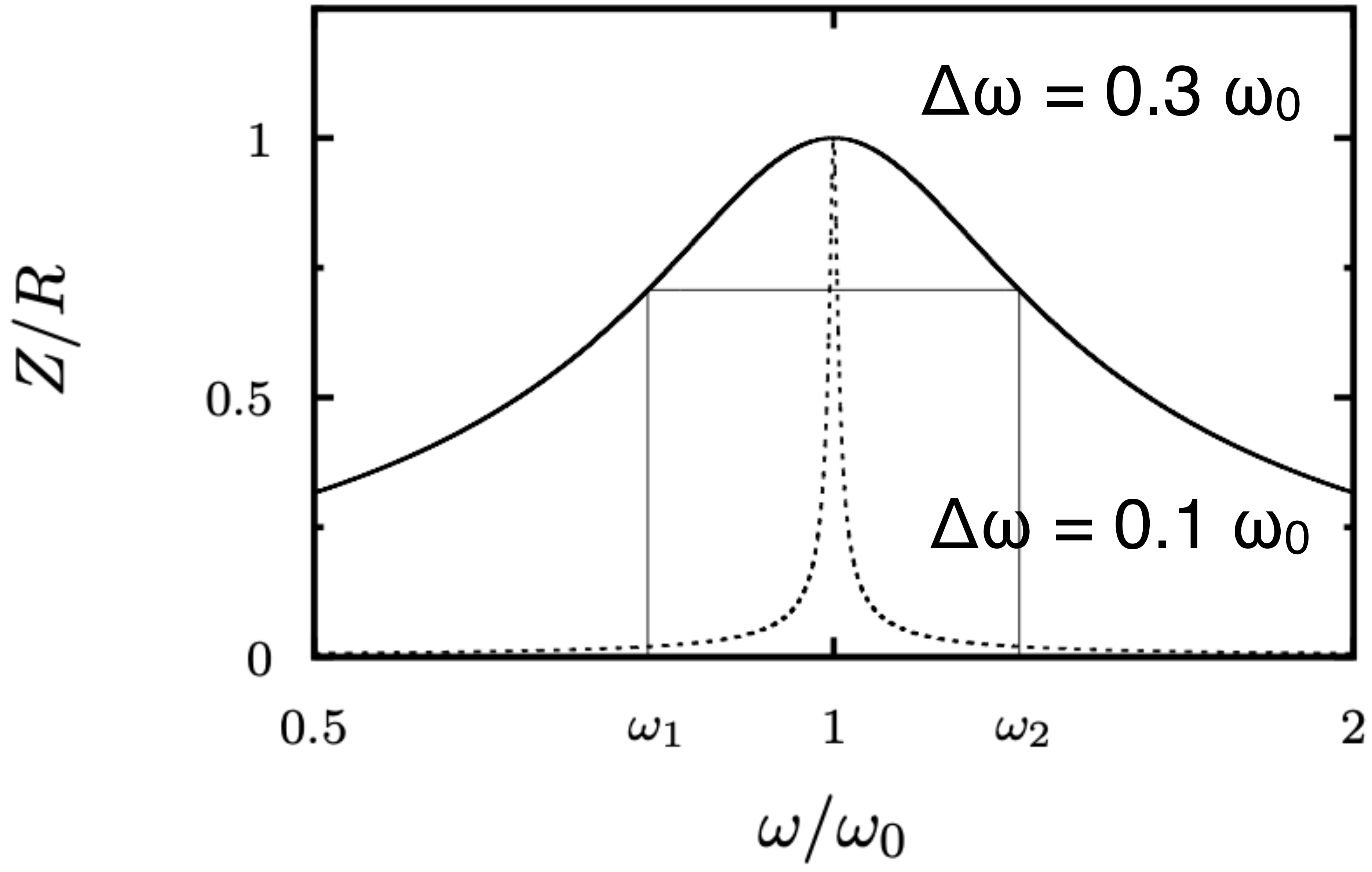
Behavior

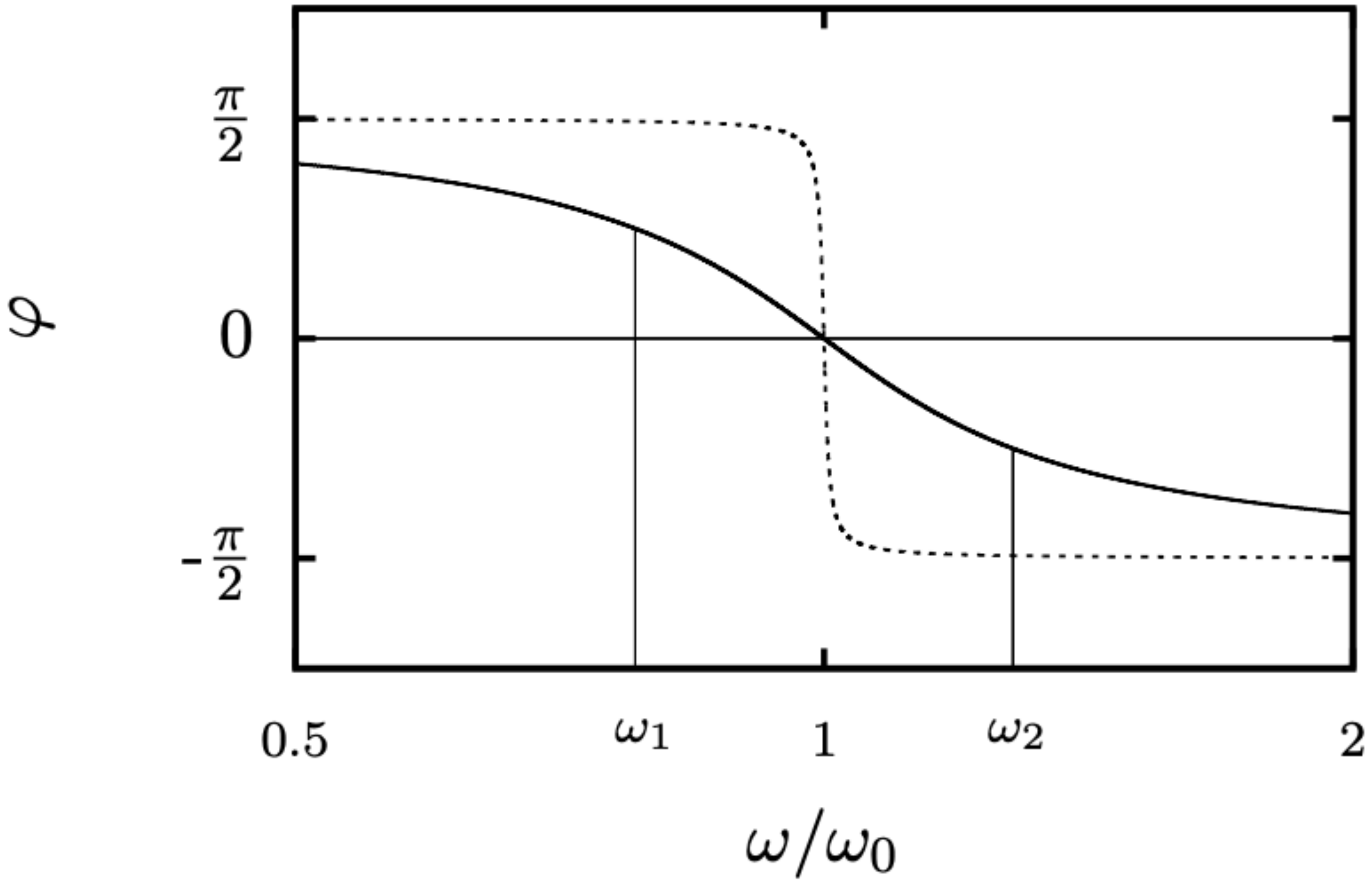


$$\omega_0 = \frac{1}{\sqrt{LC}}$$

Basic considerations:

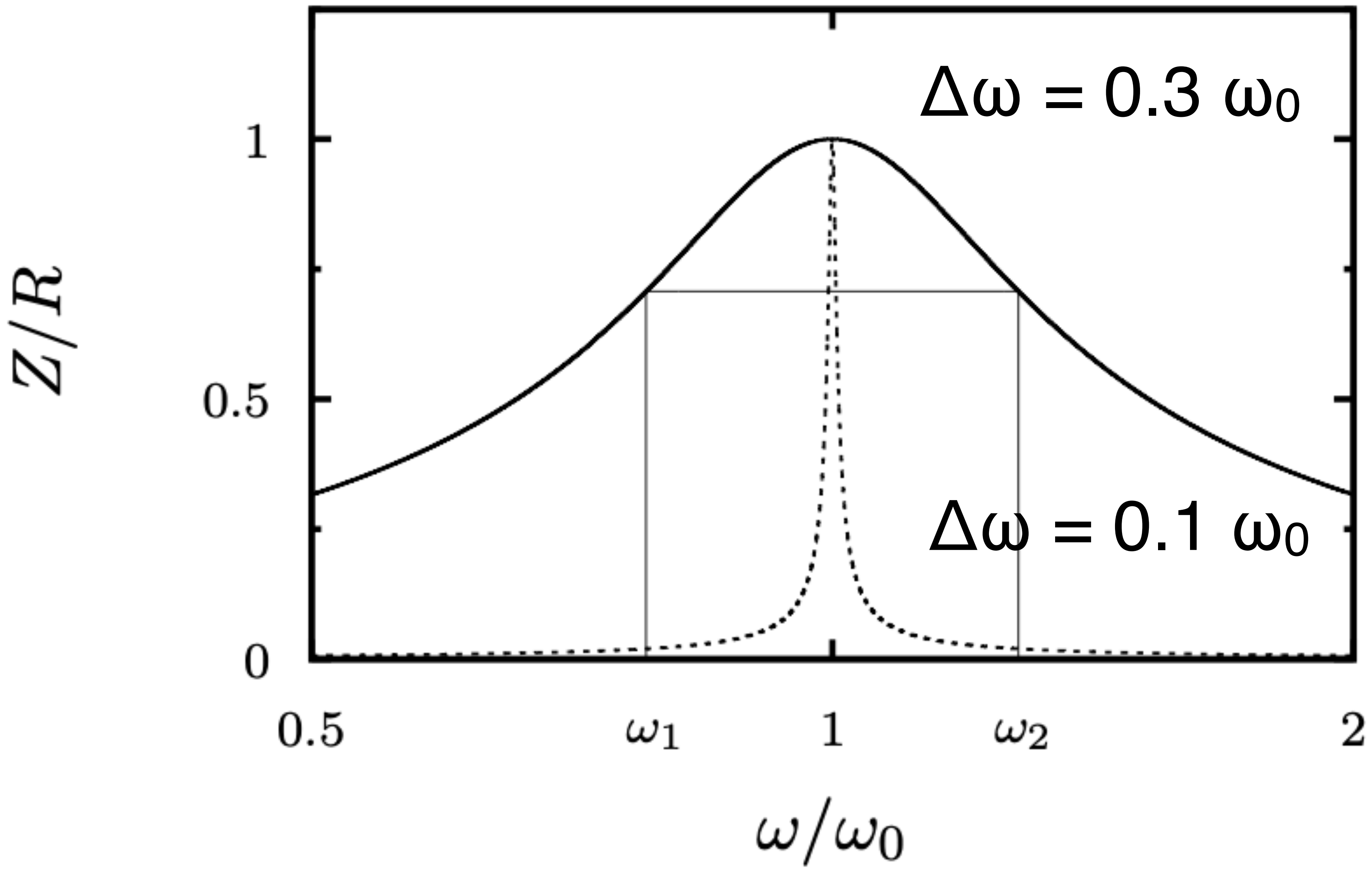
- small output signal for very small and very large ω
- for small ω: Inductor shorts the circuit;
  for large ω: Capacitor shorts the circuit





Precise behavior as a function of ω depends on R!

- Crucial quantity: The bandwidth (*Bandbreite*)



bandwidth: $\Delta\omega = \omega_2 - \omega_1$; ω_1, ω_2: amplitude $1/\sqrt{2}$ below maximum

(corresponds to a phase $\phi_{1,2} = \pm 45°$)

$$Z = \frac{1}{\sqrt{\frac{1}{R^2} + \left(\omega C - \frac{1}{\omega L}\right)^2}}$$

Z maximal for ω_0: Z = R

Results in: $Z_{1,2}$ for $\left(\omega C - \frac{1}{\omega L}\right)^2 = \frac{1}{R^2}$

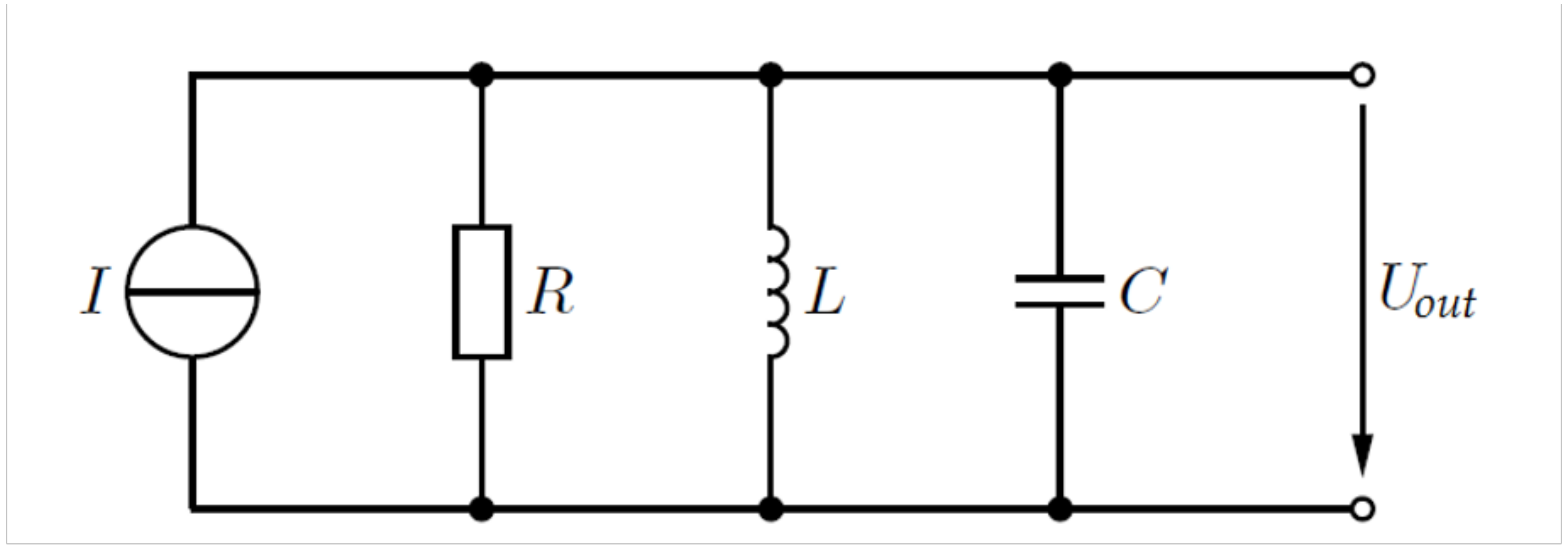
$$\pm\left(\omega^2 - \frac{1}{LC}\right)^2 - \frac{\omega}{RC} = 0$$

positive solutions: $\omega_1 = -\frac{1}{2RC} + \sqrt{\frac{1}{(2LC)^2} + \frac{1}{LC}}$ $\quad \omega_1 = \frac{1}{2RC} + \sqrt{\frac{1}{(2LC)^2} + \frac{1}{LC}}$

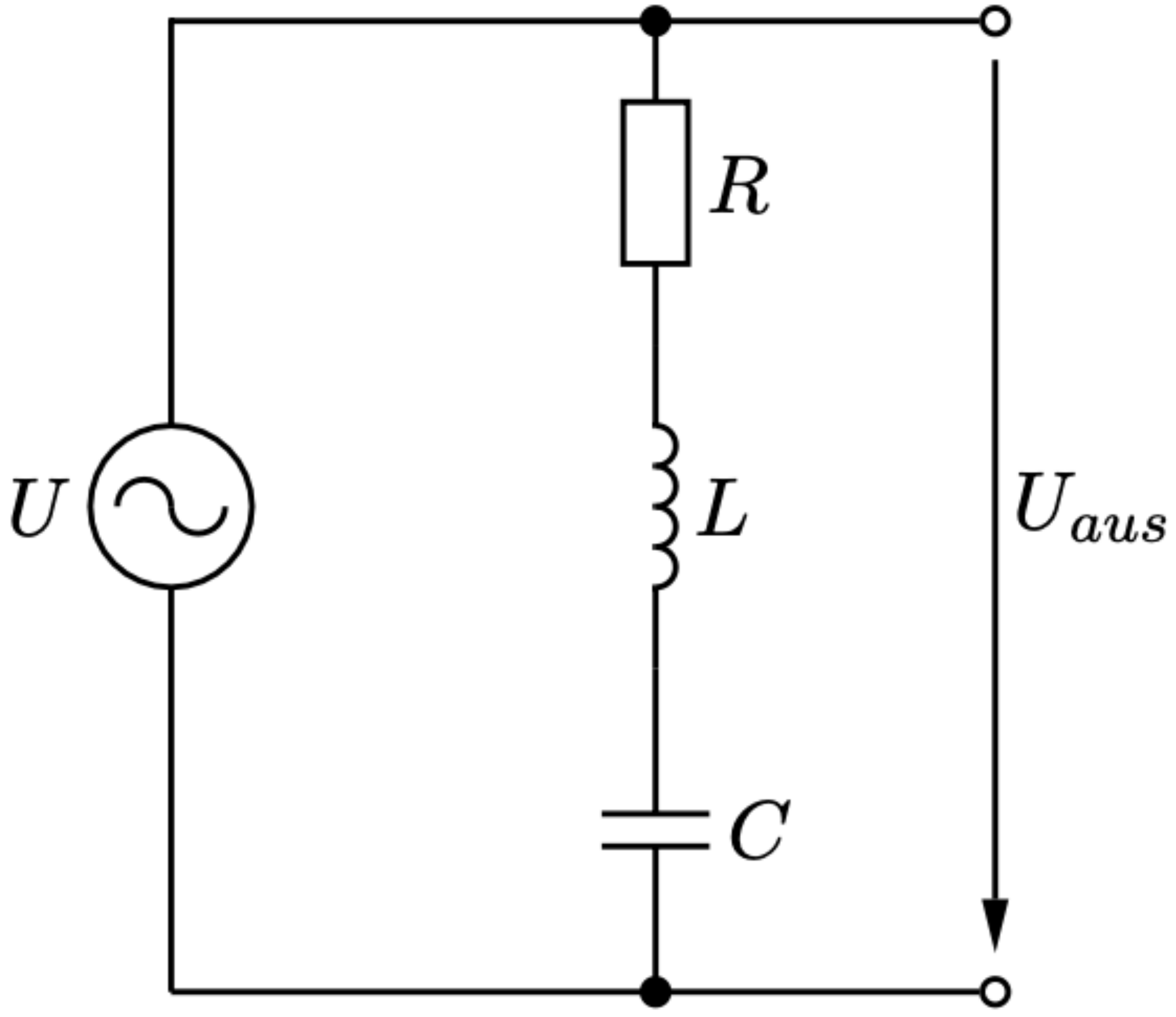
Q factor ("*Güte*"): $Q = \frac{\omega_0}{\Delta\omega} = \frac{\omega_0}{\omega_2 - \omega_1}$ here: $Q_P = \frac{RC}{\sqrt{LC}} = R\sqrt{\frac{C}{L}}$

RLC Oscillators: Compact Summary

Series and Parallel



Parallel



Series

	ω_0	$\Delta\omega$	Q
Series oscillator	$\frac{1}{\sqrt{LC}}$	$\frac{R}{L}$	$\frac{1}{R}\sqrt{\frac{L}{C}}$
Parallel oscillator	$\frac{1}{\sqrt{LC}}$	$\frac{1}{RC}$	$R\sqrt{\frac{C}{L}}$

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Chapter 3

Diodes

- Basic Properties
- Semiconductor Basics
- Diode Circuits - Examples

Overview

Chapter 3.1

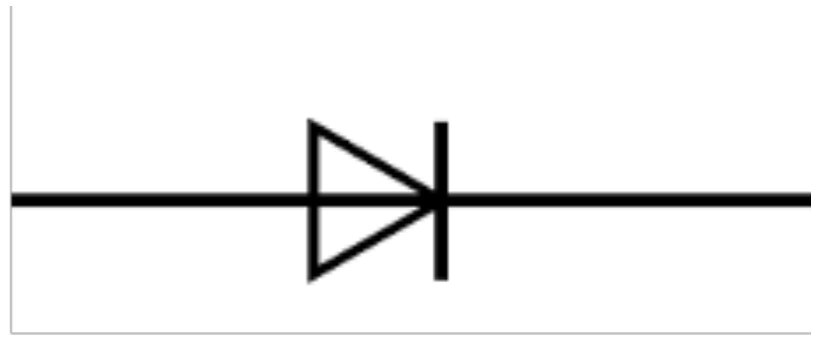
Basic Properties

In: Diodes

The Diode

Diode

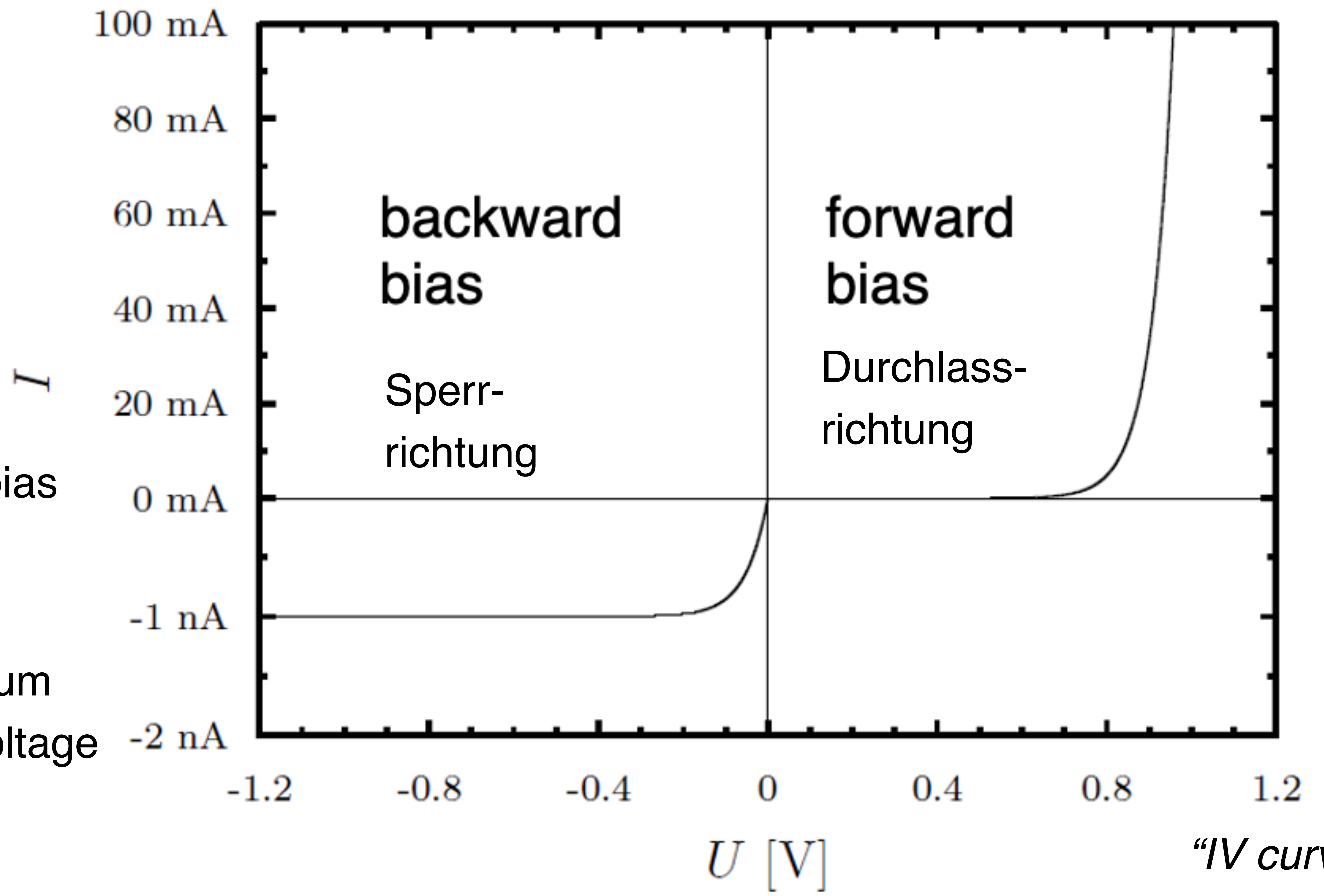
- A passive, non-linear component.



Basic behavior:

Large current for forward bias.

Minimum leakage current for reverse bias



For a constant, not too small current in forward direction (~ 10% of the maximum current of the component) there is a voltage drop of U_S over the diode, (almost) independent of the current.

"IV curve"

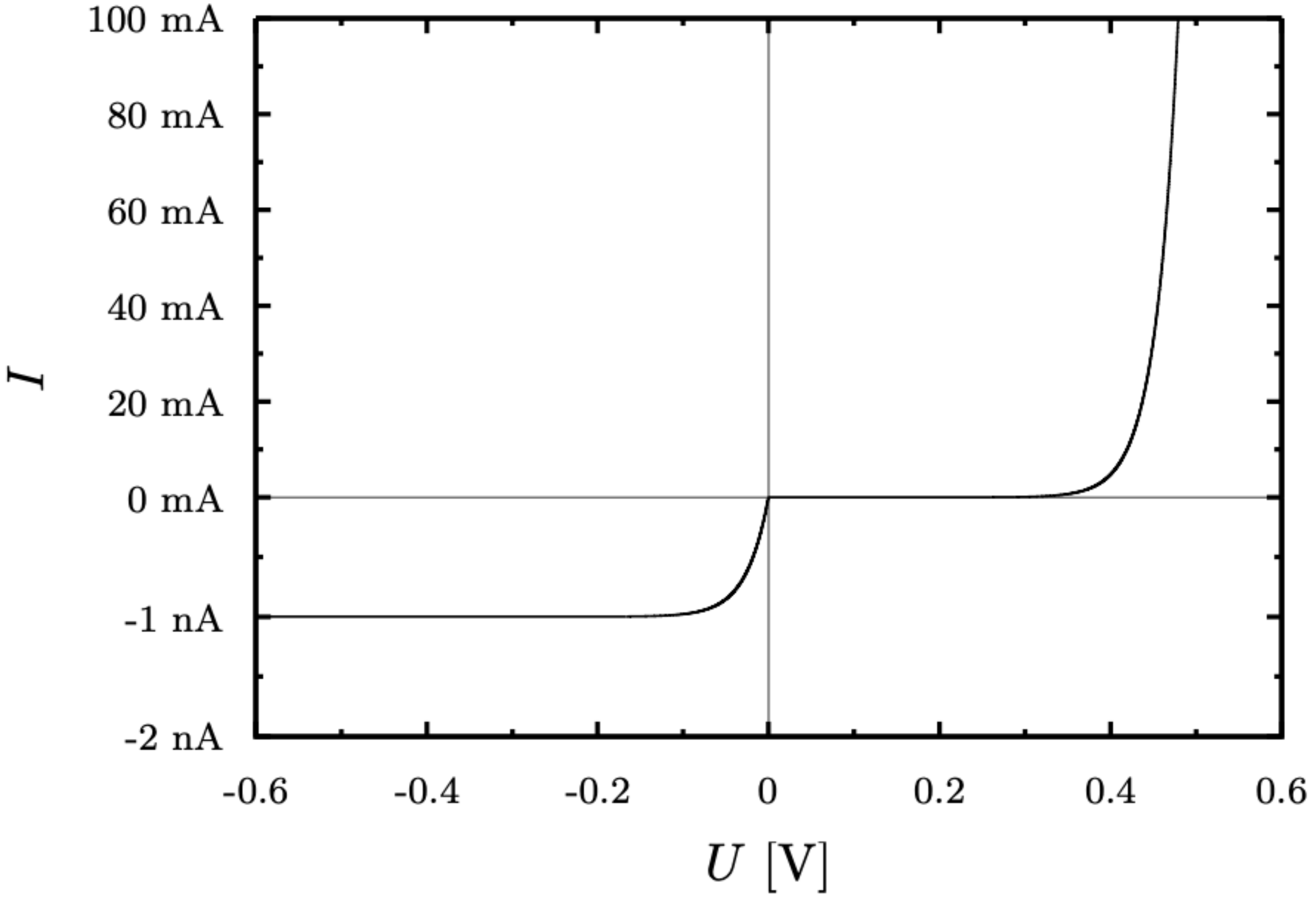
"Kennlinie"

For Si diodes: $U_S \sim 0.7$ V *voltage drop / forward threshold voltage "Schwellenspannung"*

Behavior of Diodes

Shockley Diode Equation

- Description of the IV Curve of a Diode: **Shockley diode equation**



$$I = I_S \left[e^{\frac{q_e U}{k T}} - 1 \right] = I_S \left[e^{\frac{U}{U_T}} - 1 \right]$$

I_S : reverse bias saturation current   "*Sperrstrom*"
(often also "leakage current")

$$\frac{k T}{q_e} = U_T$$

-> ~ 26 mV at 300 K

k: Boltzmann constant

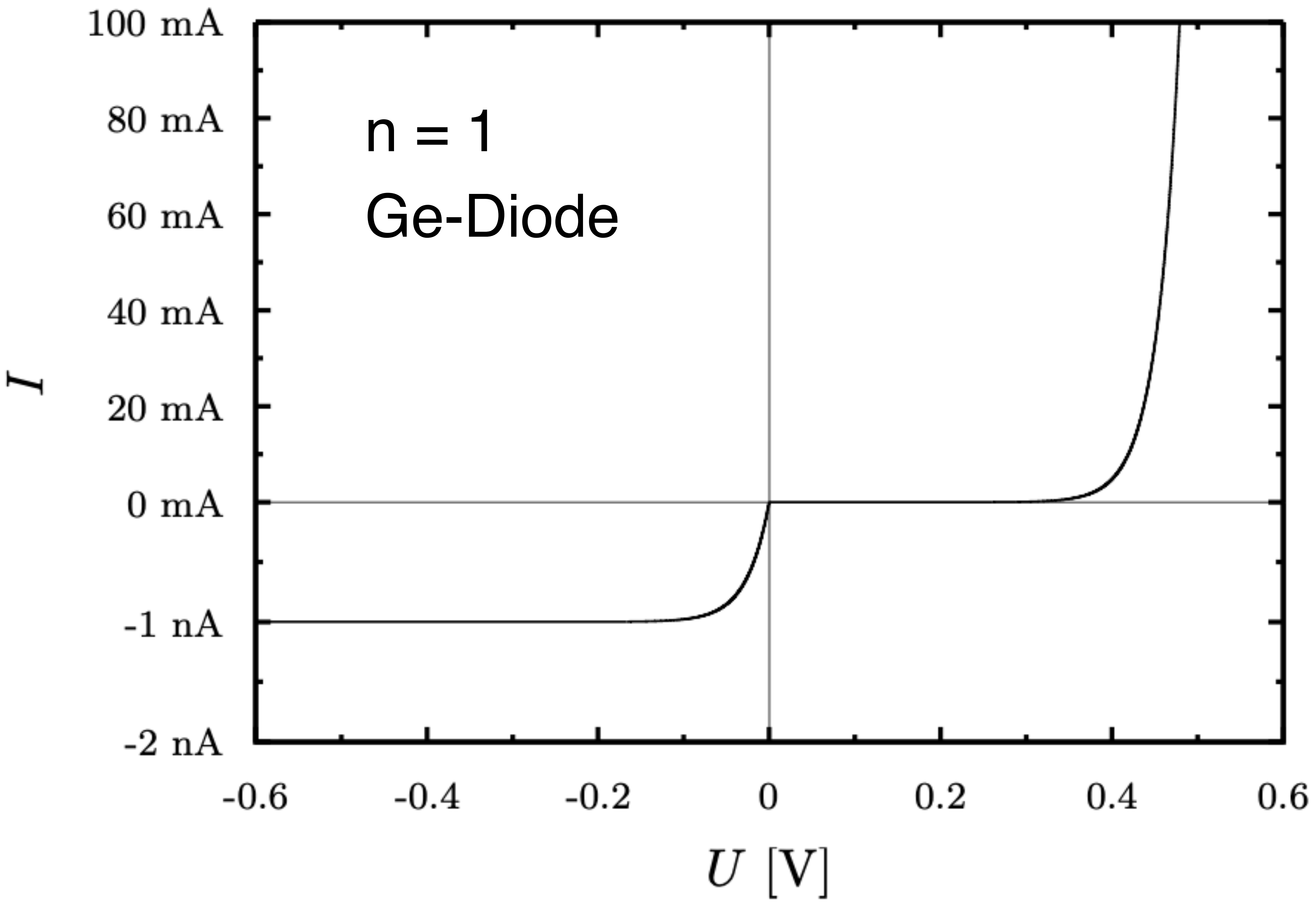
q_e: elementary charge

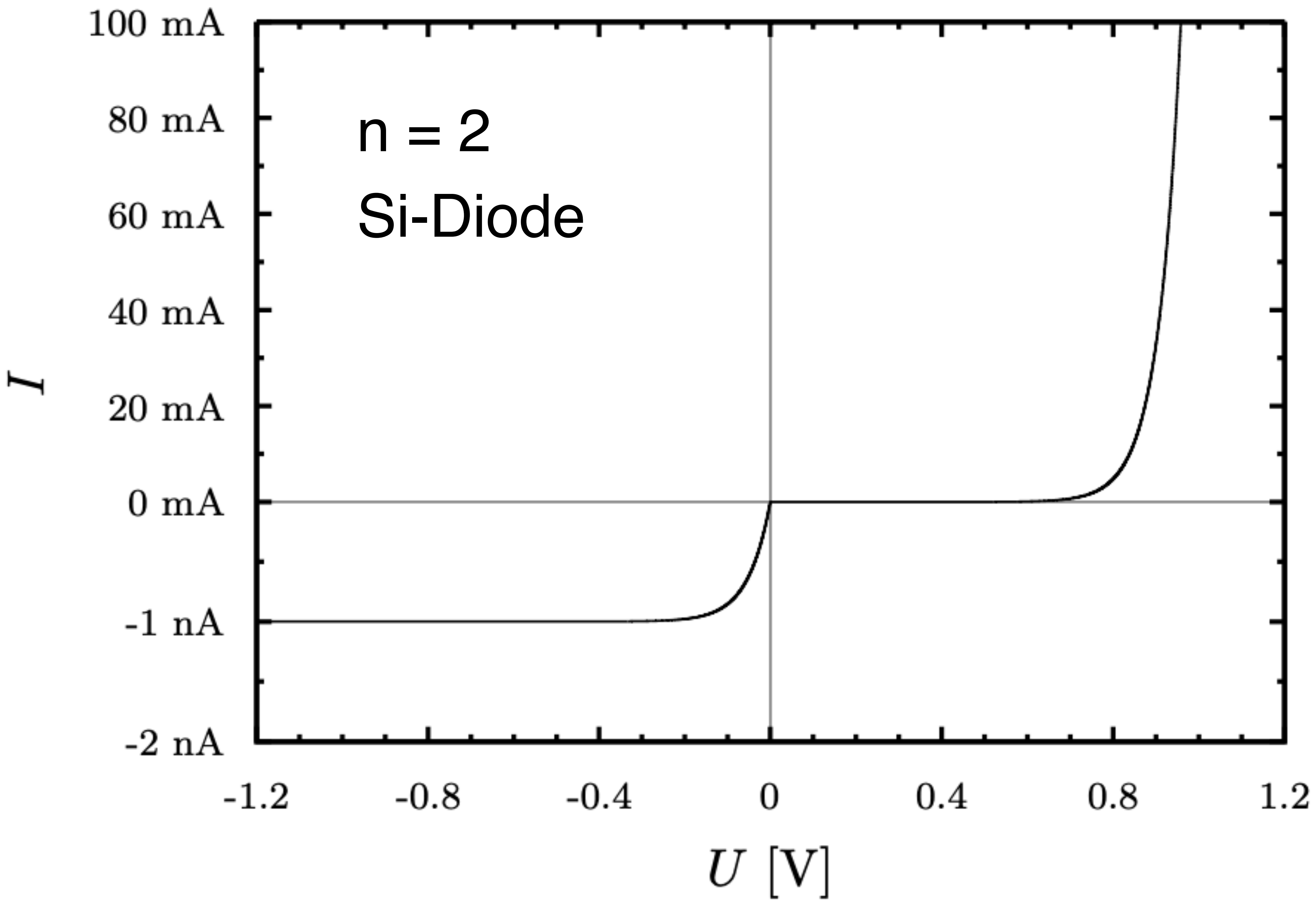
Behavior of Diodes

Extension of the Shockley Equation

- Depending on material diodes show different behavior: Cannot be described by the simple Shockley equation.

$$I = I_S\left[e^{\frac{q_e U}{kT}} - 1\right] = I_S\left[e^{\frac{U}{U_T}} - 1\right] \quad \Rightarrow \quad I = I_S\left[e^{\frac{U}{nU_T}} - 1\right] \qquad n = 1 \dots 2$$

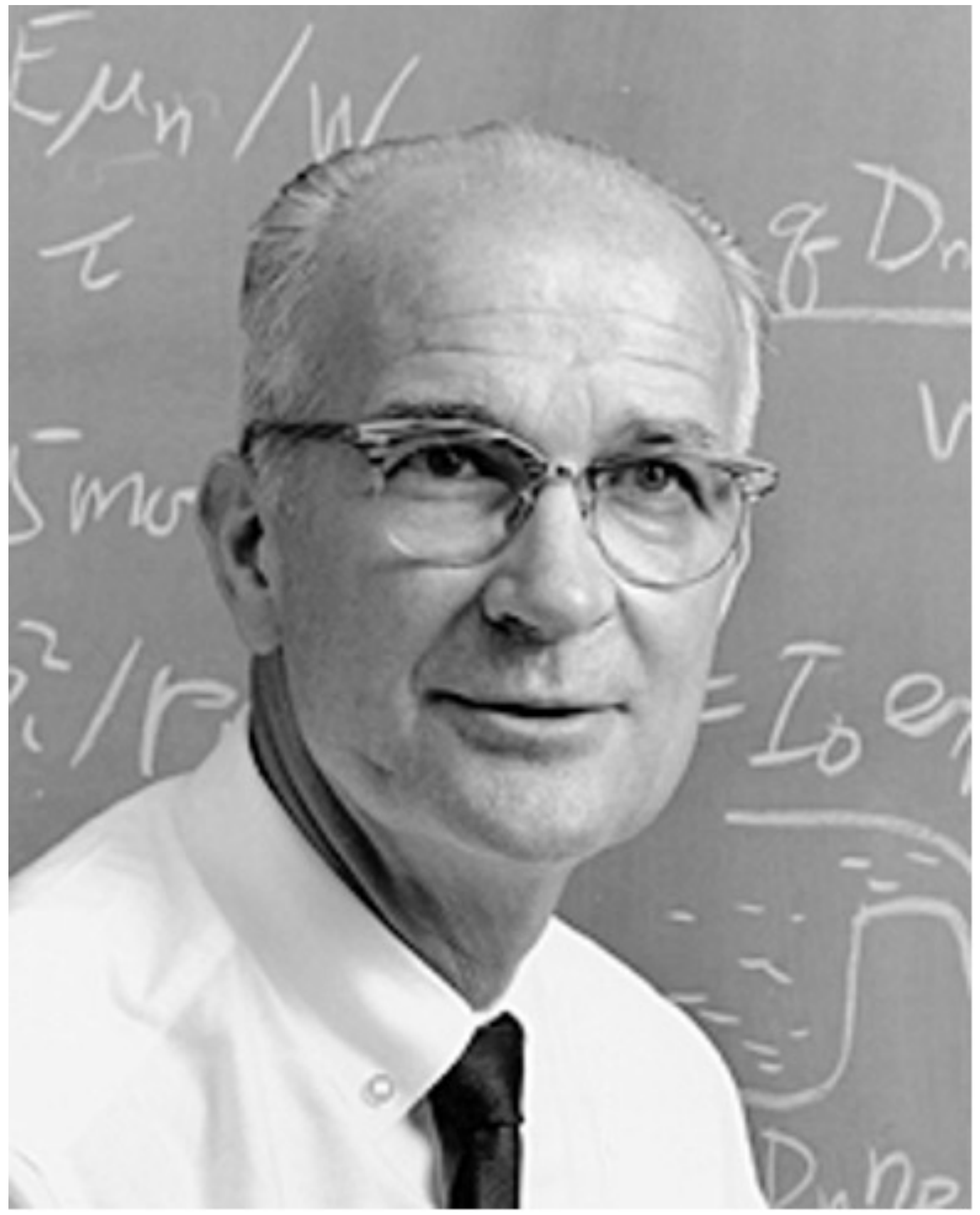




Historical Perspective

William B. Shockley

- Physicist and electrical engineer
- Nobel Prize in physics 1956 (together with Bardeen, Brattain) "for their researches on semiconductors and their discovery of the transistor effect"



One of the "founders" of Silicon Valley
(but also a very controversial person)

Chapter 3.2

Semiconductor Basics

In: Diodes

Semiconductors

Halbleiter

- The basis for diodes (and transistors,…): semiconductors.
  Characterized by a (small) band gap between the (filled) valence and (empty) conduction band.
  Electrons move from valence into the conduction band via thermal excitation -> “holes” in valence band.

Semiconductors: Elements of the IV main group: Si, Ge, C (as diamond); but also compounds:
GaAs, GaN, SiC, HgCdTe, CdZnTe, …

Typical values at room temperature

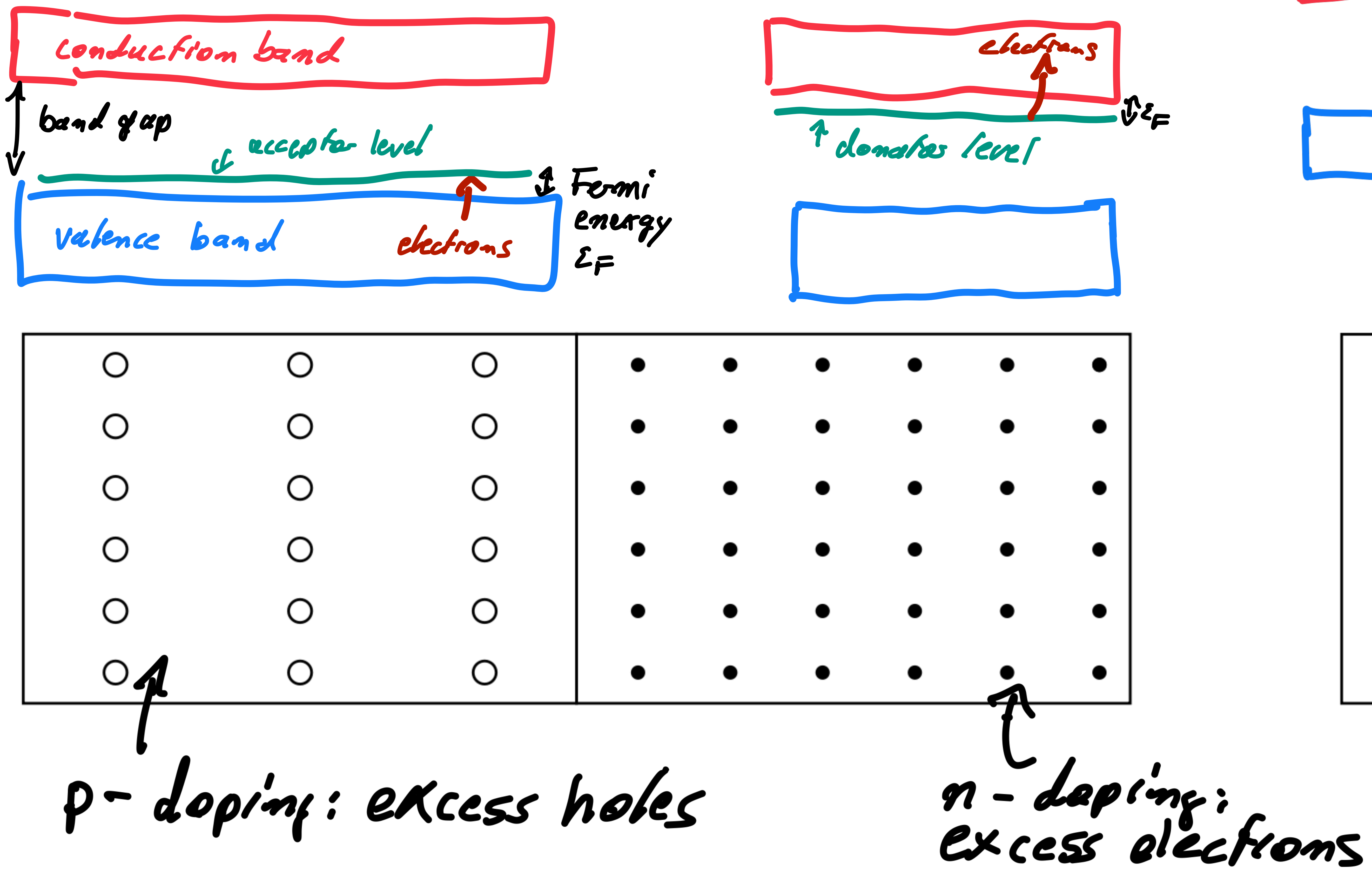
		Si	Ge	GaAs	Diamond	GaN
Band gap	E_G [eV]	$1,12$	$0,67$	$1,42$	$5,5$	3.4
Intrinsic charge density (due to thermal excitation)	n_i [cm^{-3}]	$1,1\,10^{10}$	$2,4\,10^{13}$	$1,8\,10^{6}$	~ 10^{-27}	2×10^{-10}

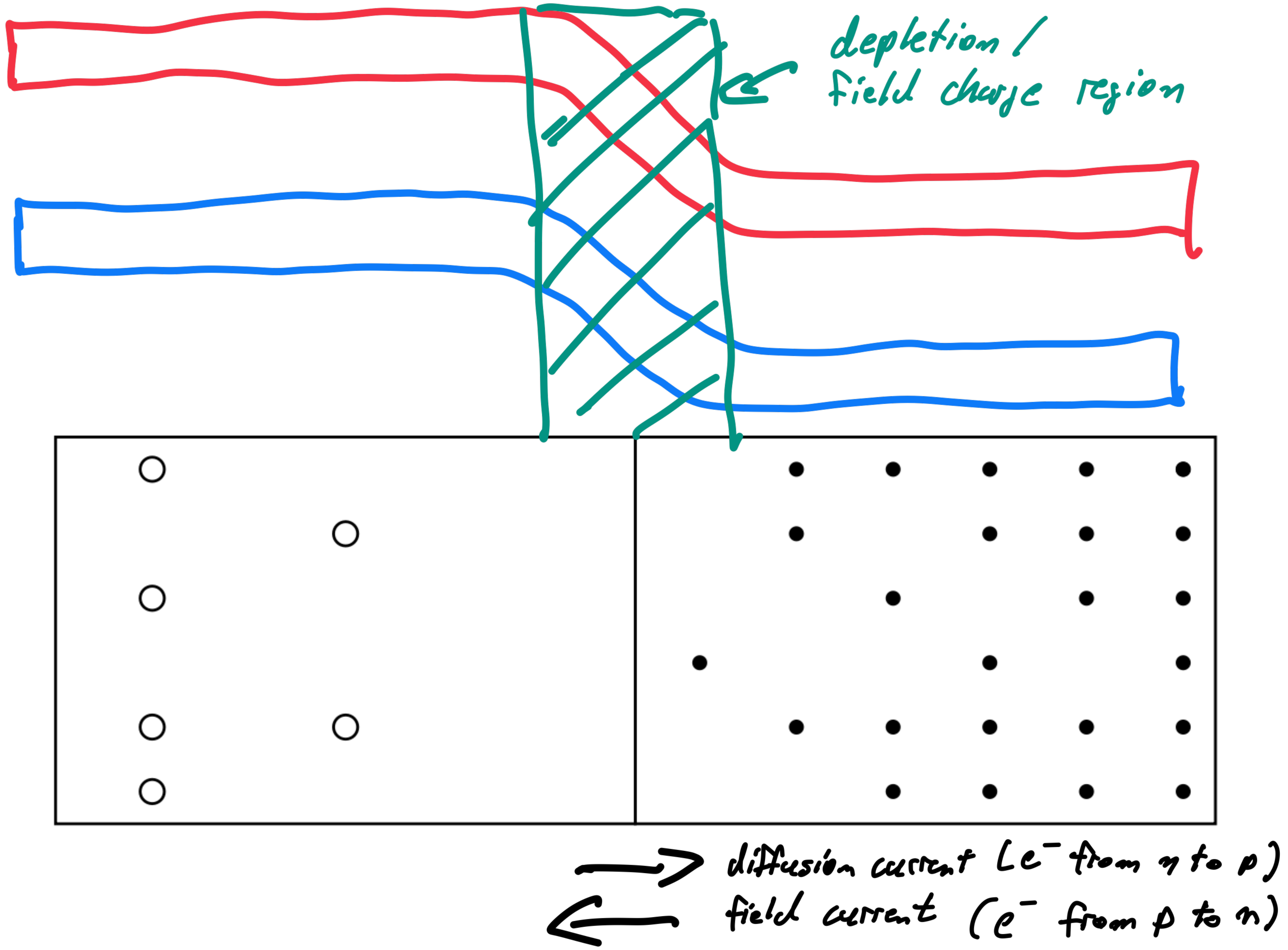
Doping, PN Junctions

Dotierte Halbleiter und PN-Übergänge

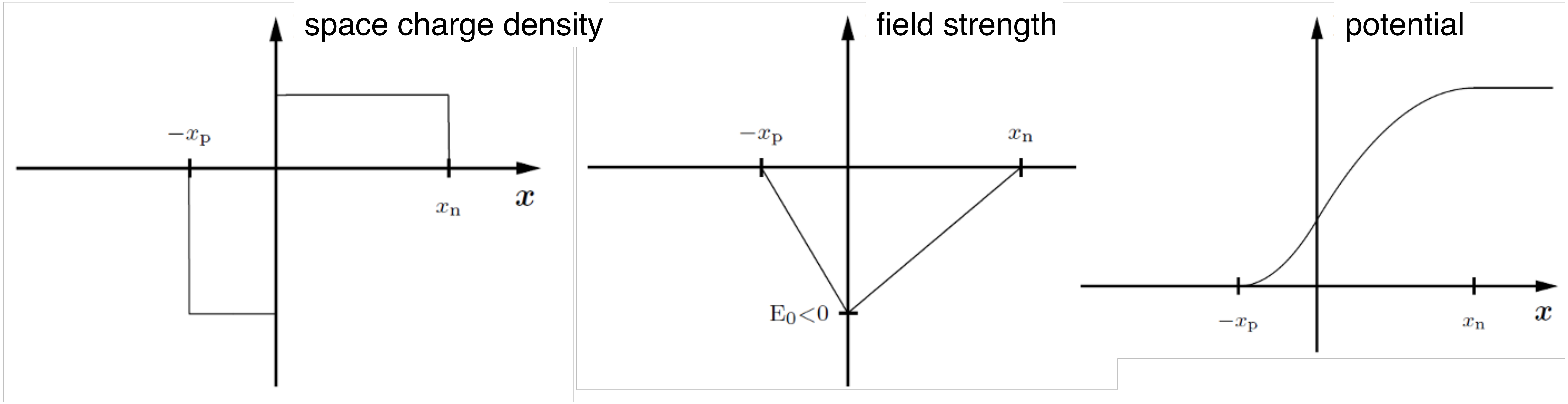
- Doping: Providing additional electrons (V main group, such as P (Z=15), n-type doping) or holes (III main group, such as B (Z = 5), p-type doping).

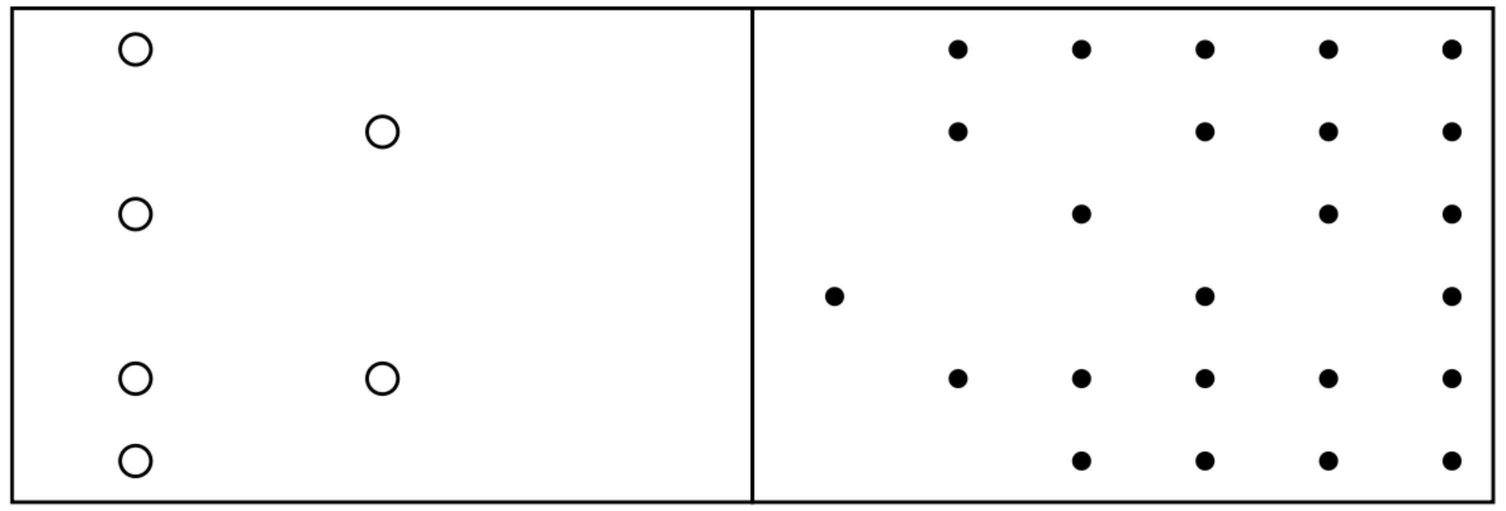
Increases the charge carrier density by several orders of magnitude





Electric Fields in Diodes

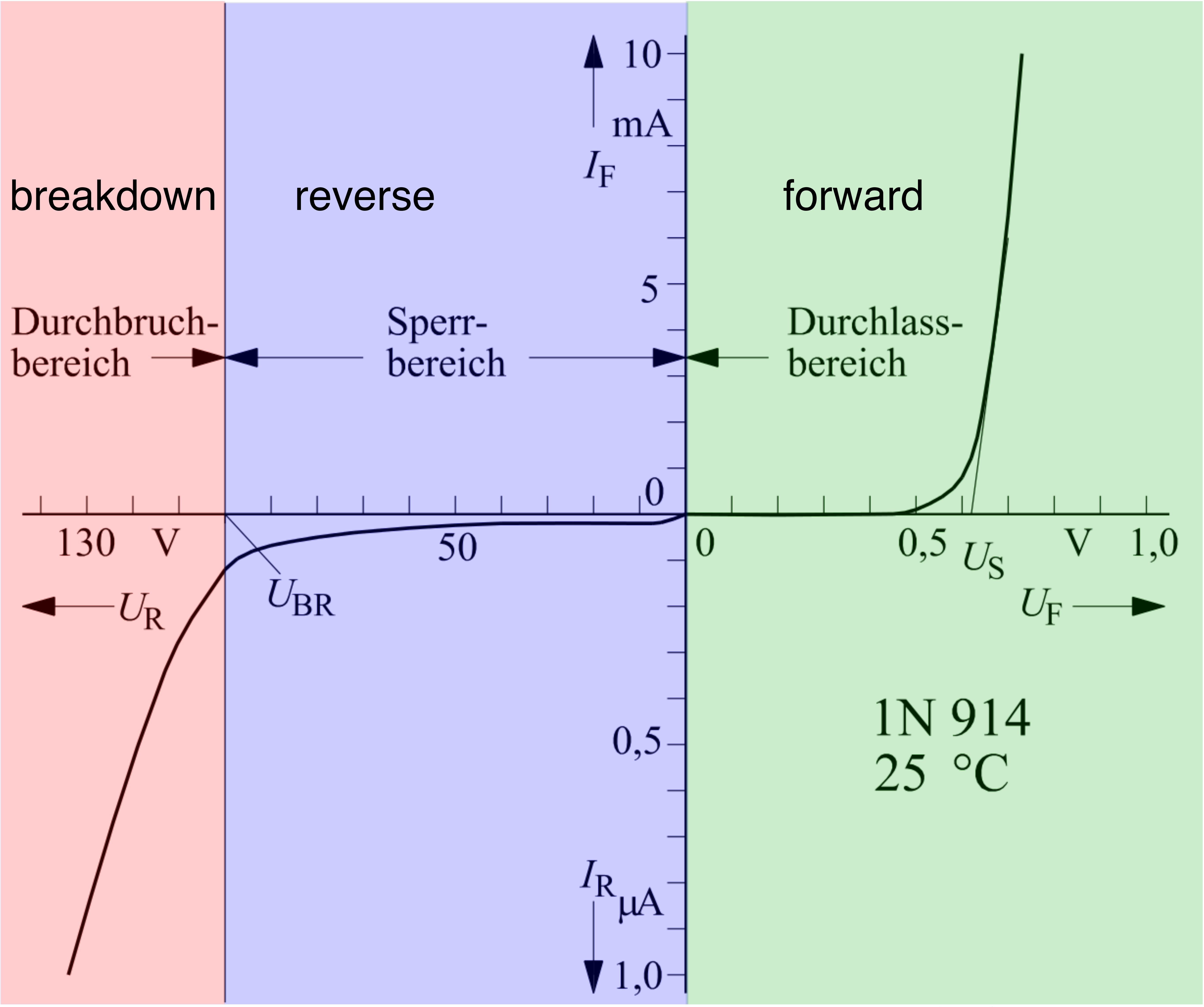




Potential difference between n side (higher due to positive net charge) und p side (lower due to negative net charge), depending (among others) on doping concentration. In silicon typically 0.6 V - 0.7 V.

Extreme Reverse Bias Voltage: Breakdown

Durchbruchspannung



- A diode cannot hold arbitrarily high reverse bias!
  Above: Breakdown

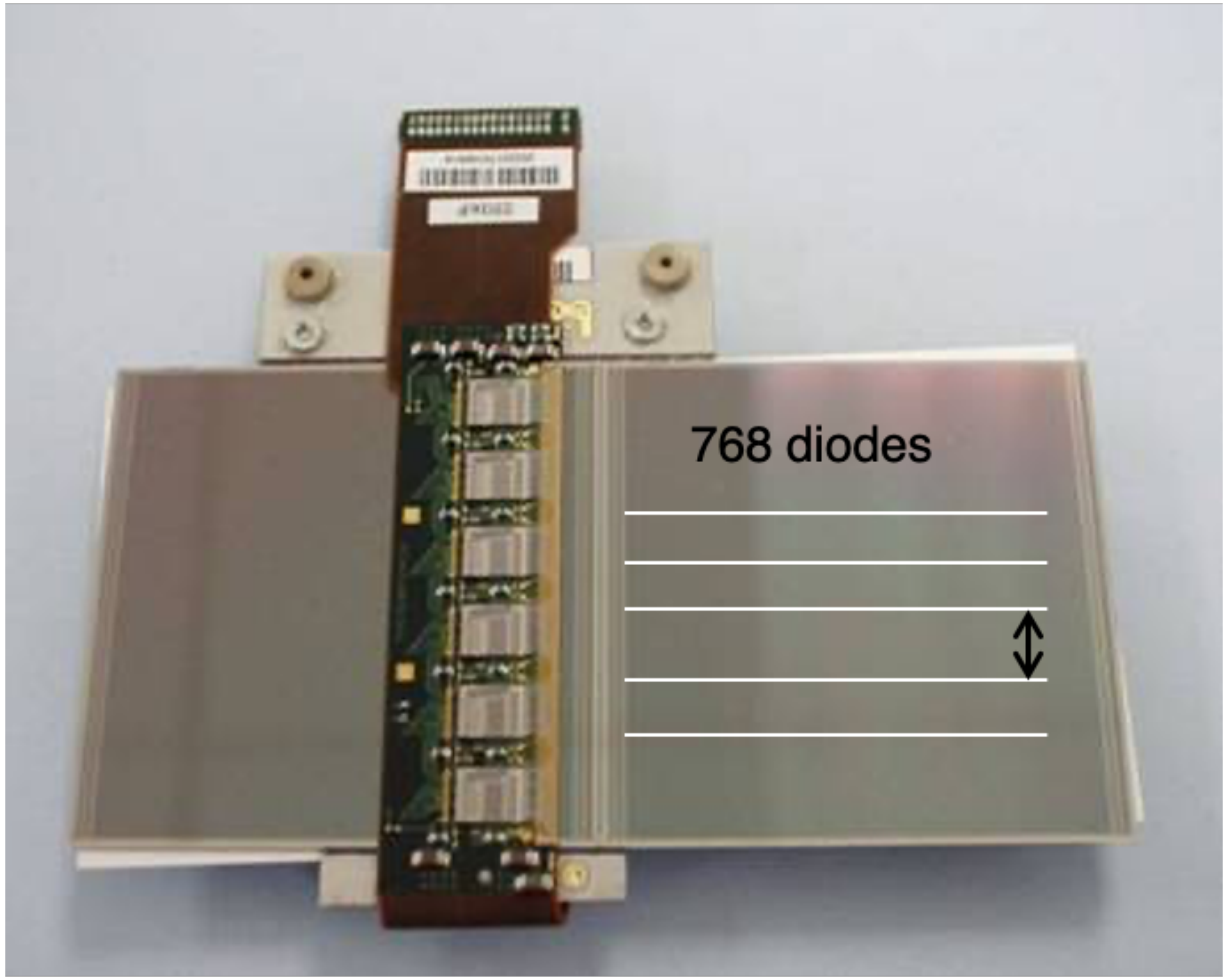
Normally unwanted:
High currents, power dissipation, temperature results in destruction of the diode.

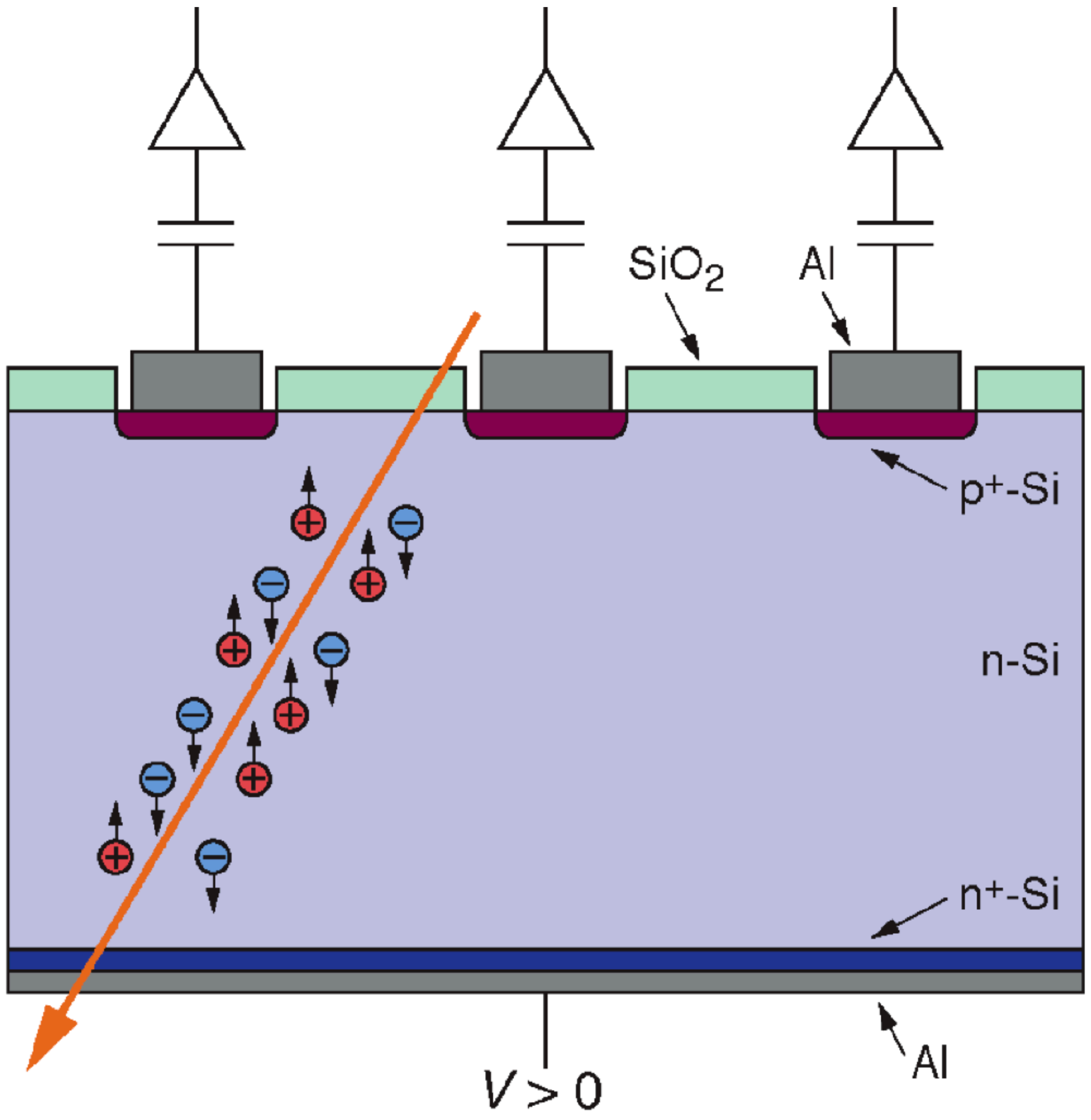
But: There are exceptions:
Zener diodes
avalanche diodes (avalanche amplification!)

Diodes beyond Electronics Components

A wide Range of Applications

- Silicon detectors in particle physics.



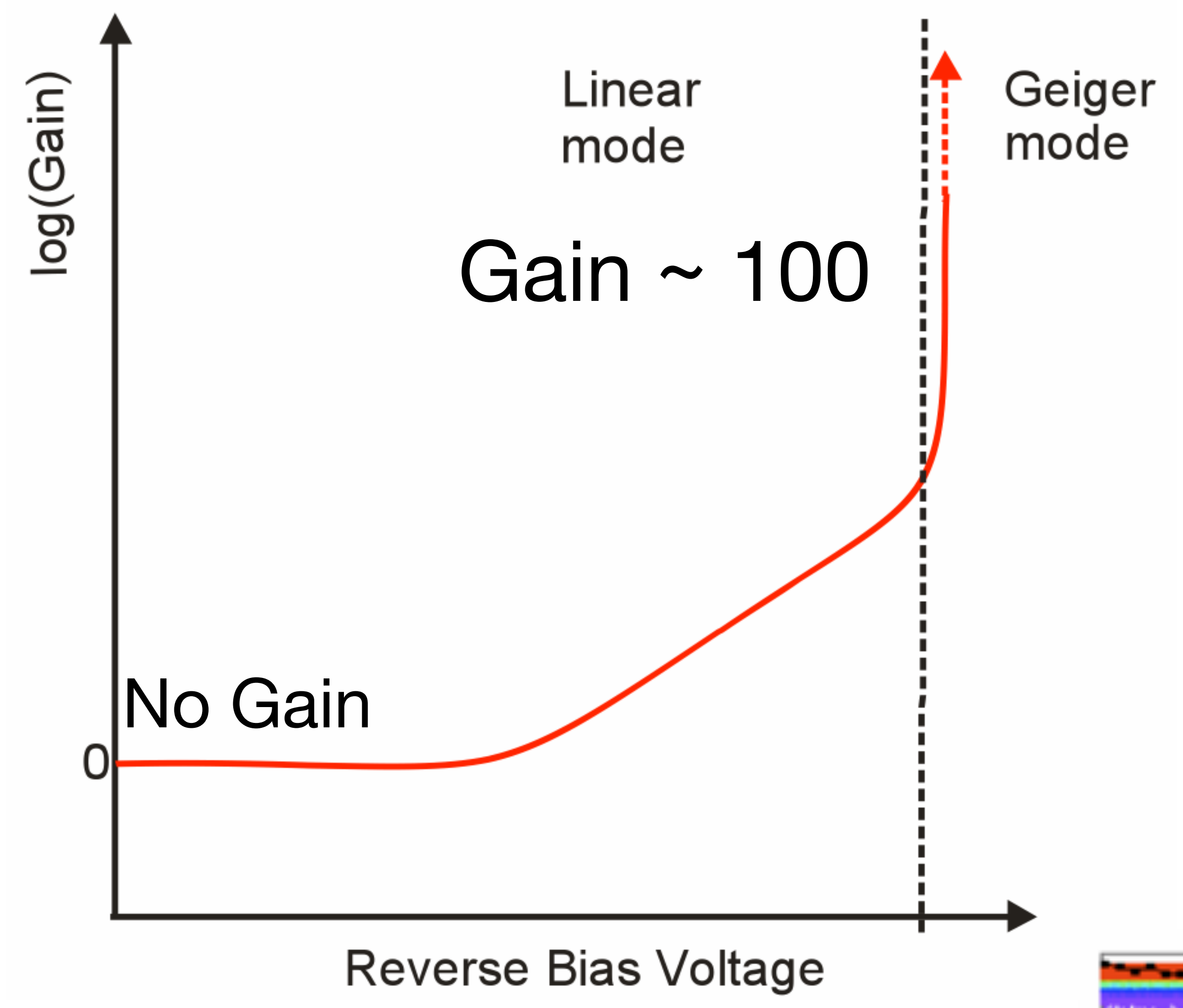


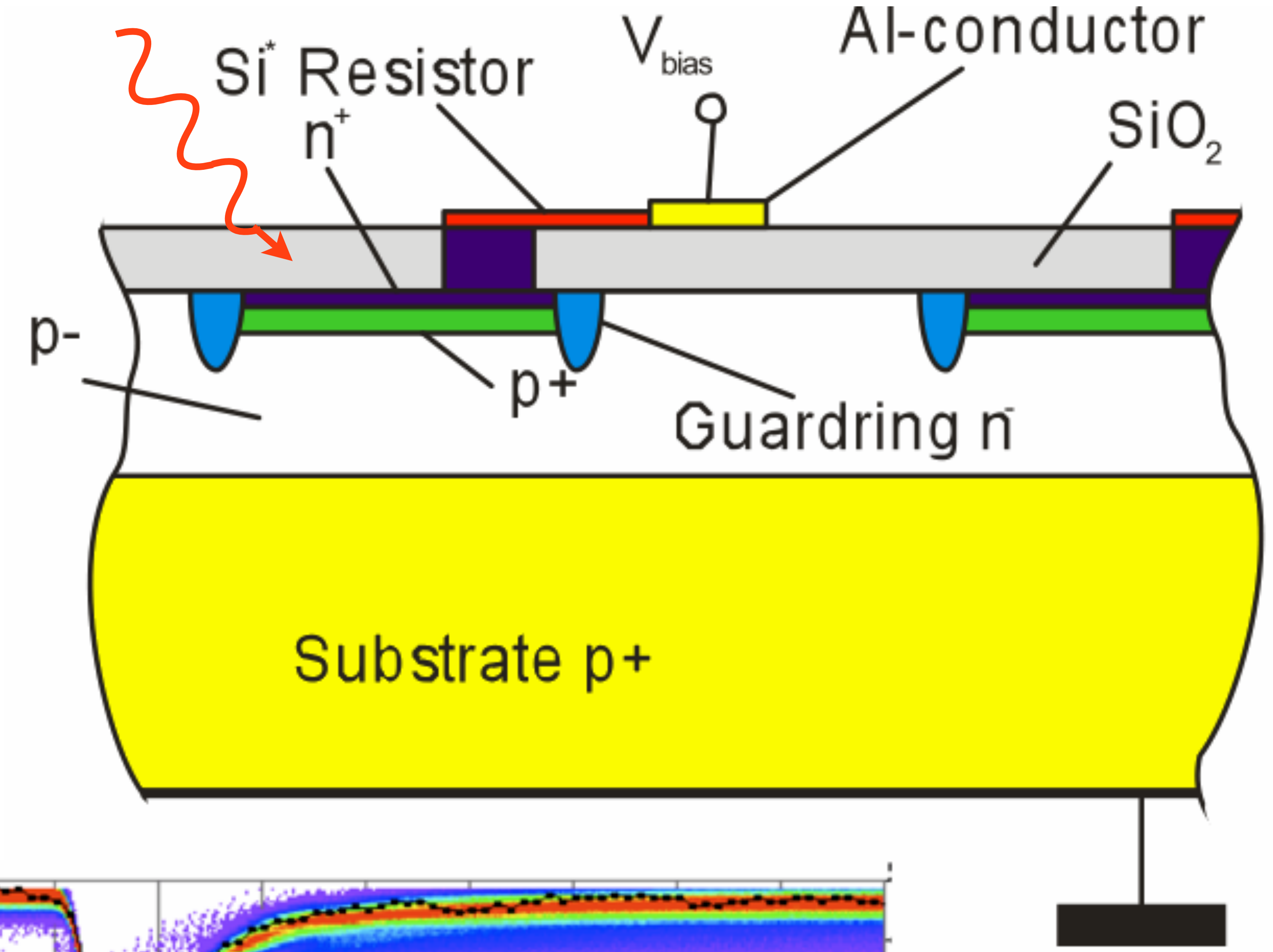
Diodes beyond Electronics Components

A wide Range of Applications

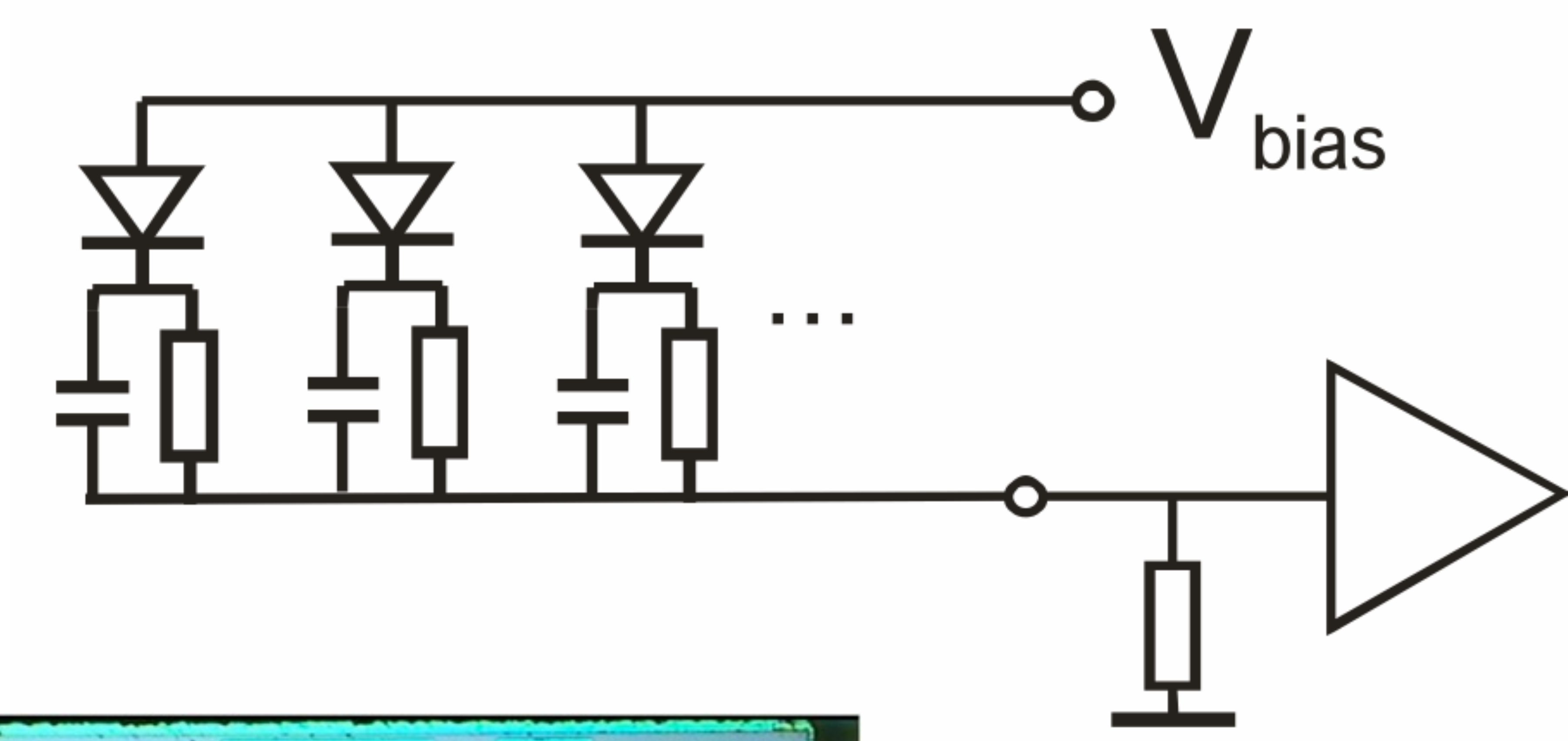
- Silicon Photomultiplier (SiPM)

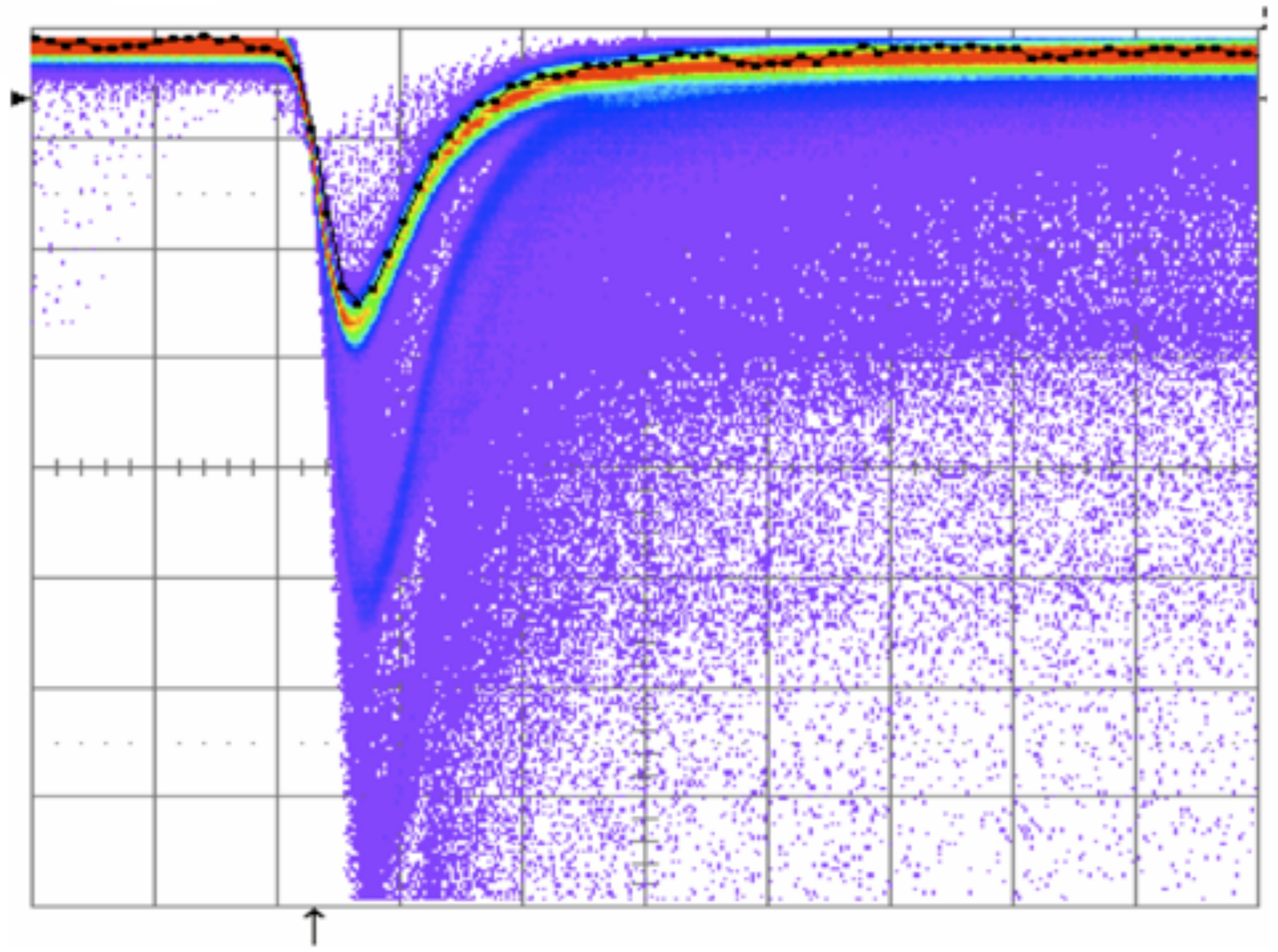
Avalanche Photo Diode APD

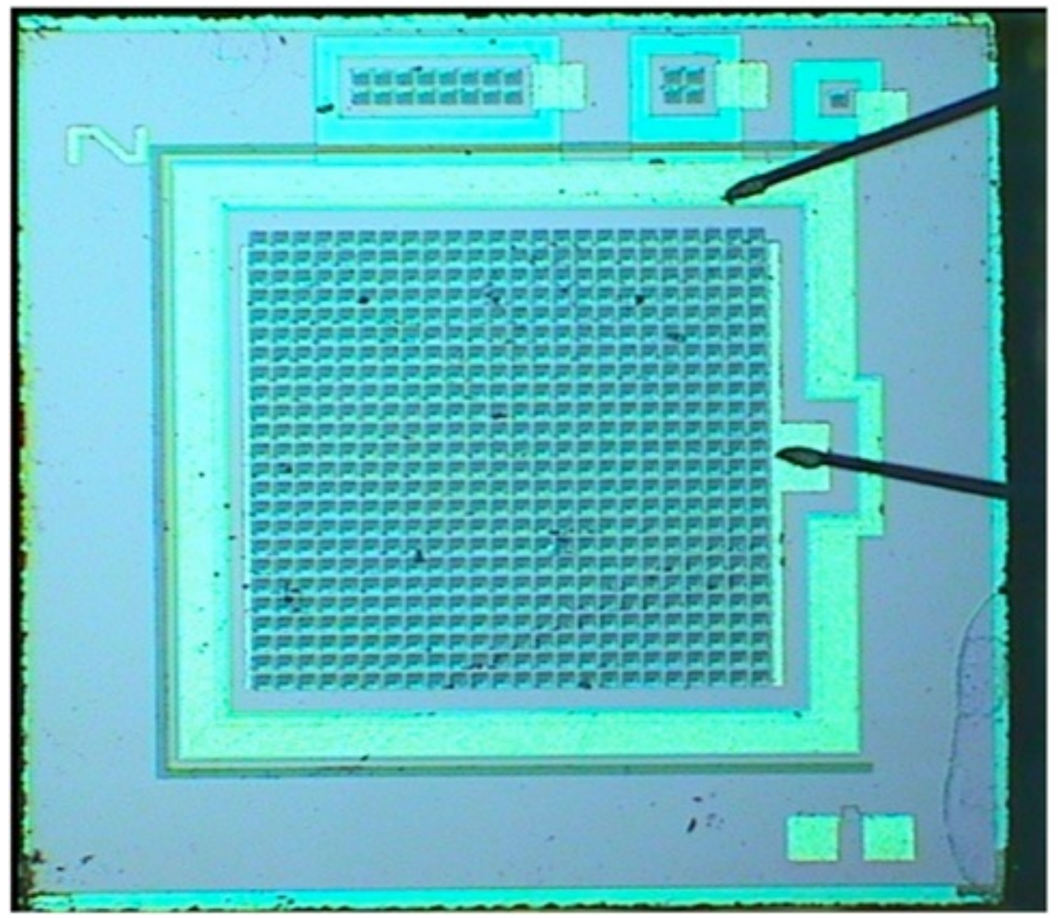




xN







Temperature Dependence of Diodes

Temperaturabhängigkeit

- The properties of diodes depend on temperature.
  Two main effects:
  - Intrinsic charge carrier density - thermal excitation
  - Dependence on U_T (IV curve / Shockley equation)

$$\frac{k\,T}{q_e} = U_T$$

Forward bias

$$\frac{dU}{dT} = \frac{U_S - U_G - 3\,U_T}{T}$$

U_G ~ 1.12 V (band gap) =>

$$\frac{dU}{dT} = -1{,}87\,\frac{\mathrm{mV}}{°\mathrm{C}}$$

(at 300 K)

in reverse bias:

$$I_S \sim T^{\frac{3}{2}}\,\mathrm{e}^{-\frac{q_e\,U_G}{2\,k\,T}}$$

Current grows with increasing temperature - doubling every ~ 7 K.

Risk of a "thermal run-away"!

Next Lectures:

Digital - Thursday, November 16 & Tuesday Nov. 21

Analog 06 - Chapters 03, 04 - Thursday, Nov. 23

Time Plan for Next Lectures

A few Changes coming up!

Calender Week	Tuesday	Thursday
45	07.11. **Analog**	09.11. **Digital**
46	14.11. **Analog**	16.11. **Digital**
47	21.11. **Digital**	23.11. **Analog**
48	28.11. **Digital**	30.11. **Digital**
49	05.12. **Digital**	07.12. **Analog**
50	12.12. **Digital**	14.12. **Analog**
51	19.12. **Analog**	21.12. **Digital**
2	09.01. **Analog**	11.01. **Analog**
3	16.01. **Digital**	18.01. **Digital**
4	23.01. **Analog**	25.01. **Digital**
5	30.01. **Analog**	01.02. **Digital**
6	06.02. **Analog**	08.02. **Digital**
7	13.02. **Analog**	15.02. **Digital**

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