Electronics for Physicists

Analog Electronics

Chapter 3; Lecture 06, Part 1

Frank Simon
Institute for Data Processing and Electronics

23.11.2023

Karlsruhe Institute of Technology

KIT, Winter 2023/24

Institute for Data Processing and Electronics

Chapter 3.2

Semiconductor Basics - Part II

In: Diodes

Temperature Dependence of Diodes

Temperaturabhängigkeit

Karlsruhe Institute of Technology

- 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) =>

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

(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”!

Chapter 3

Diodes

- Basic Properties
- Semiconductor Basics
- Diode Circuits - Examples

Overview

Chapter 3.3

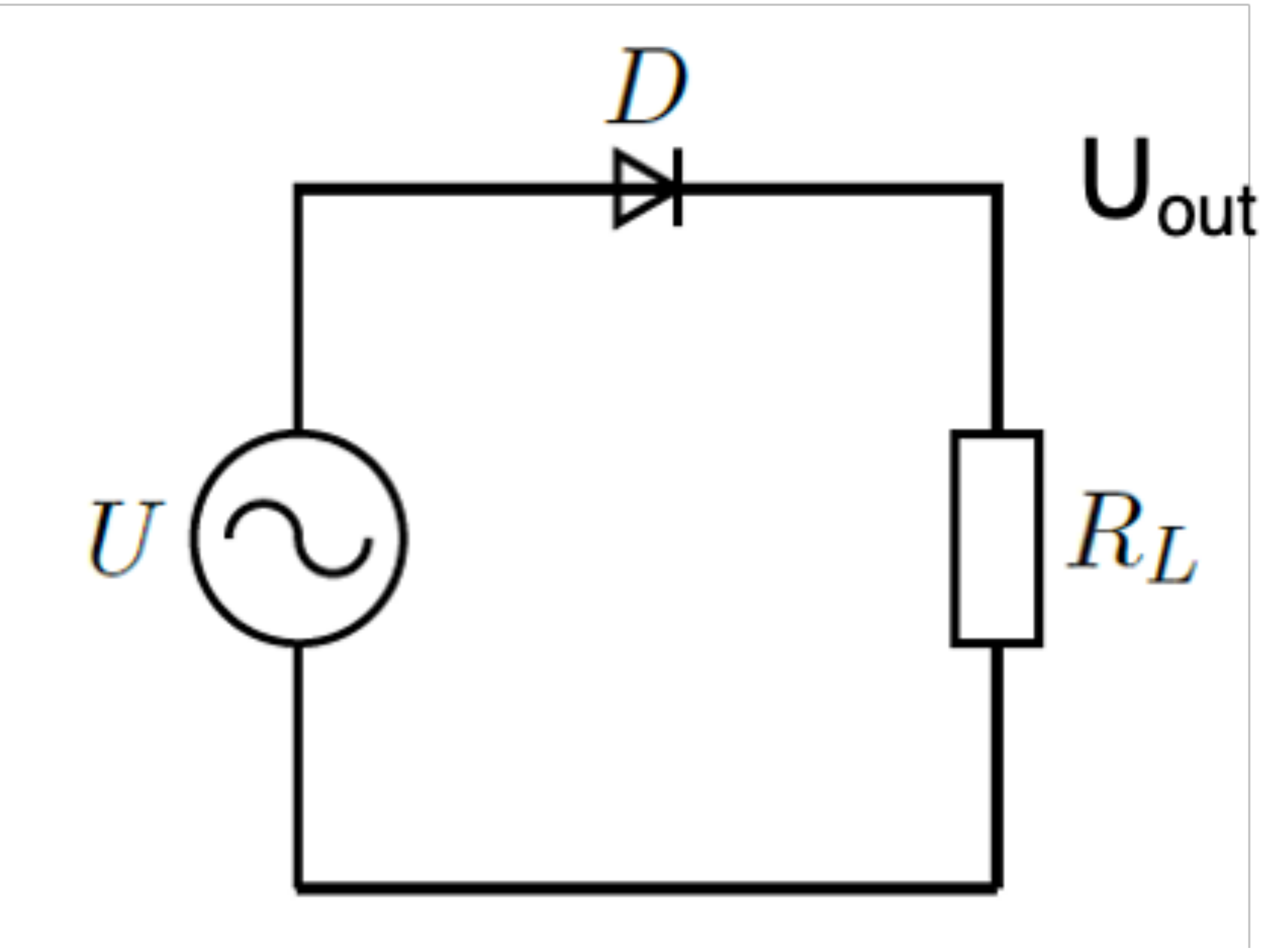
Diode Circuits

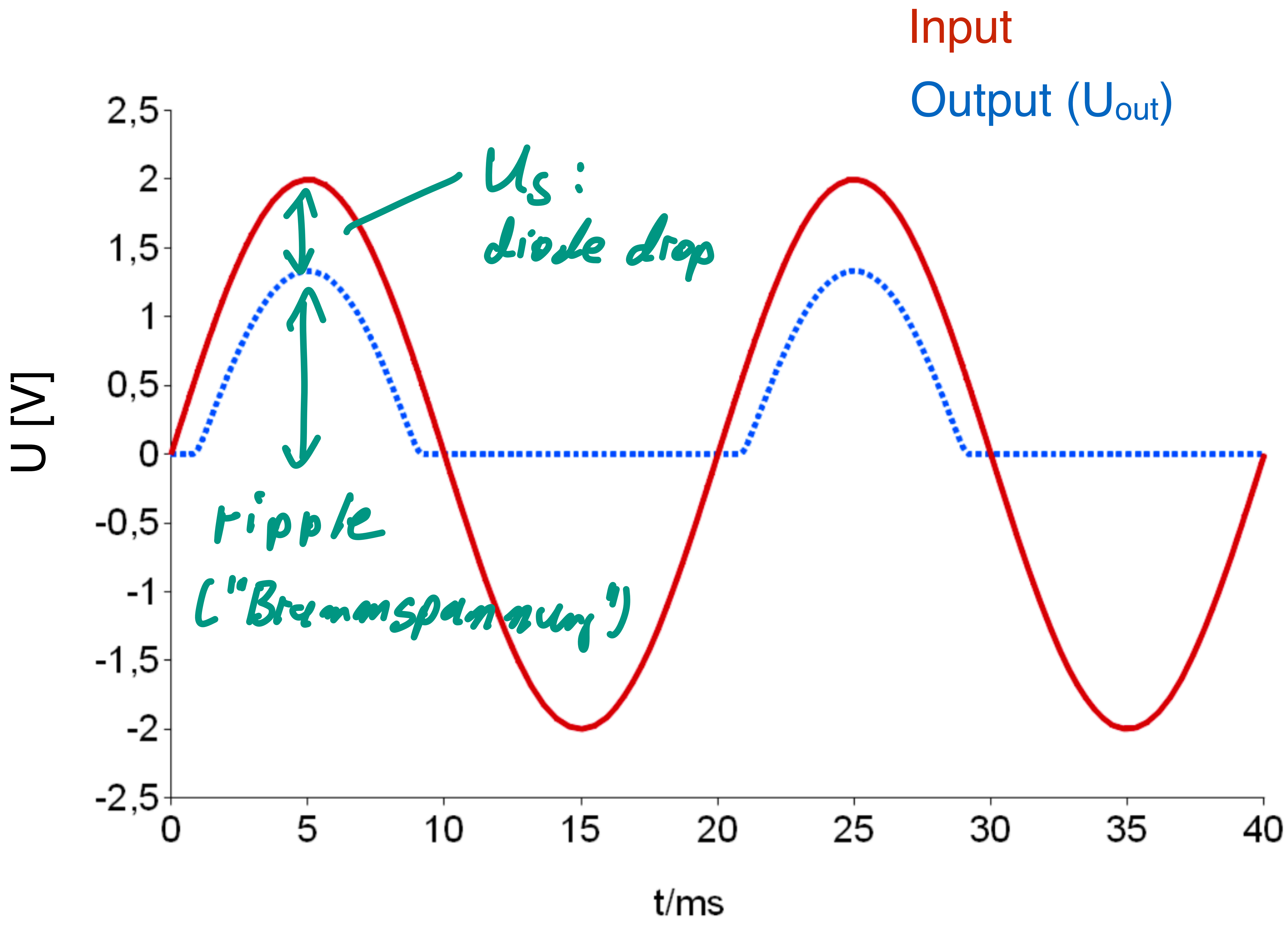
In: Diodes

Diode Circuits: Simple Rectifier

Gleichrichter

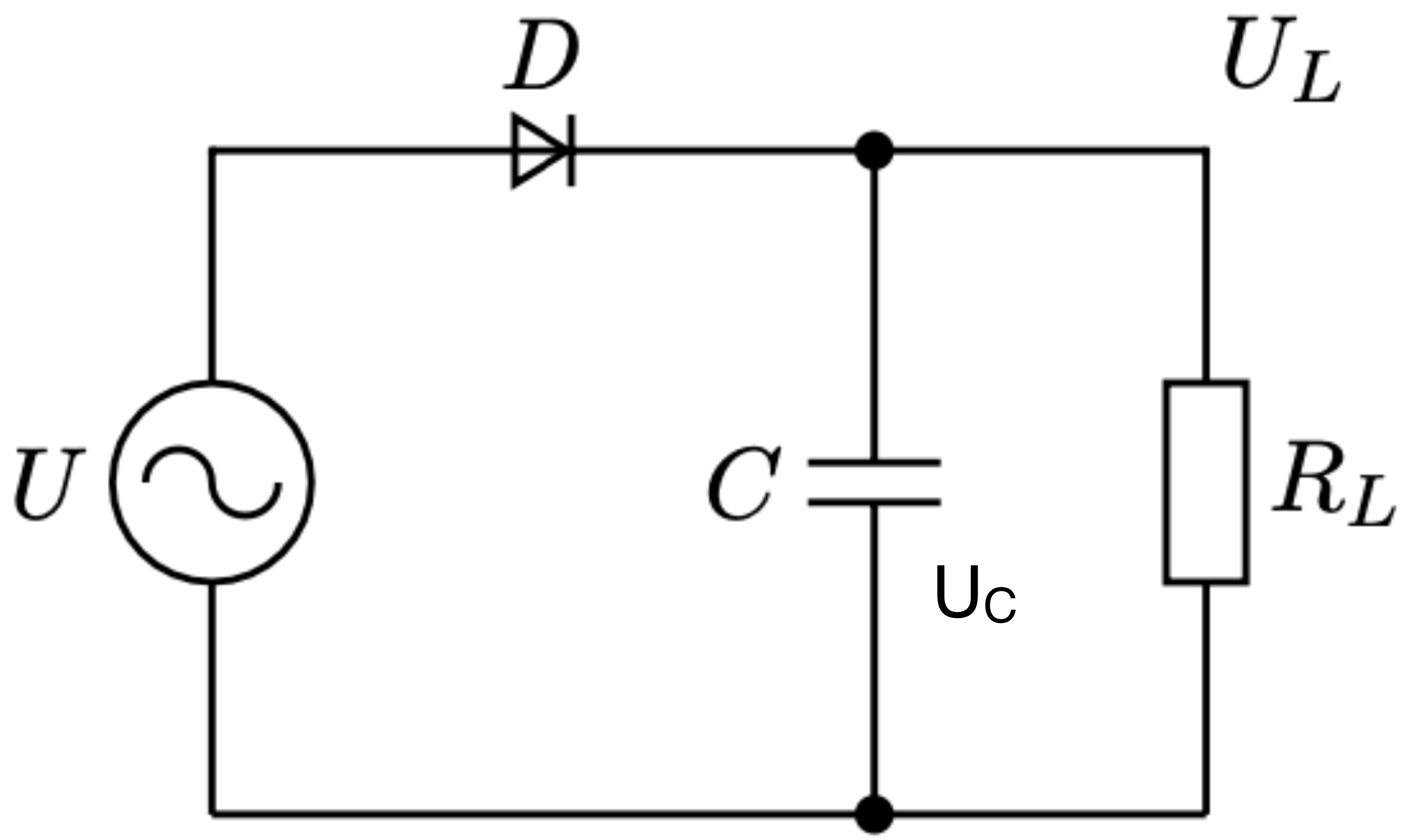
- An important application of diodes: rectifying



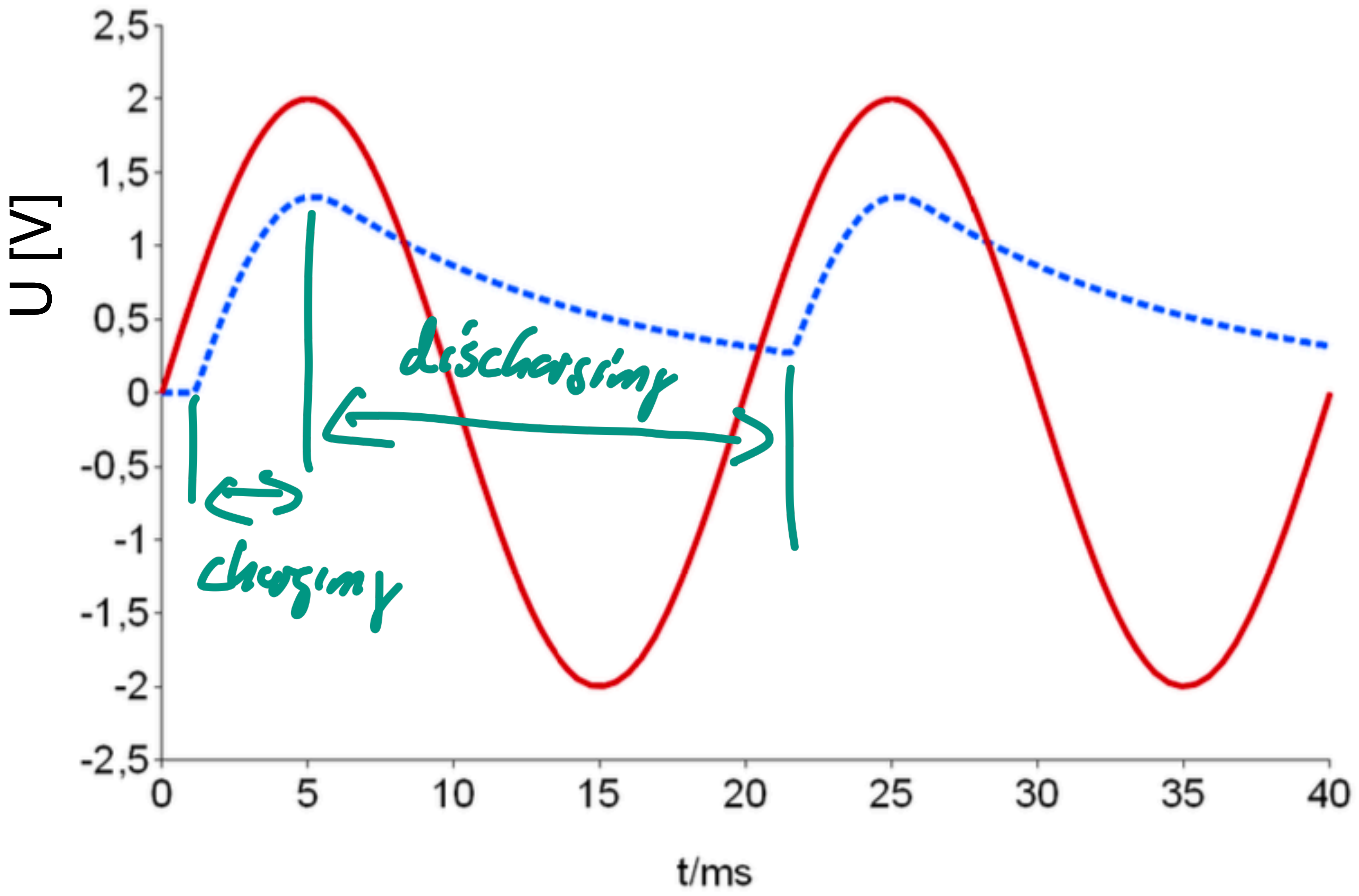


Diode Circuits: Simple Rectifier

Improvement with a Capacitor



Smoothing of output voltage by capacitor:



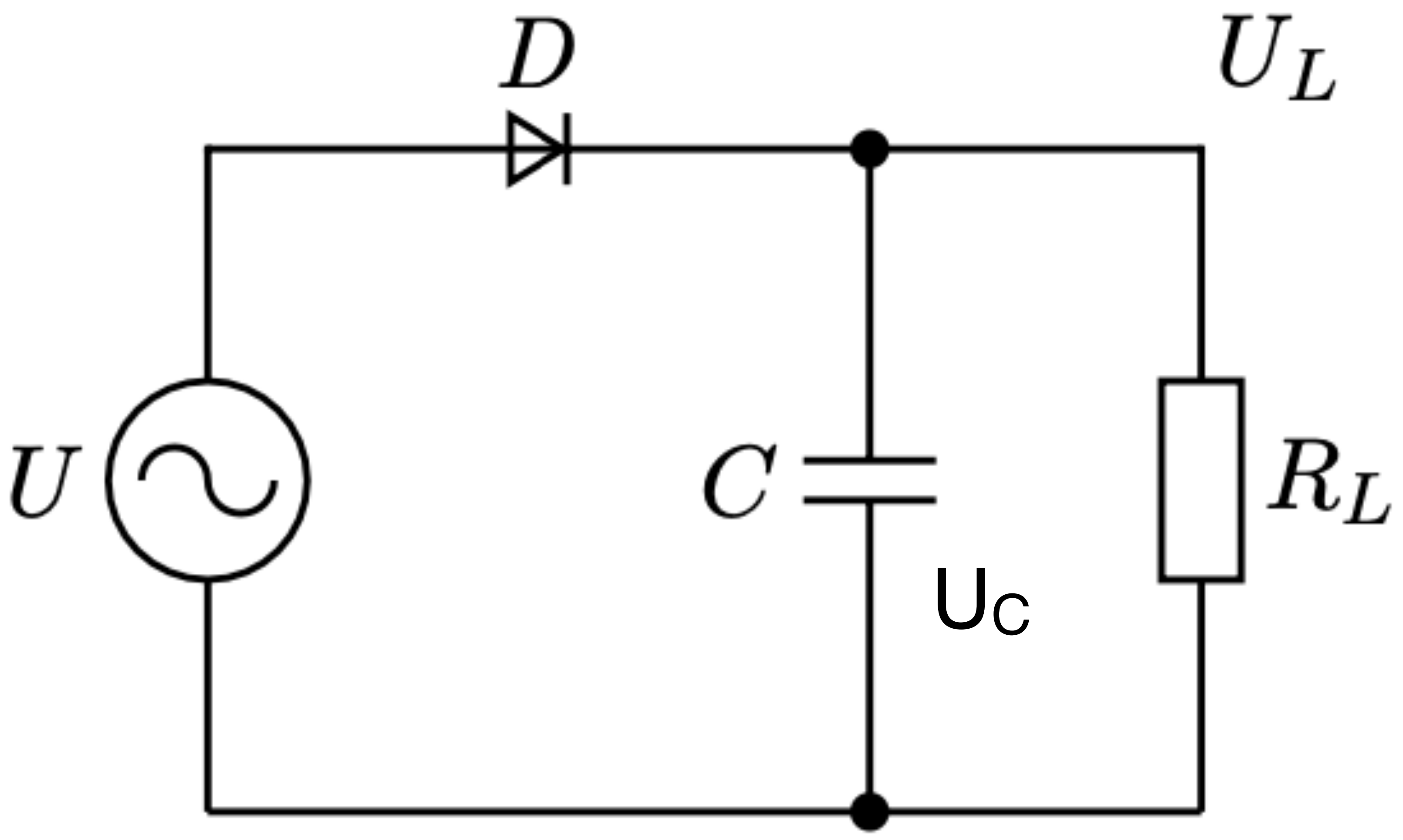
What is happening here?

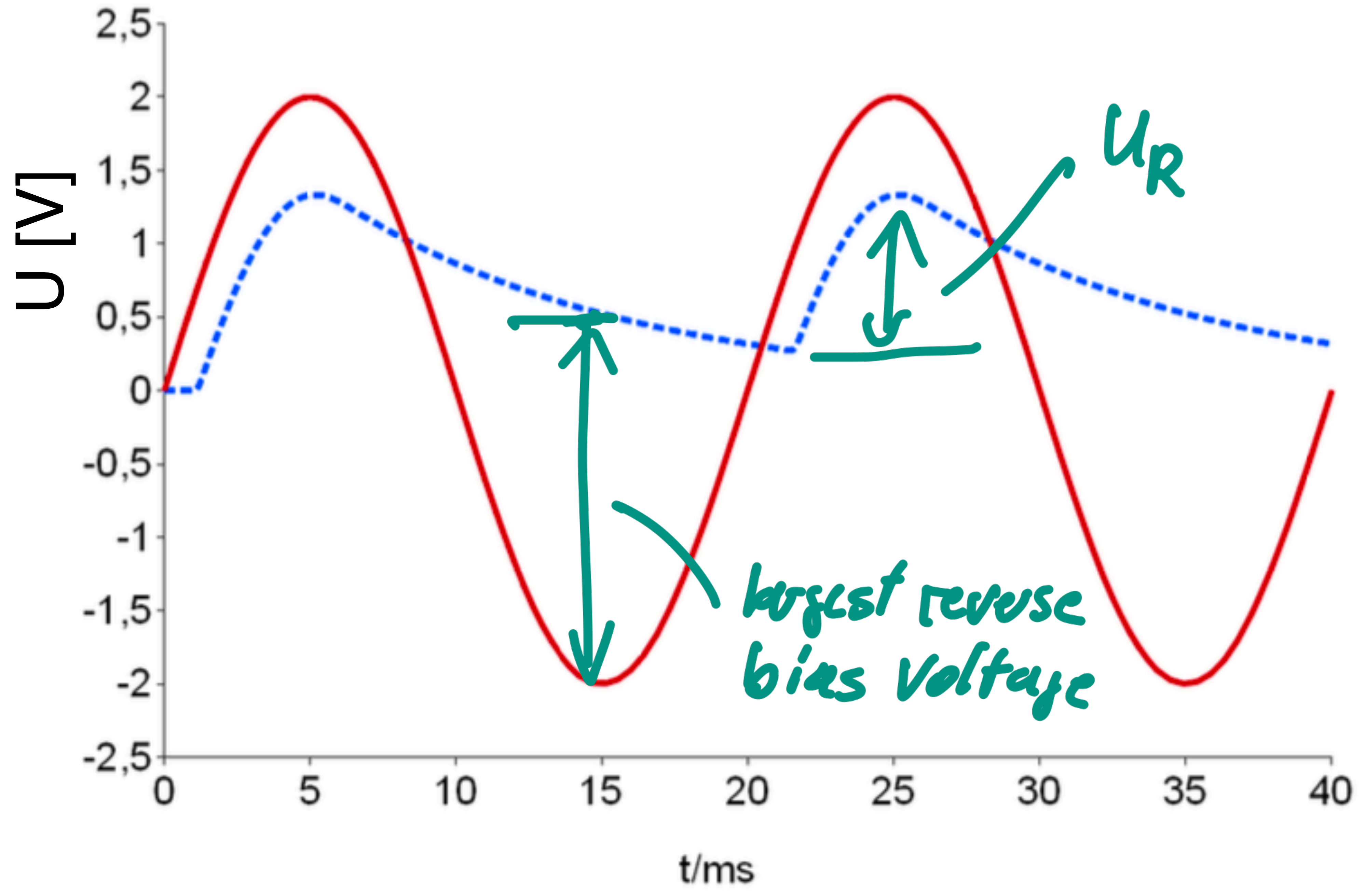
- Capacitor is charged for $U > U_C + U_S$
  NB: large charging current! Limited (only) by R_i
- Below this: Diode in reverse bias, C provides load current

$$U_C = U_0 e^{-\frac{t}{R_L C}} \approx U_0 \left(1 - \frac{t}{R_L C}\right)$$

Diode Circuits: Simple Rectifier

Improvement with a Capacitor





Additional considerations

- Discharging of capacitor for $U_C > U_0 - U_s$

$$U_C = U_0 e^{-\frac{t}{R_L C}} \approx U_0 (1 - \frac{t}{R_L C})$$

=> Works well for $\tau \gg 1/f$

- Ripple: $$U_R = \frac{\Delta Q}{C} = \frac{1}{C}\int I_L dt \approx I_L \frac{T}{C} = I_L \frac{1}{Cf}$$

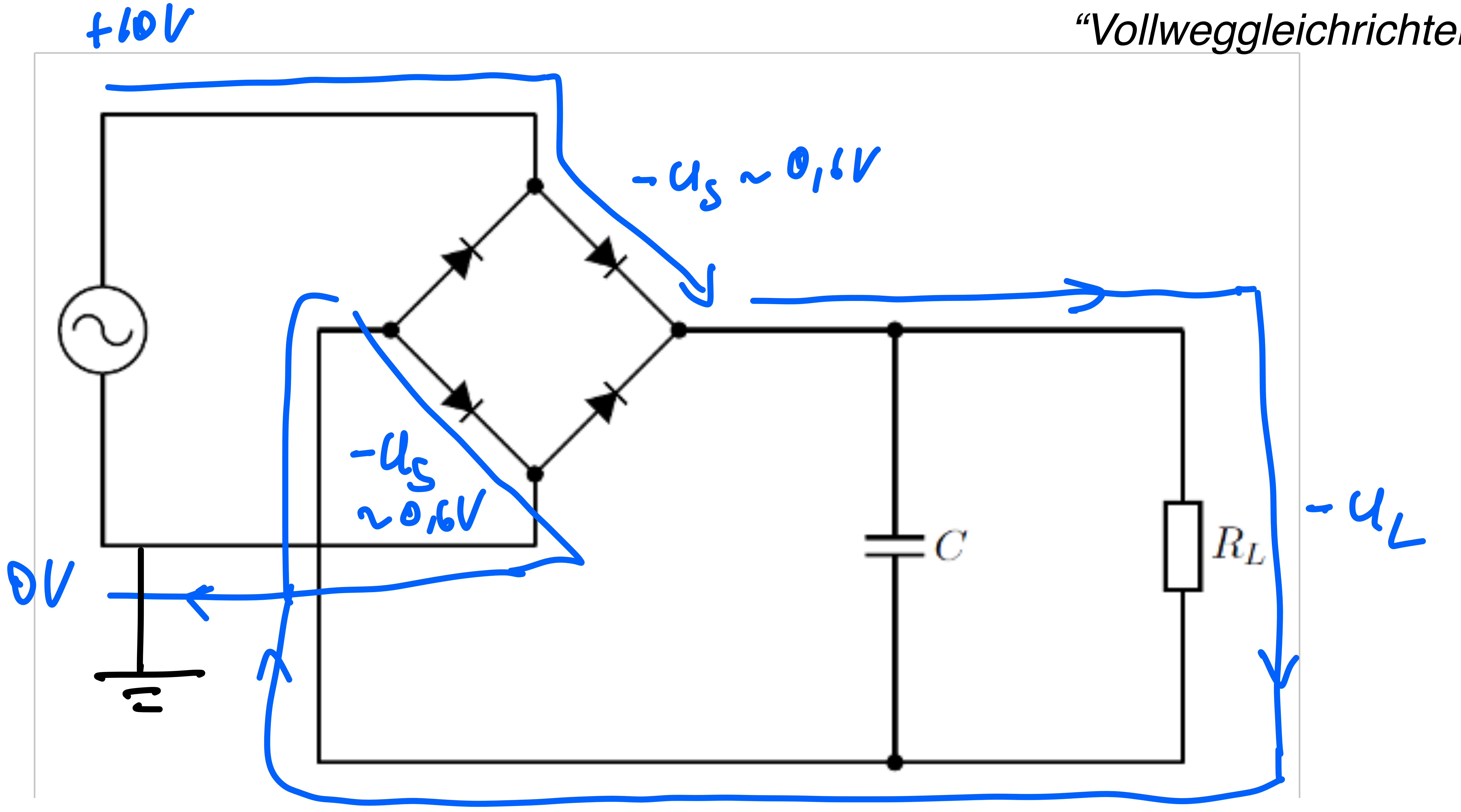
- Requirements for diode: minimum sustainable reverse bias: $2\,U_0 - U_s - U_R/2$

Diode Circuit: Grätz Rectifier

Full Bridge

- Using both positive and negative cycle: “full bridge” instead of “half bridge”

“Vollweggleichrichter” / “Halbweggleichrichter”



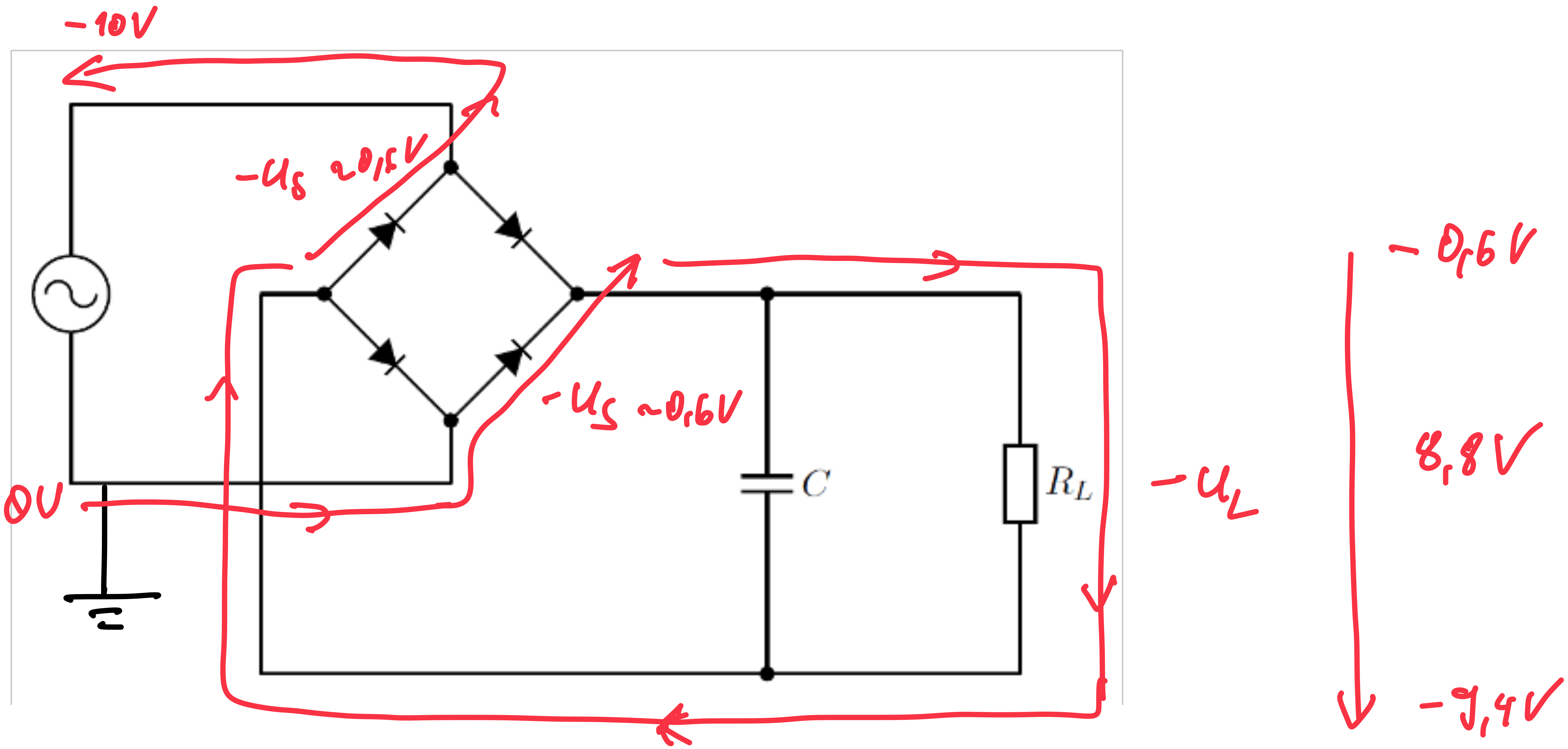
How it works

positive cycle

Diode Circuit: Grätz Rectifier

Full Bridge

- Using both positive and negative cycle: “full bridge” instead of “half bridge”



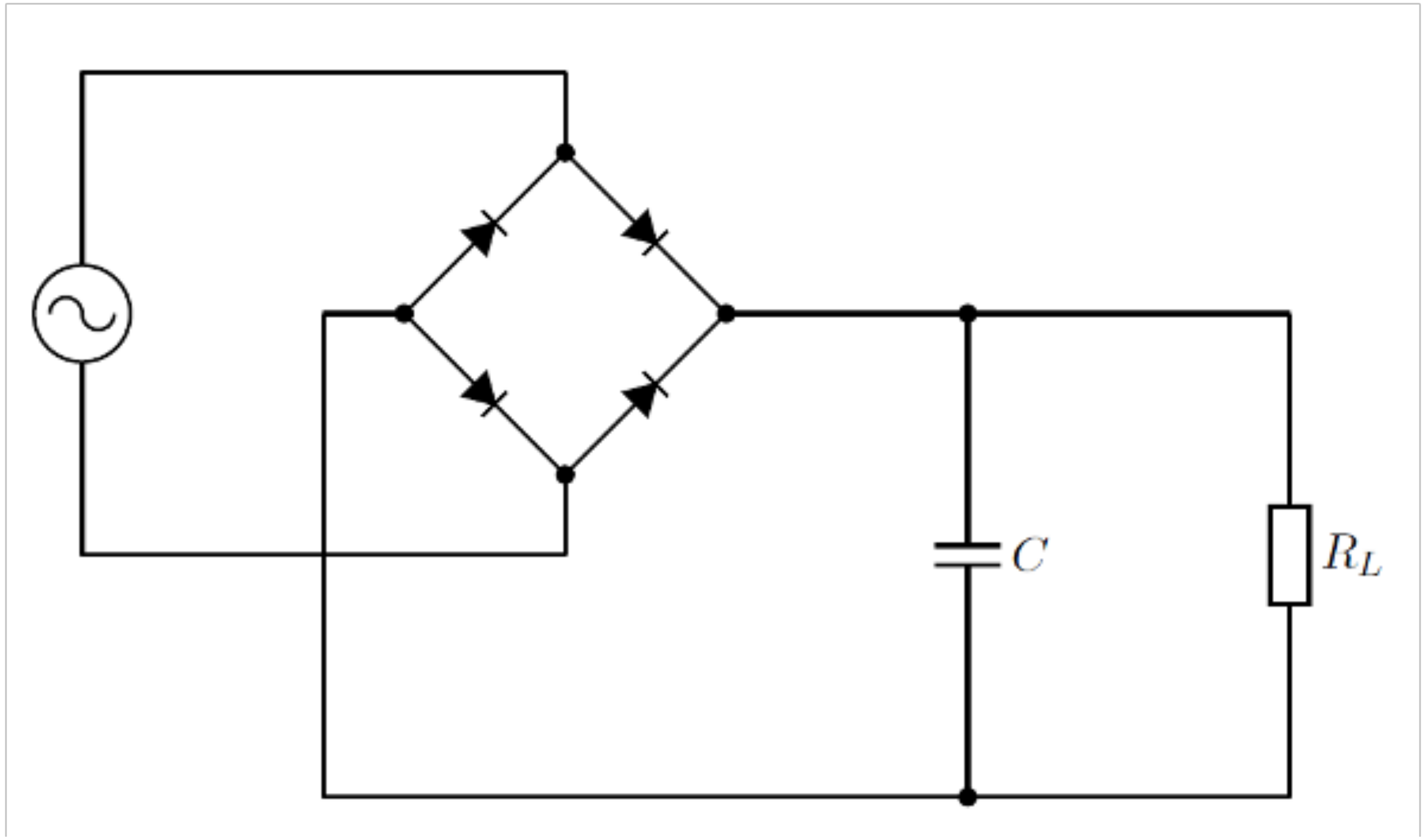
How it works

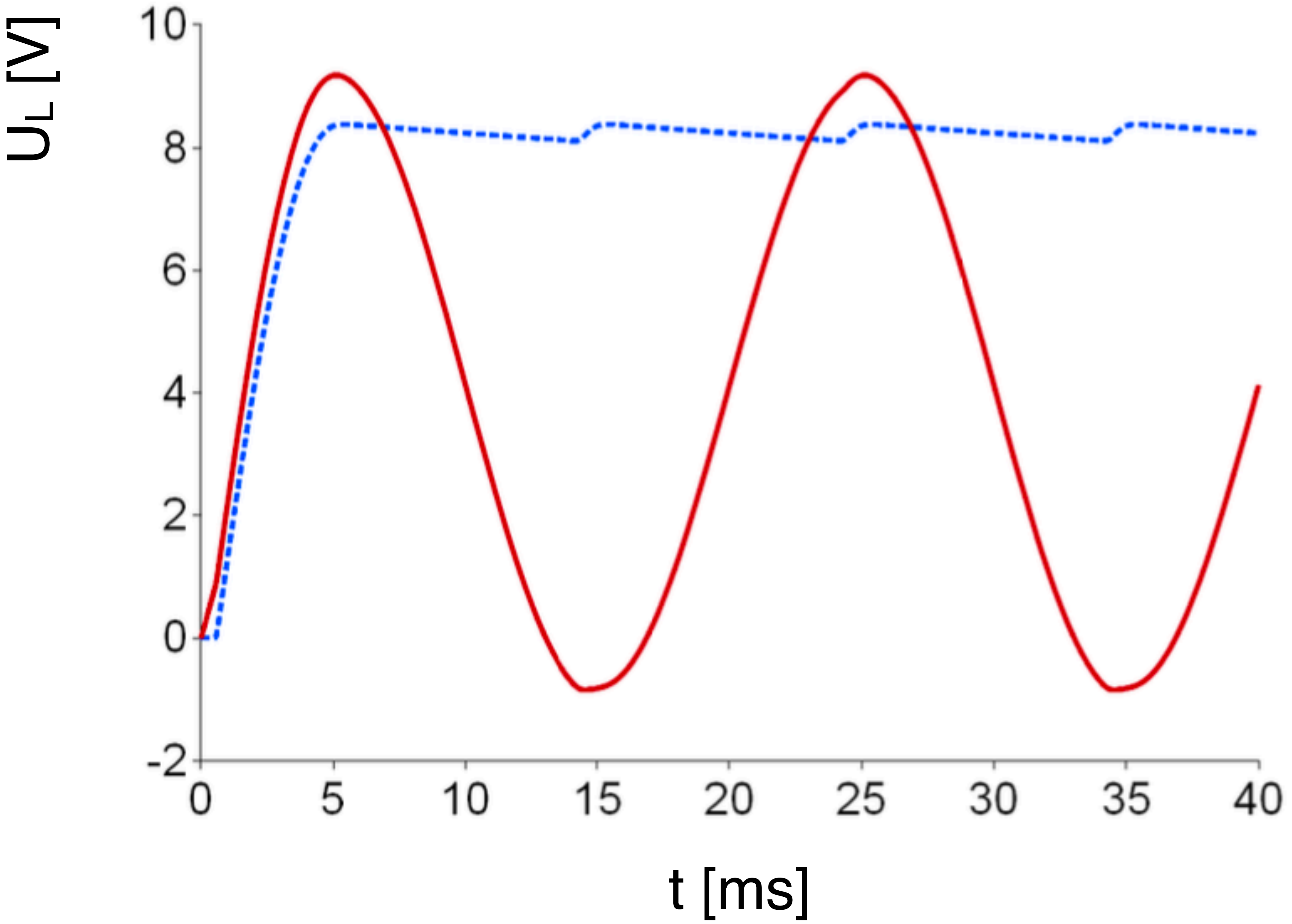
positive cycle

Diode Circuit: Grätz Rectifier

Result

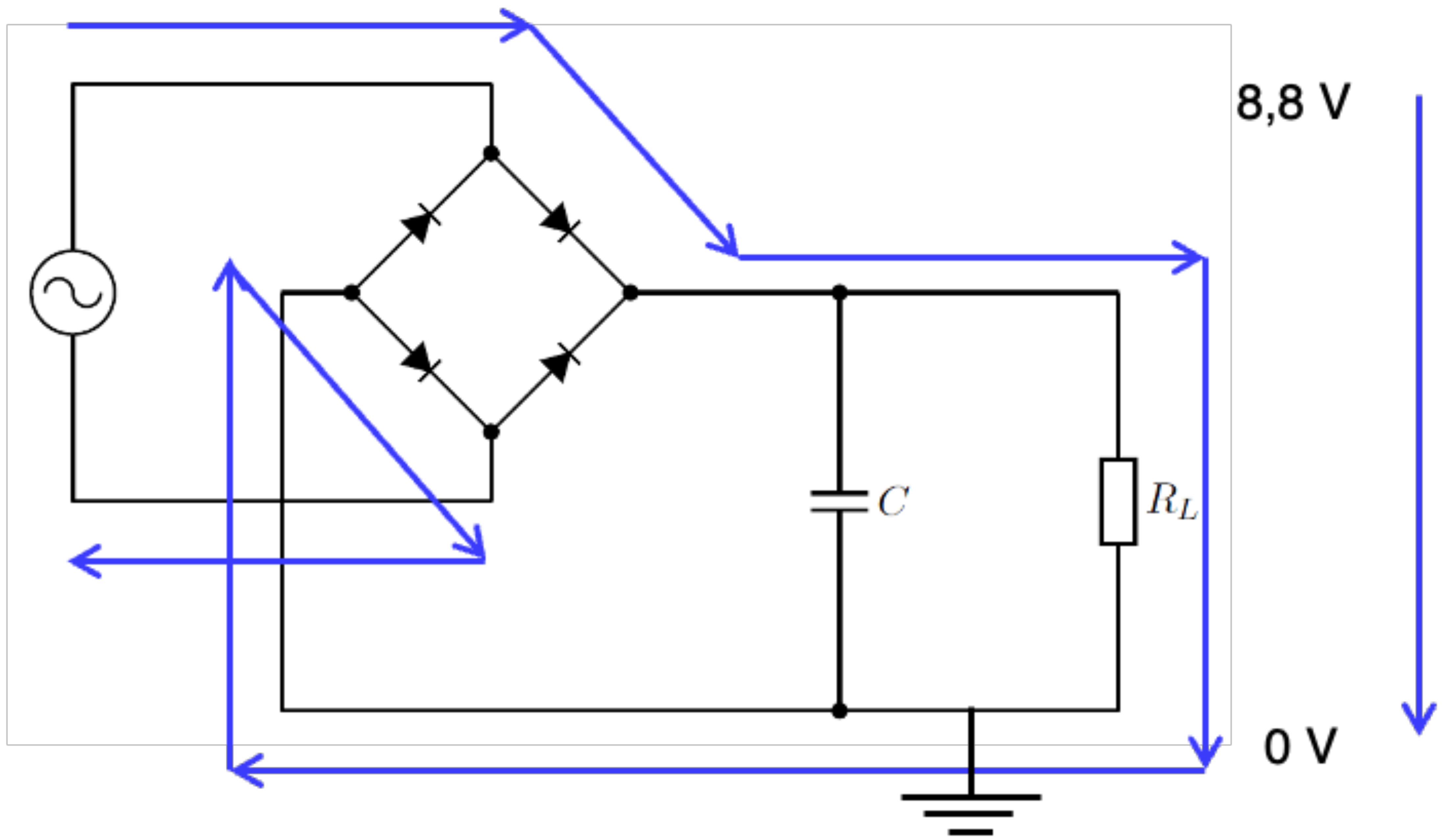
- Using both positive and negative cycle: “full bridge” instead of “half bridge”

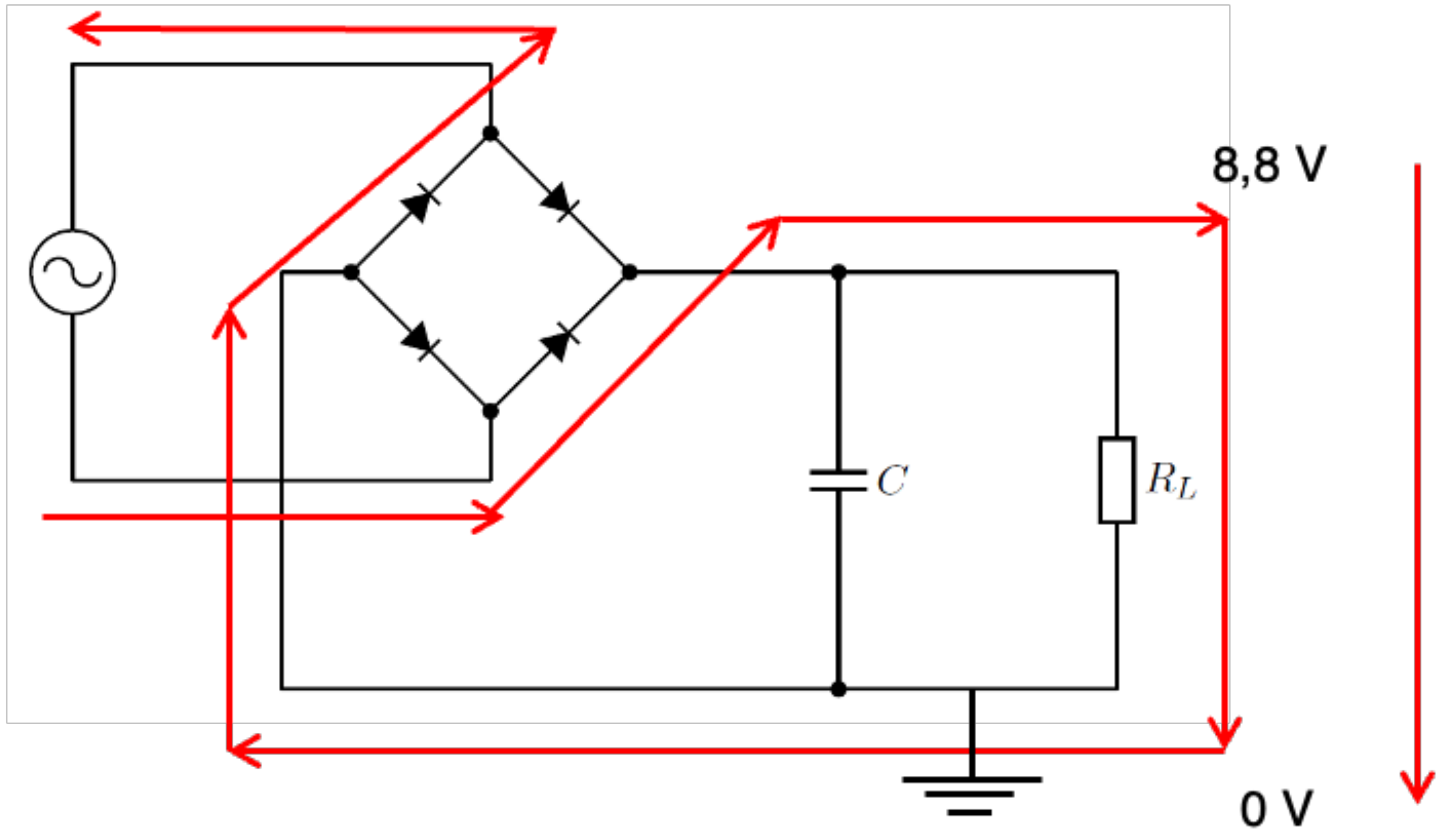




Diode Circuit: Grätz Rectifier

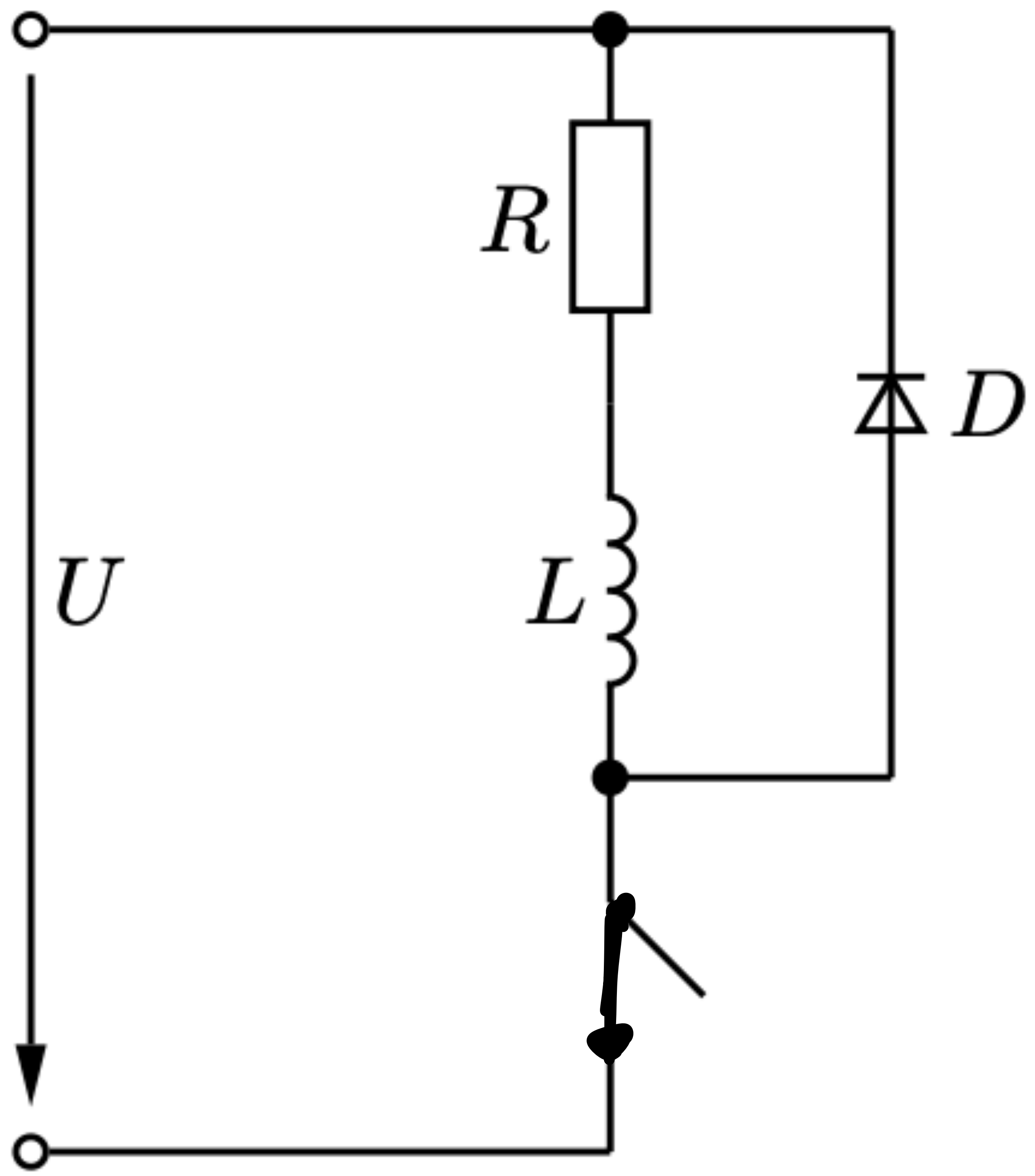
With "floating" voltage source

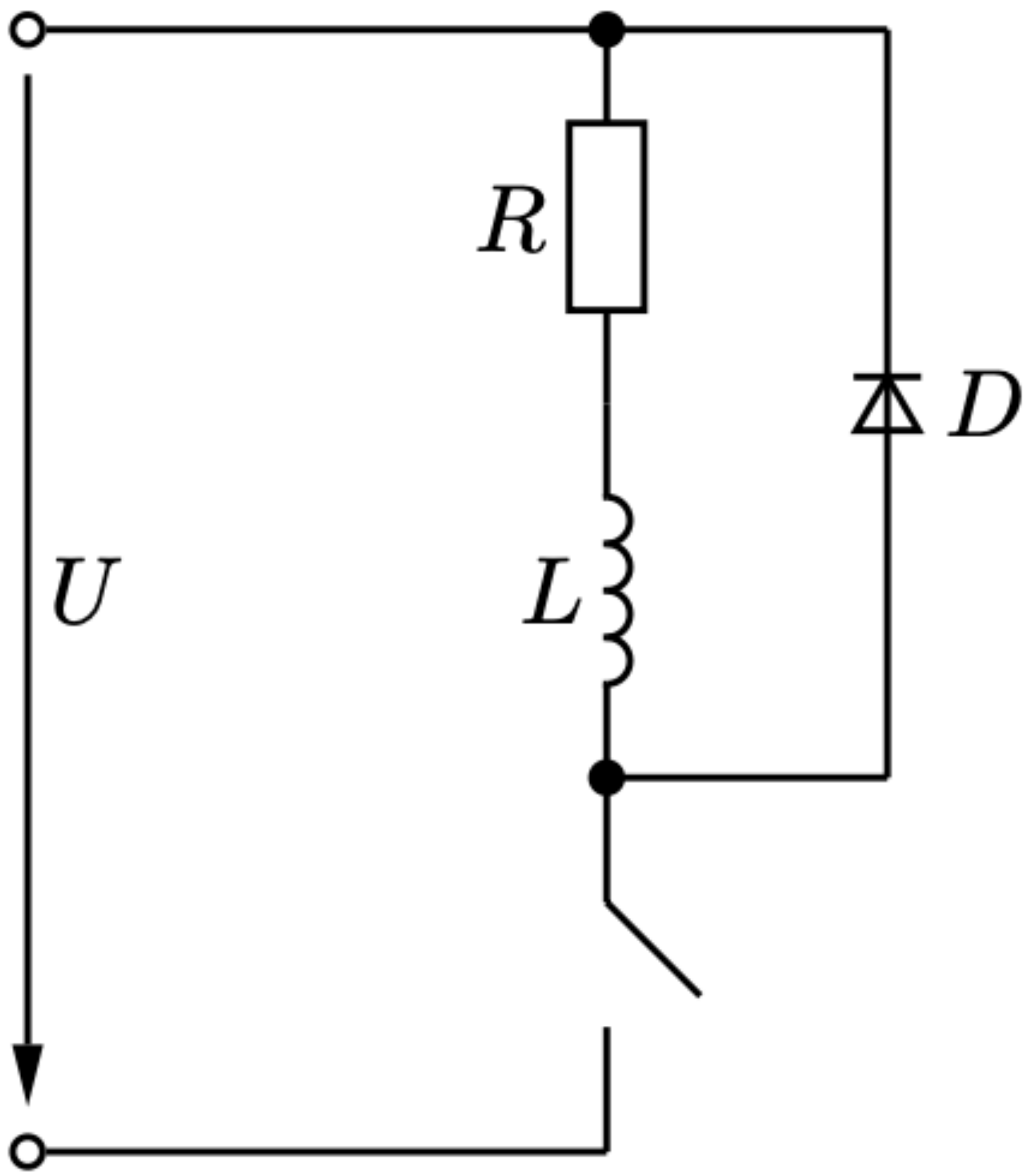




Protection Circuits with Diodes

Schutzschaltungen



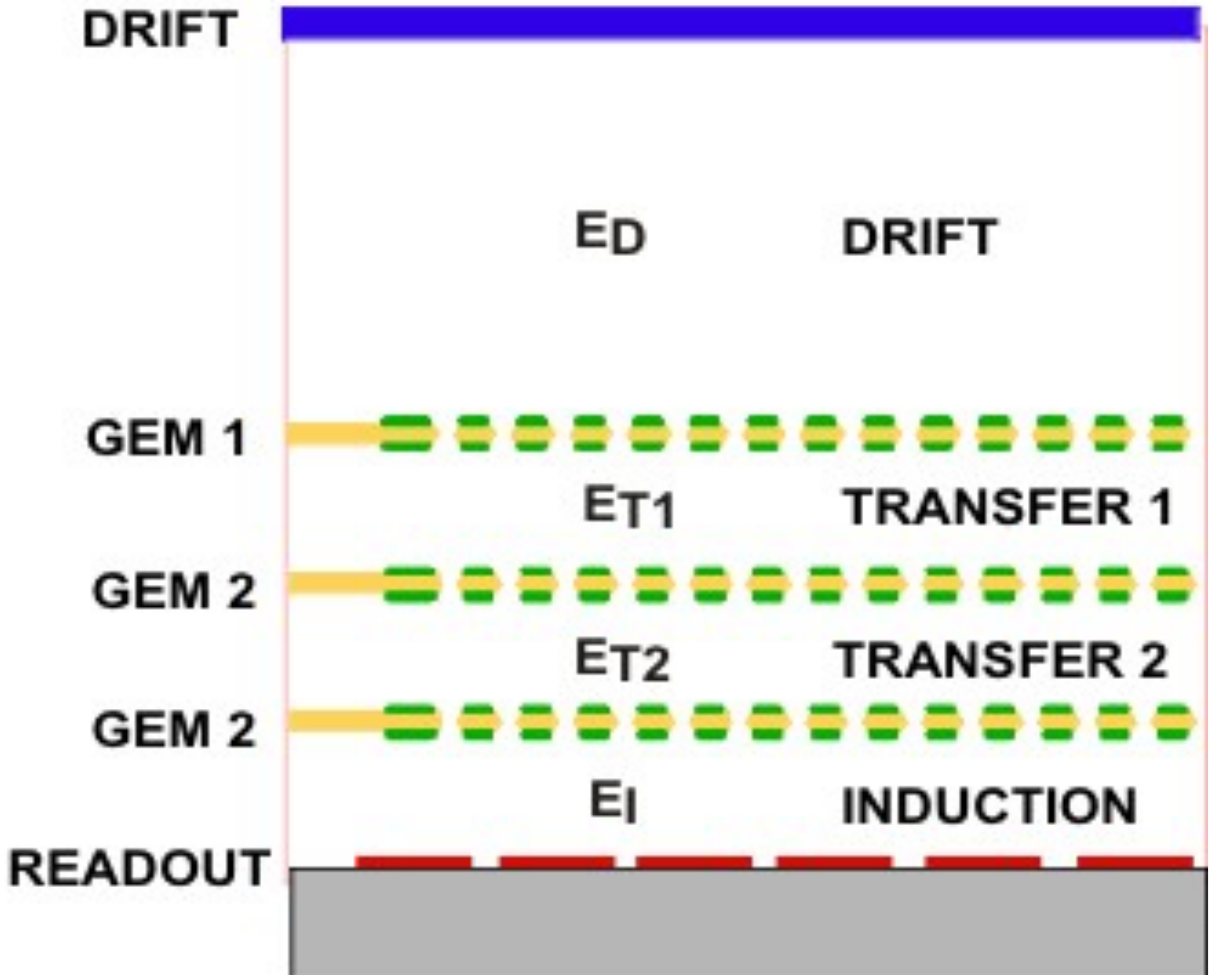


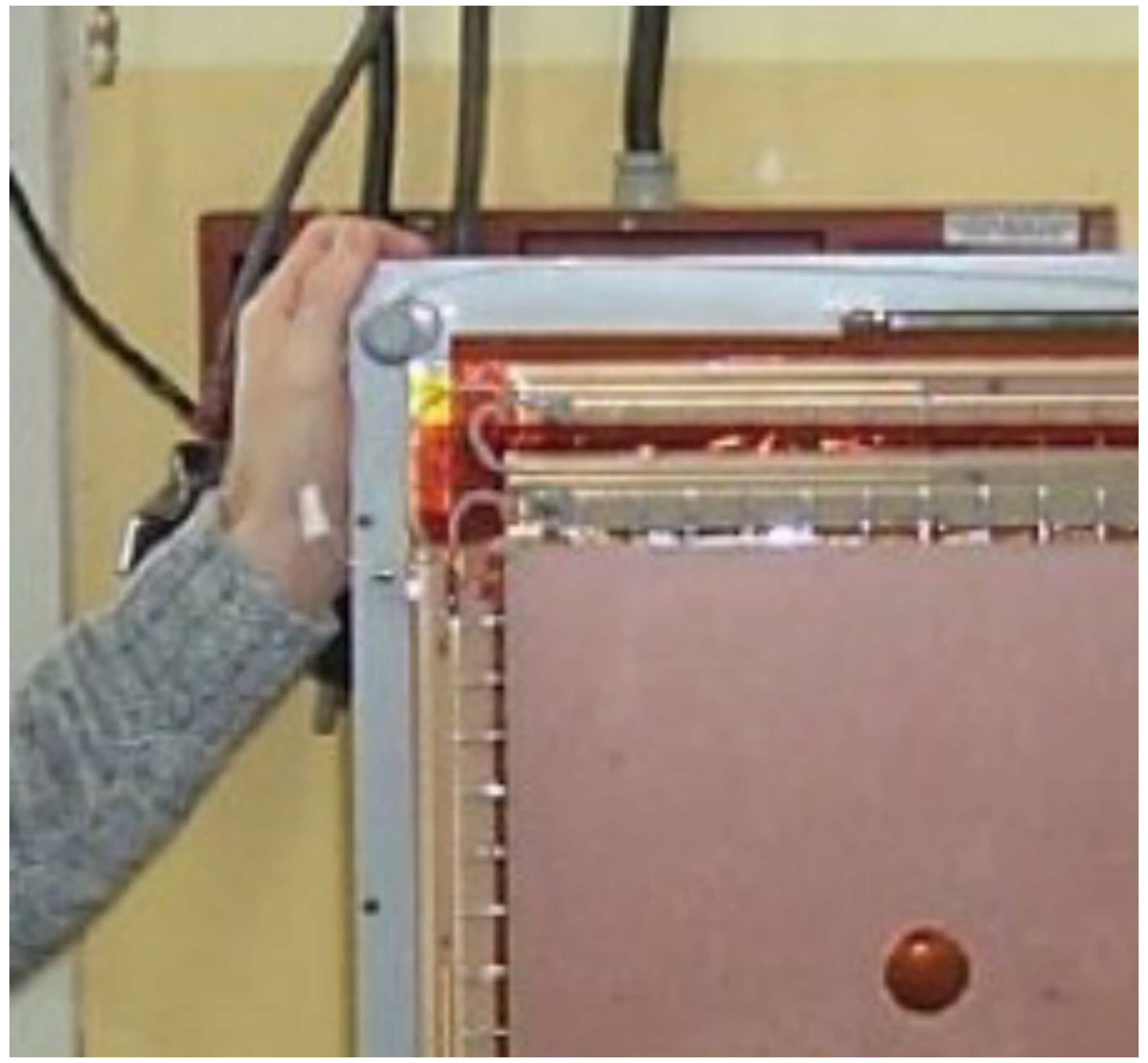
Closed switch:
Diode in reverse bias,
no current through diode, $U_L = 0V$

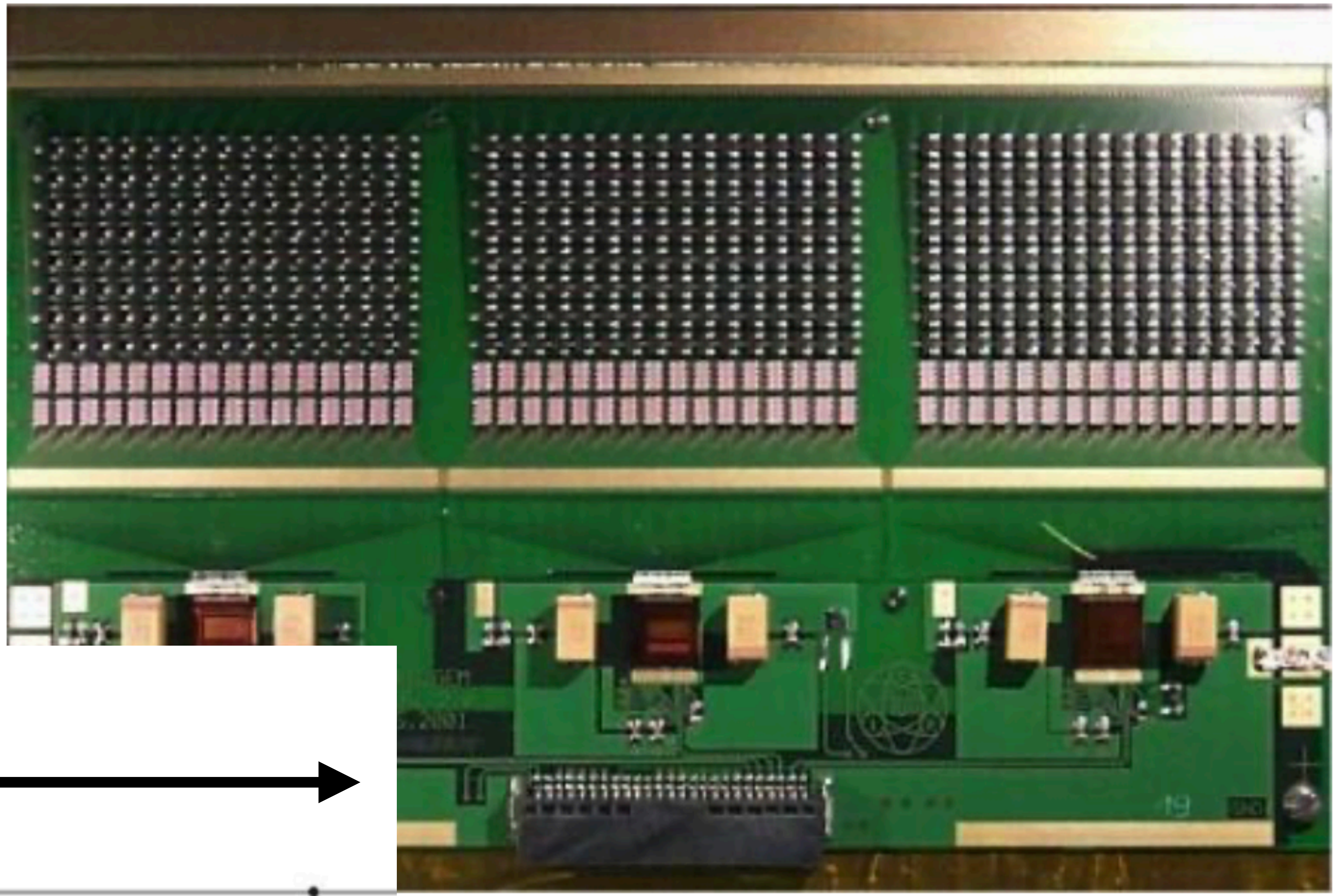
Open switch:
U_L rises strongly ($U_L = L\, dI/dt$),
positive potential at the switch
diode limits U_L to ~ 0.7 V

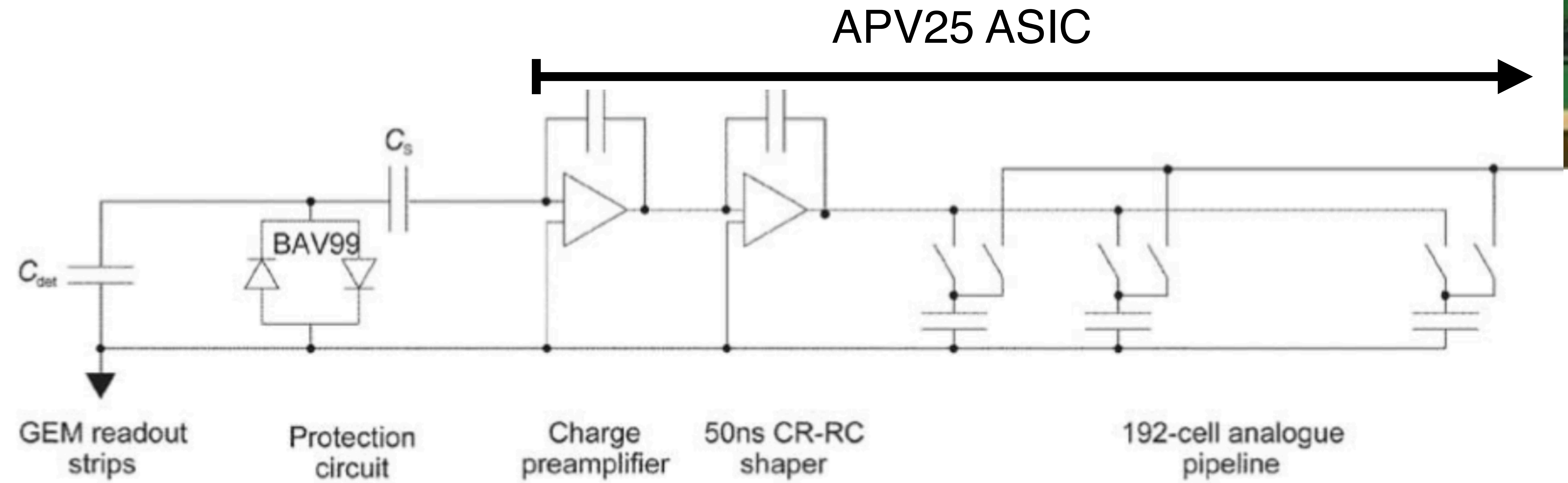
Protection Circuit with Diodes

Example: COMPASS GEM Detectors





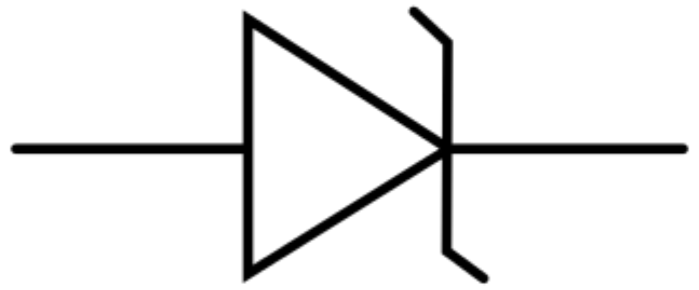




Zener Diodes

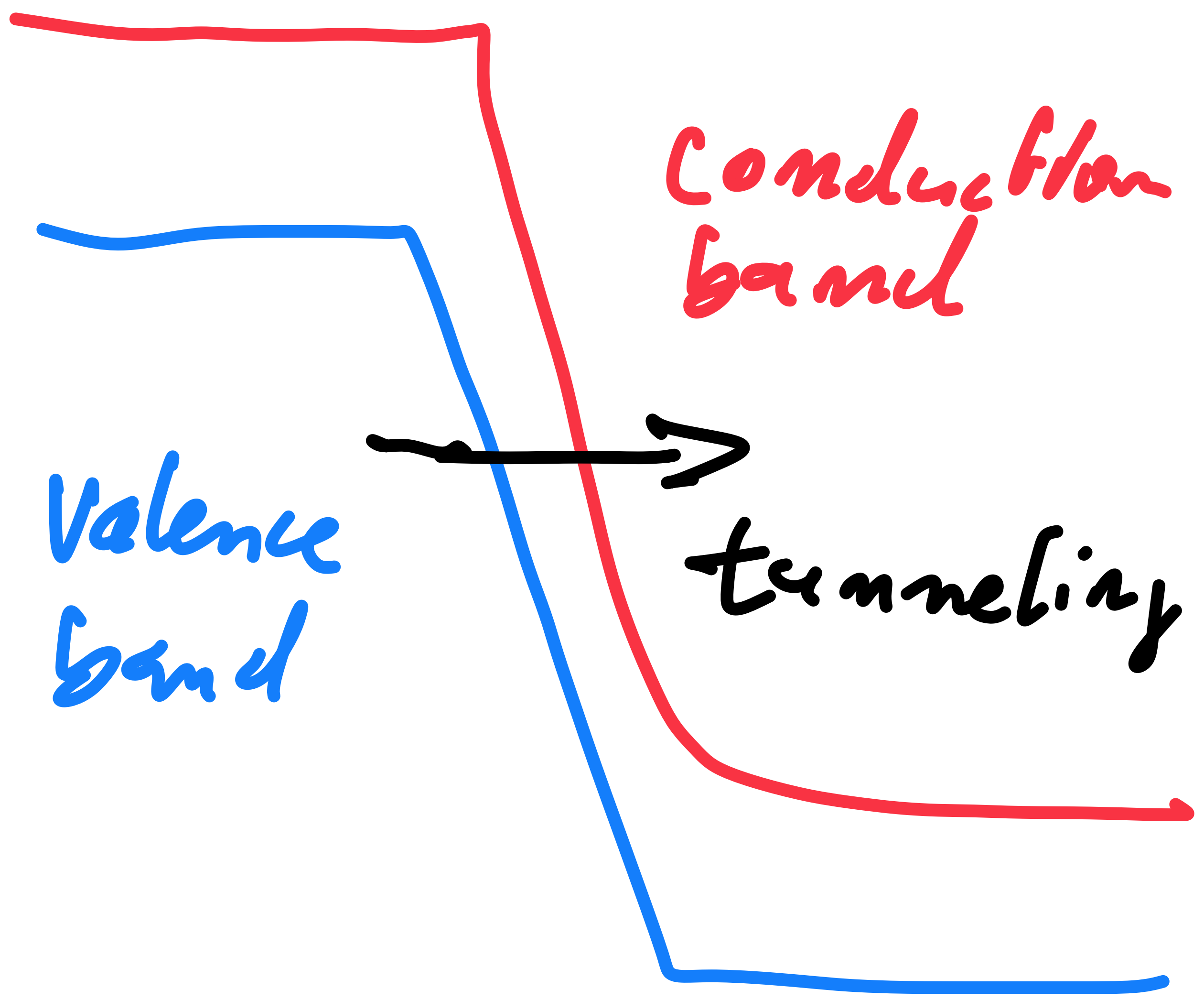
Zener-Dioden

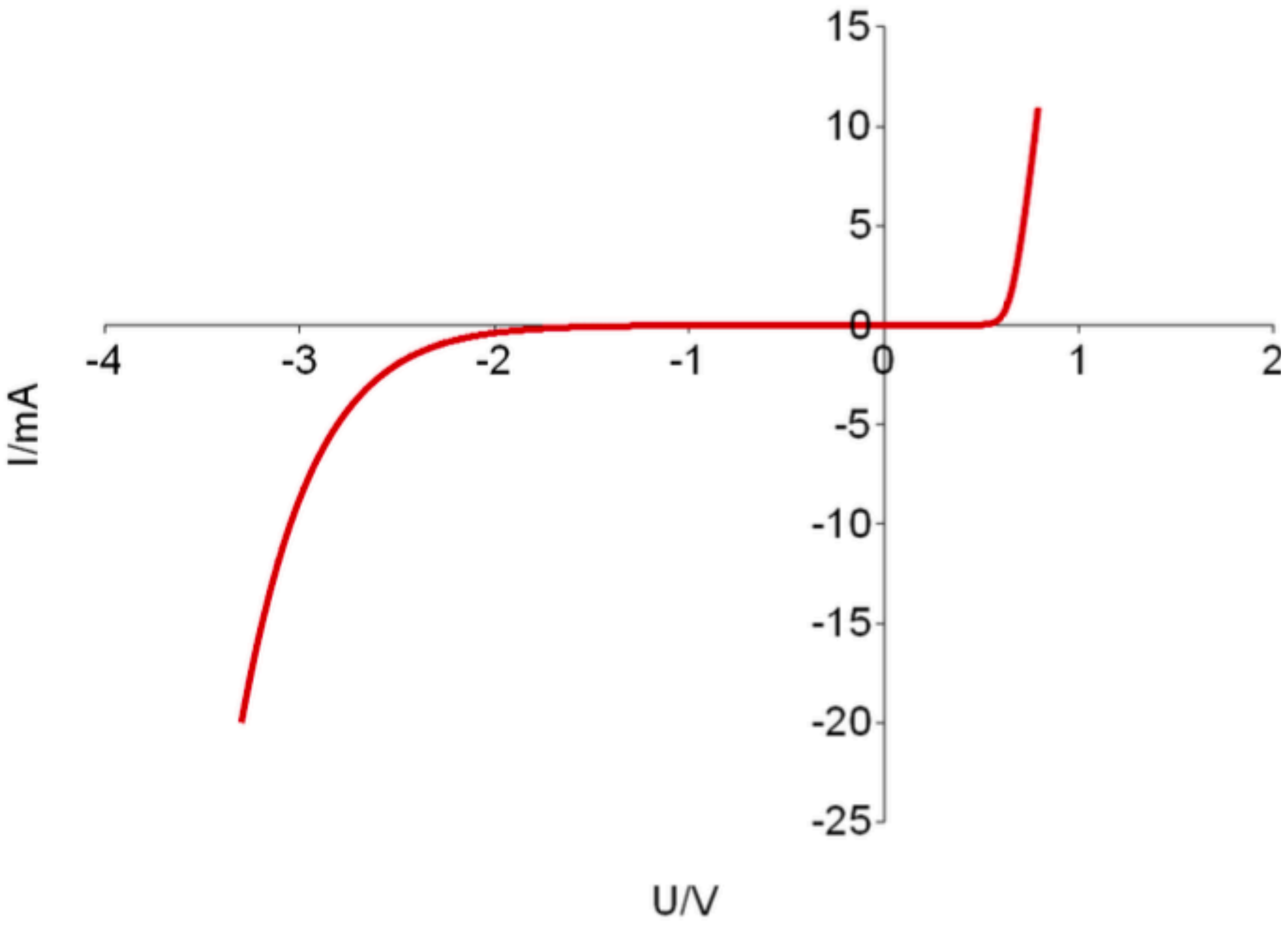
- Special type of diodes: Allows reverse current above a particular voltage (“Zener voltage”) without damaging the diode.

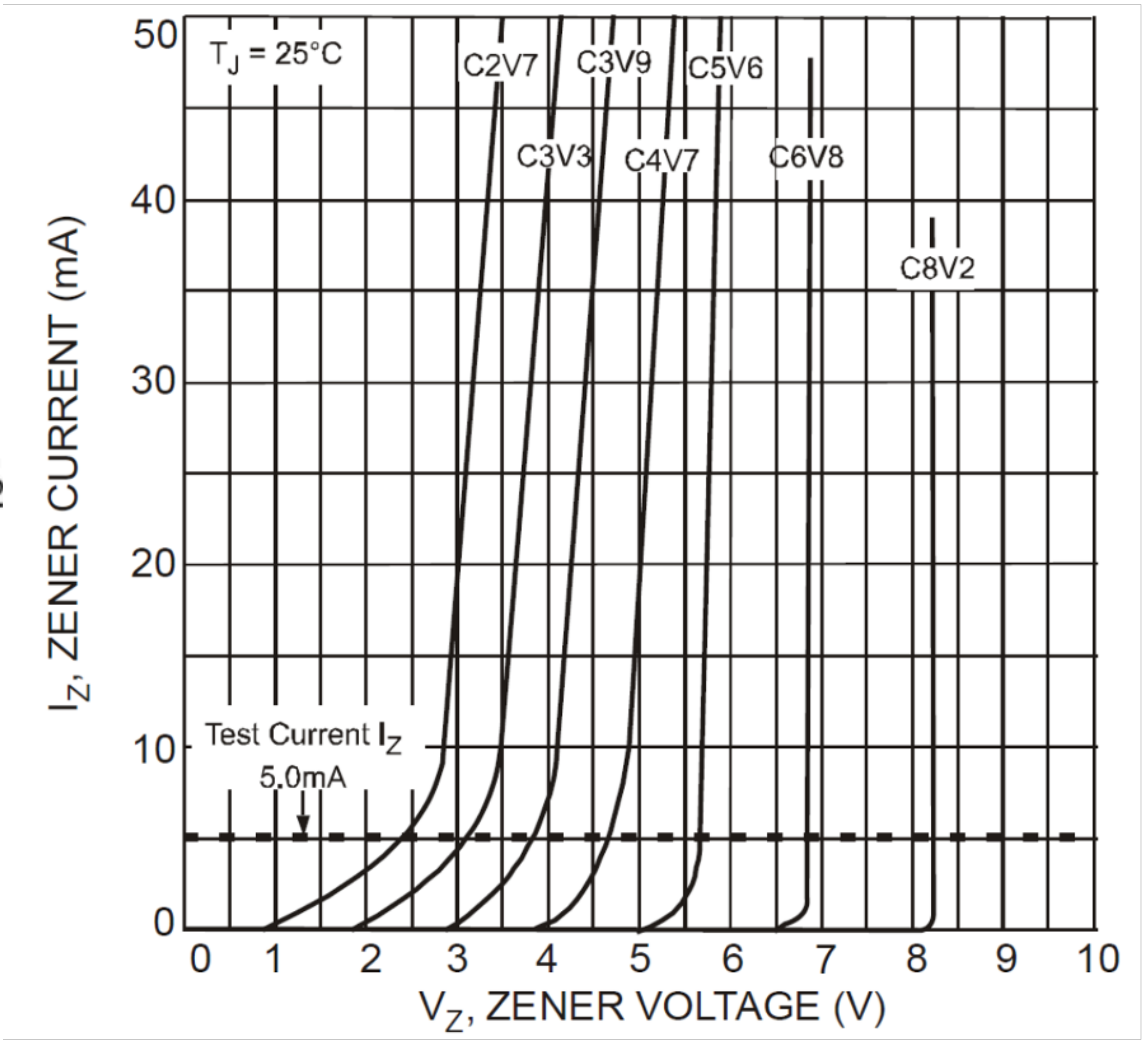


Mechanism: Zener effect - tunneling of electrons at the pn junction from valence to conduction band

for higher voltages: In addition an avalanche breakdown - per design also possible continuously.



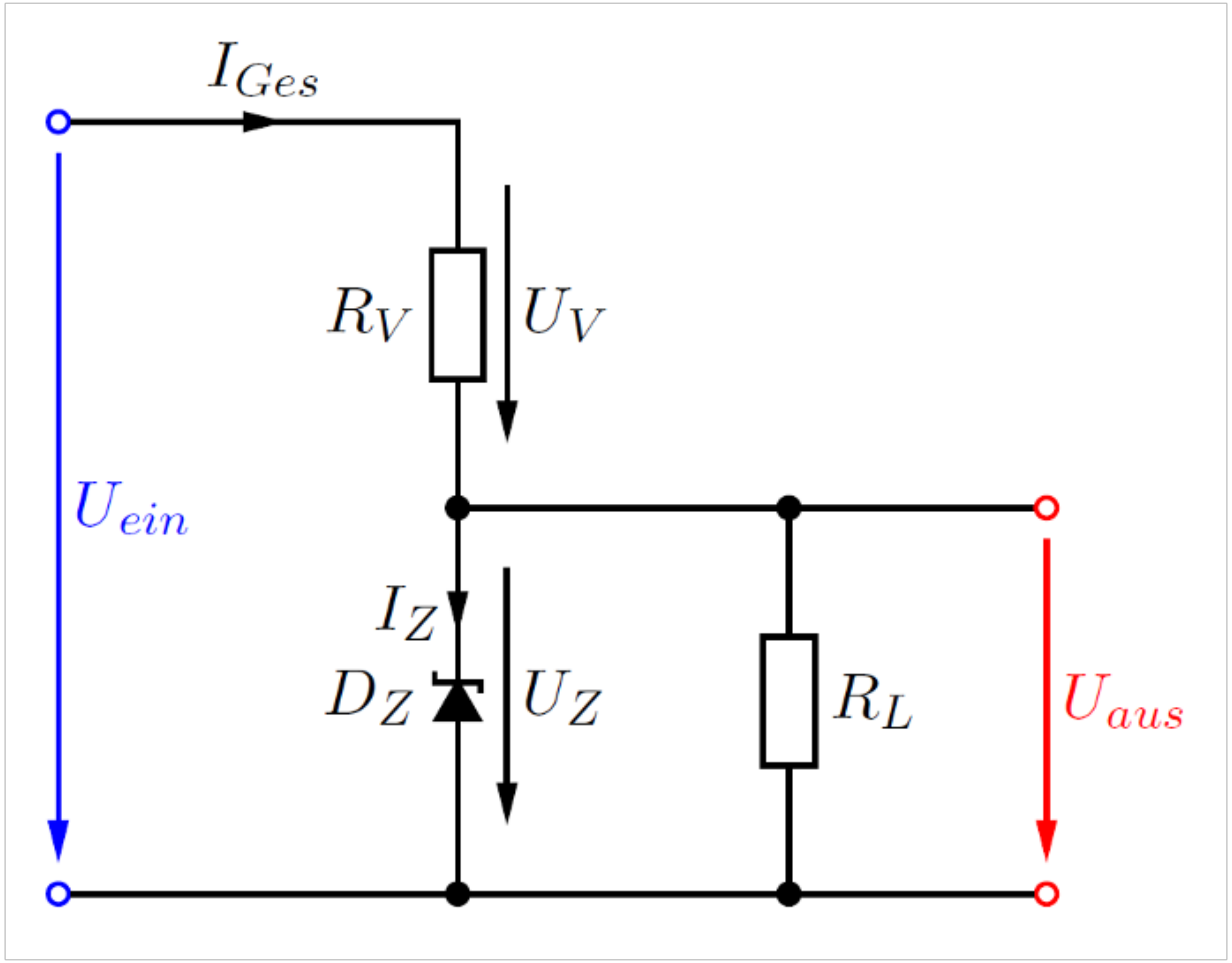




Circuits with Zener dioden

Voltage Stabilization

- Voltage stabilization



For sufficiently high voltage U_{ein}:

$U_{aus} = U_Z$; independen of U_{ein}.

Remains stable also for fluctuating load currents due to the very steep IV curve: und U_Z (almost) independent on I_L.

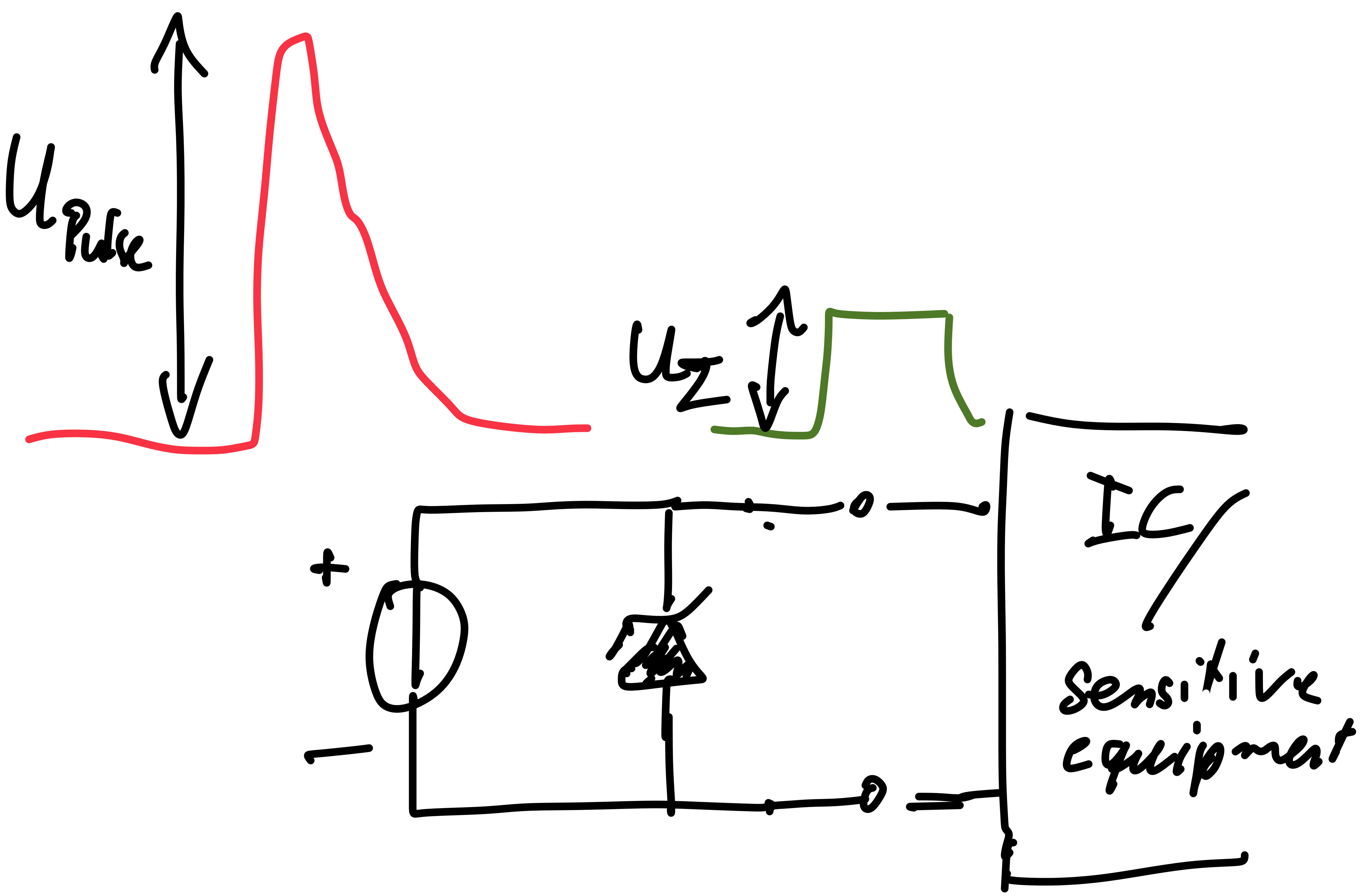
$$\frac{dU_{aus}}{dU_{ein}} = \frac{R_Z \parallel R_L}{(R_Z \parallel R_L) + R_V} \approx \frac{R_Z}{R_V}$$

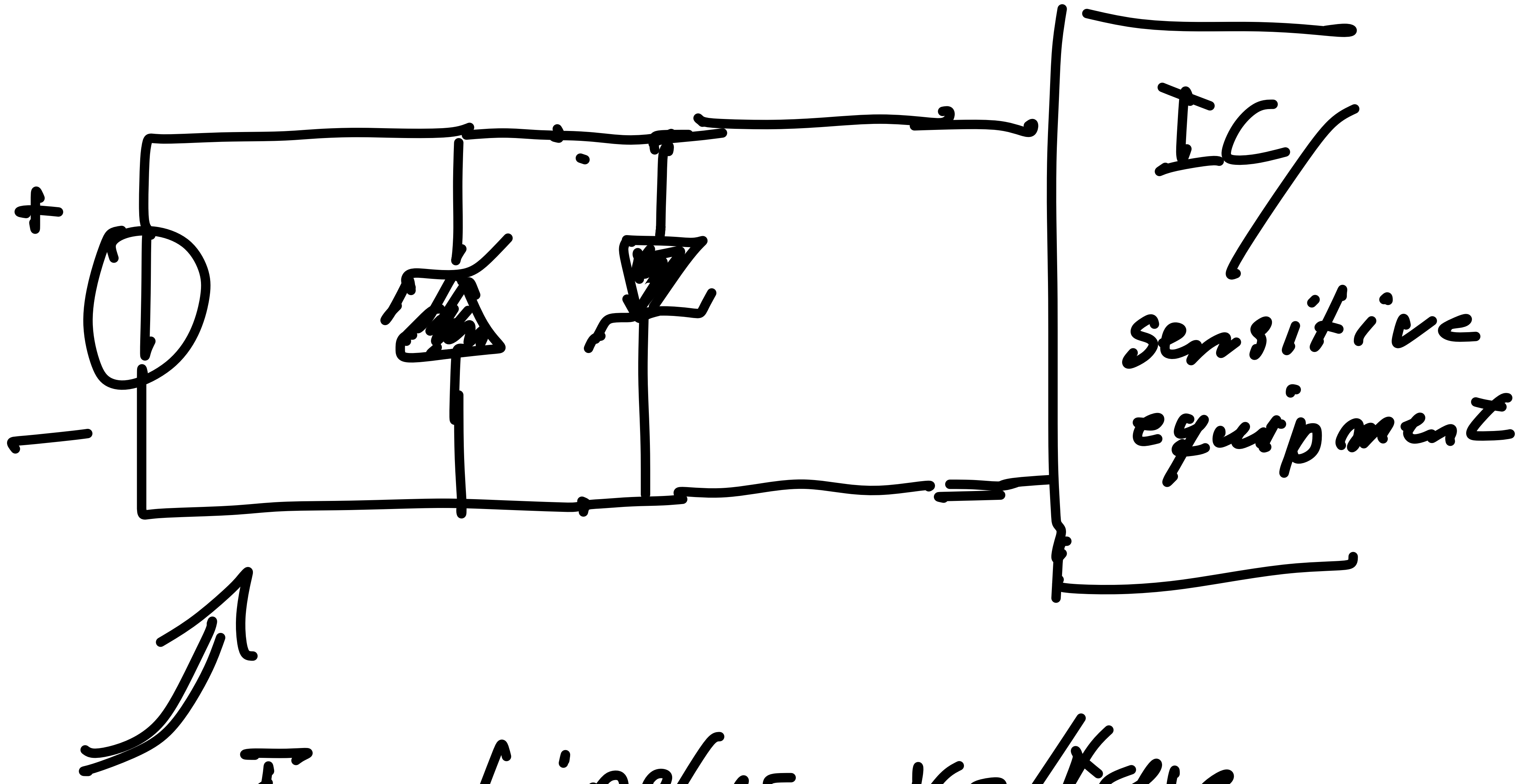
(good approximation: $R_Z << R_L$)

Circuits with Zener Diodes

Protection Circuits

- Protection circuit



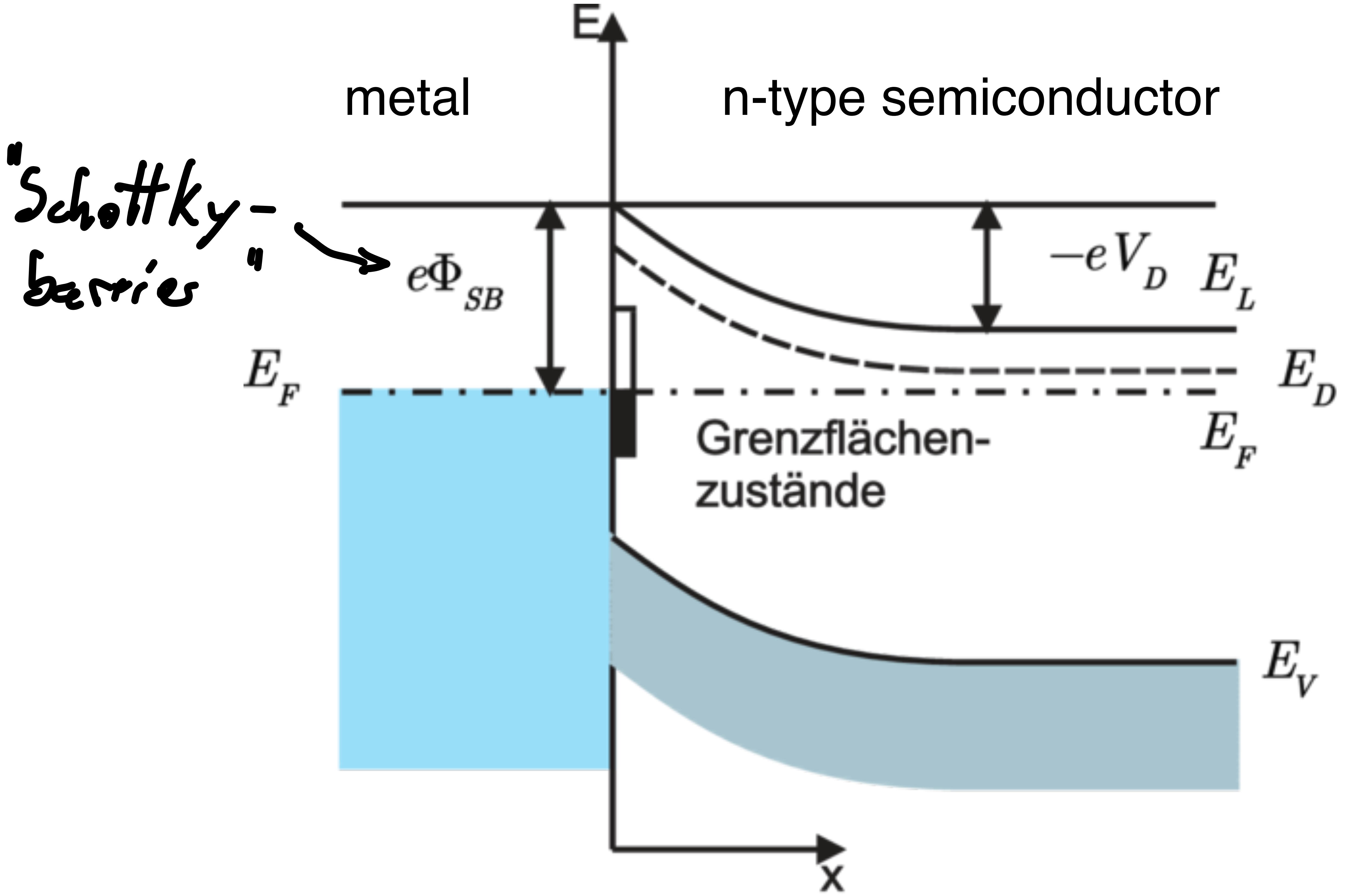


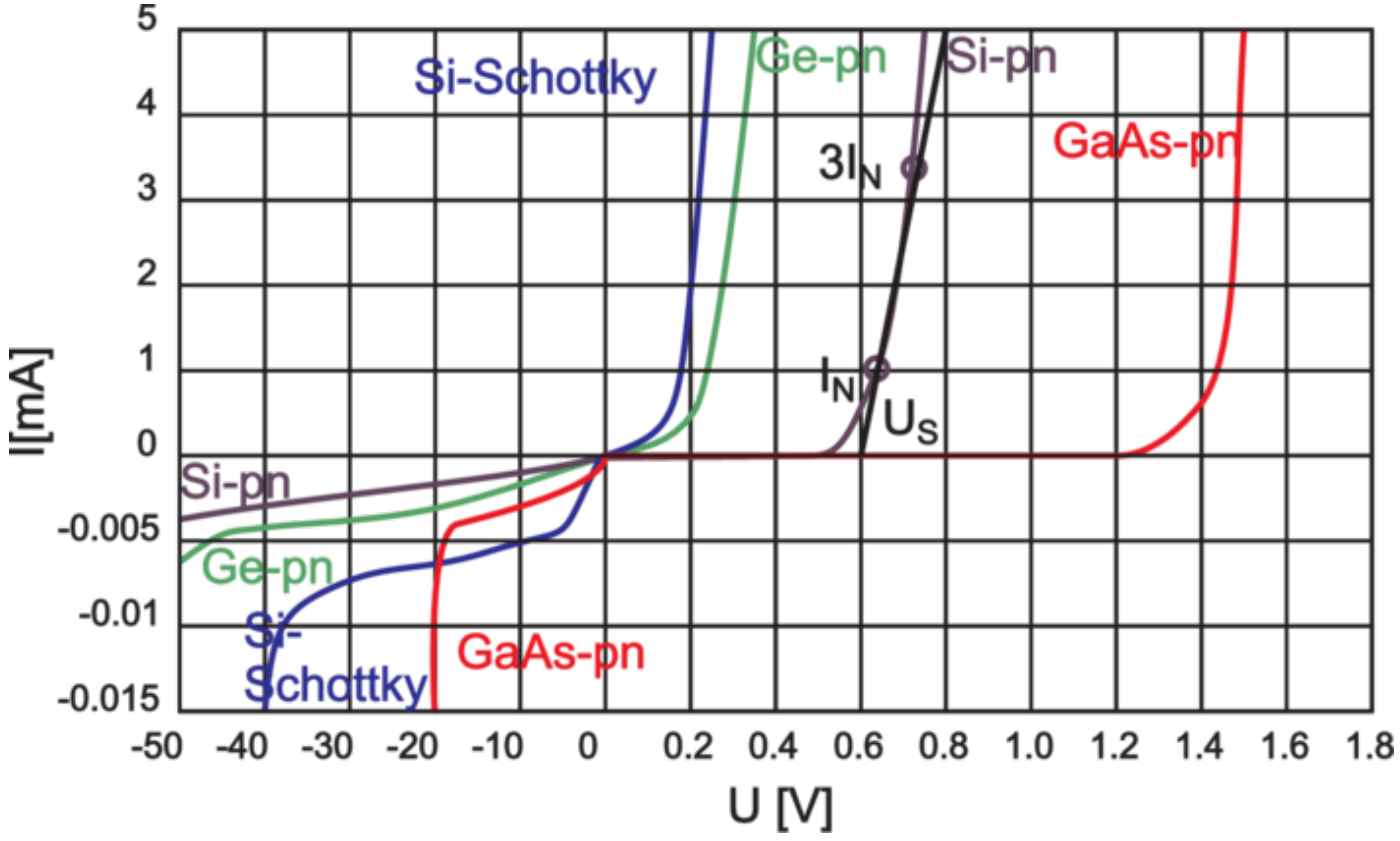
For bipolar voltage peaks.

Schottky Diodes

Another Example

- Metal-semiconductor transition: Metal-n instead of pn for “classical” diodes



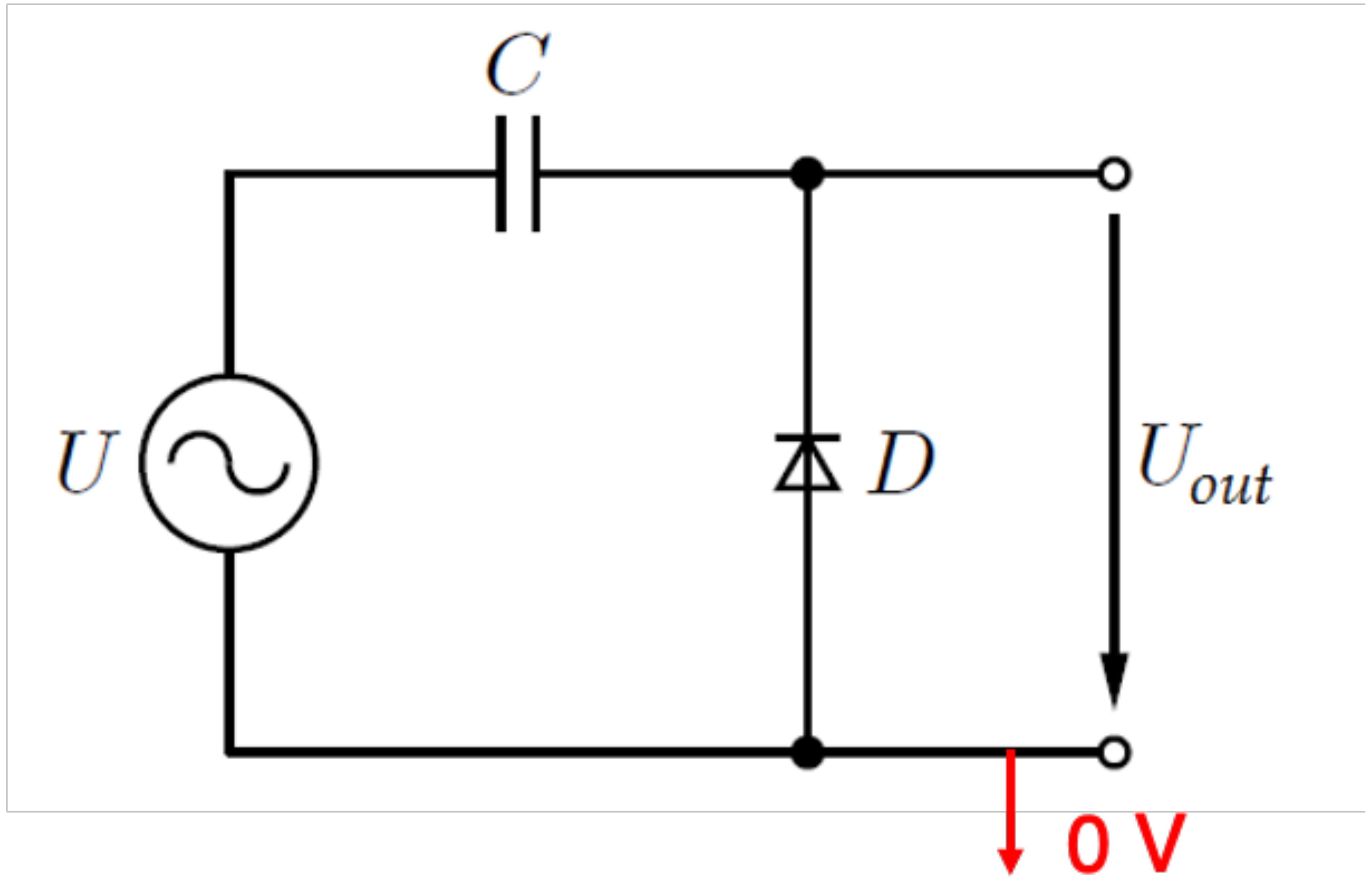


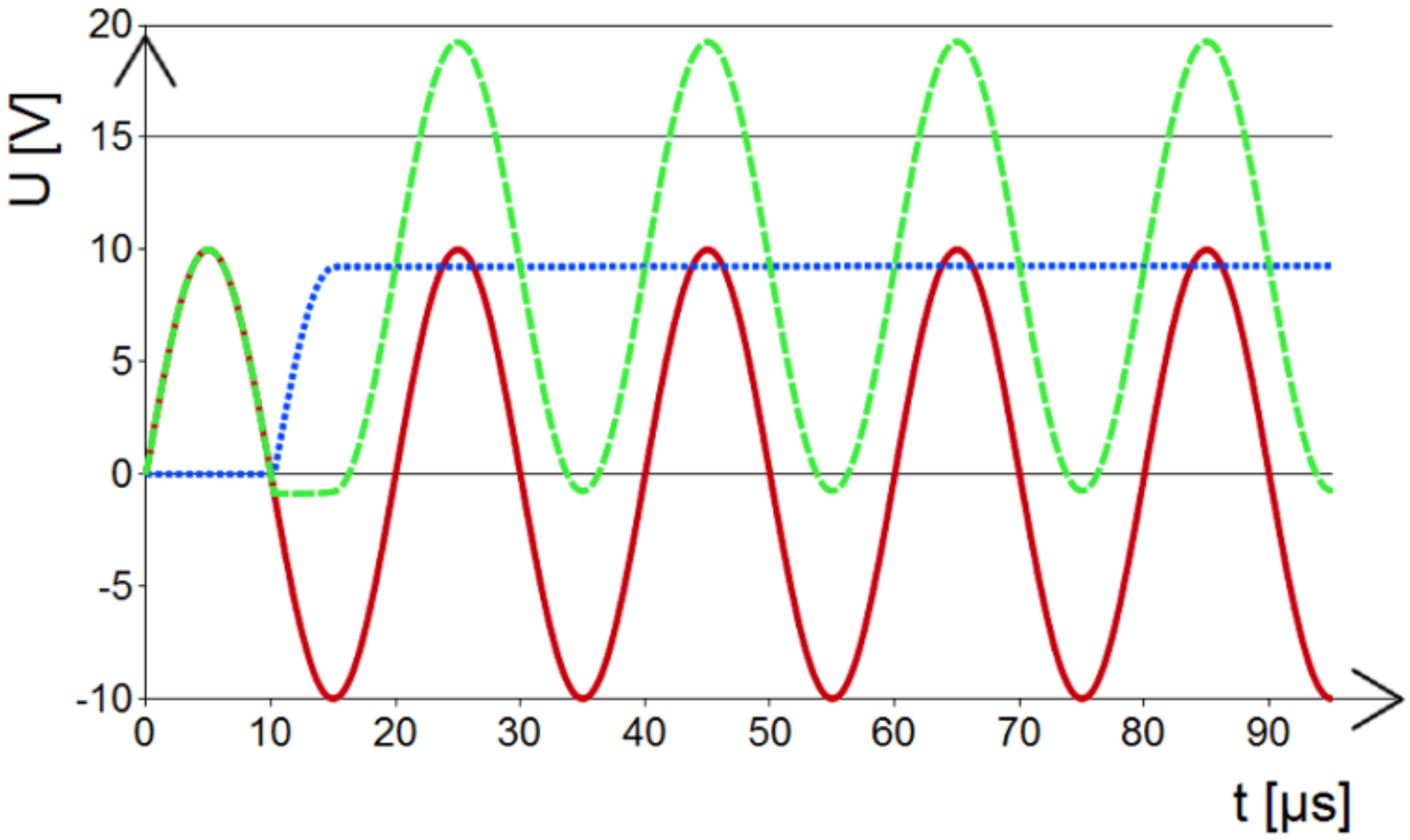
by Othmar Marti, Uni Ulm

very fast (up to several 10 GHz), small threshold voltage, but higher leakage current

Voltage Doubler

Villard Circuit



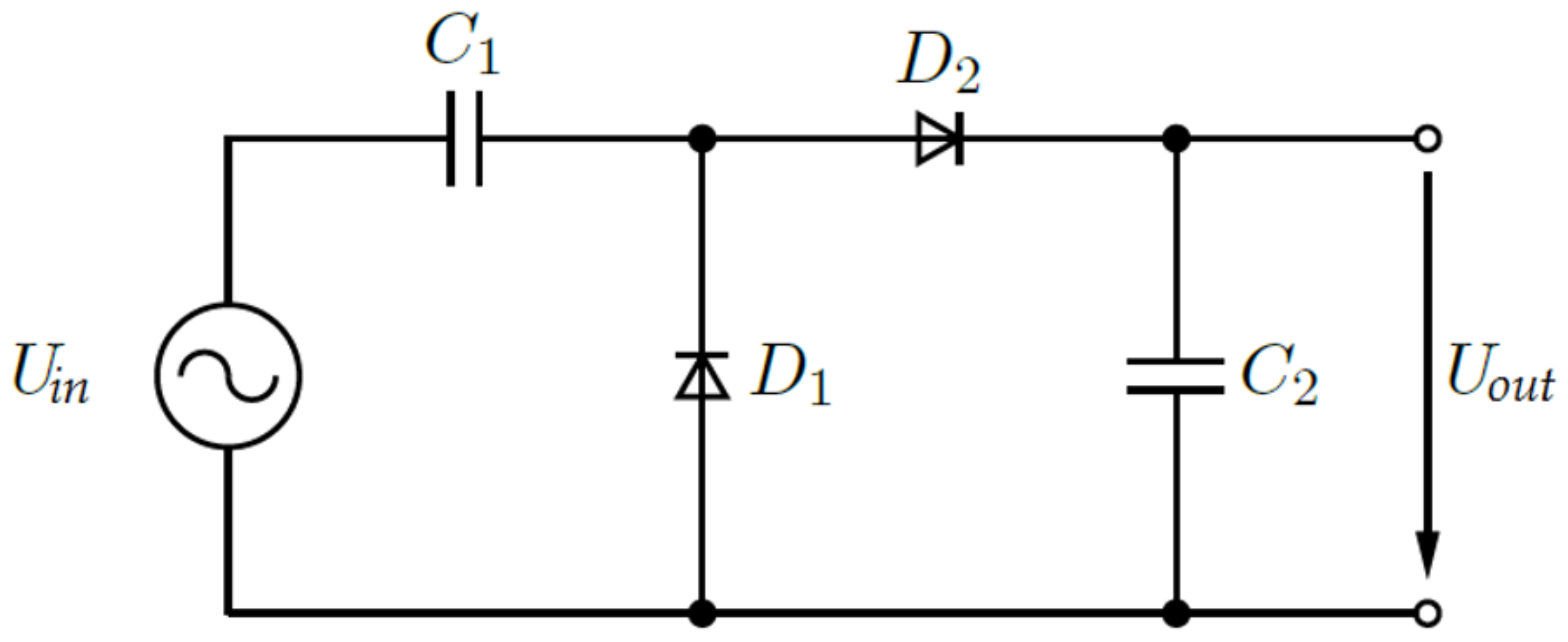


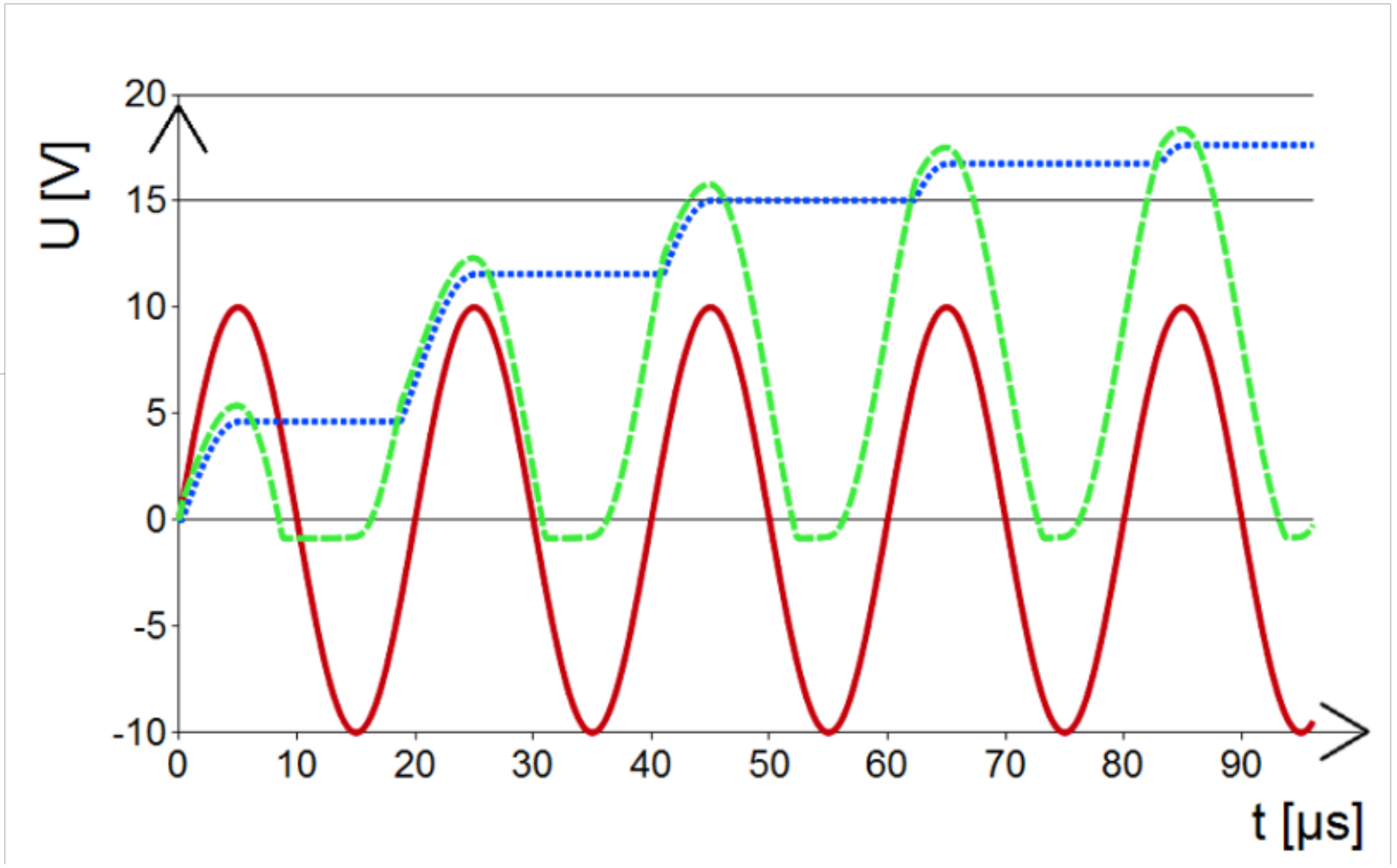
Diode and capacitor switches with respect to rectifier.

How does this circuit work?

Greinacher Circuit

- The combination of a voltage doubler and rectifier

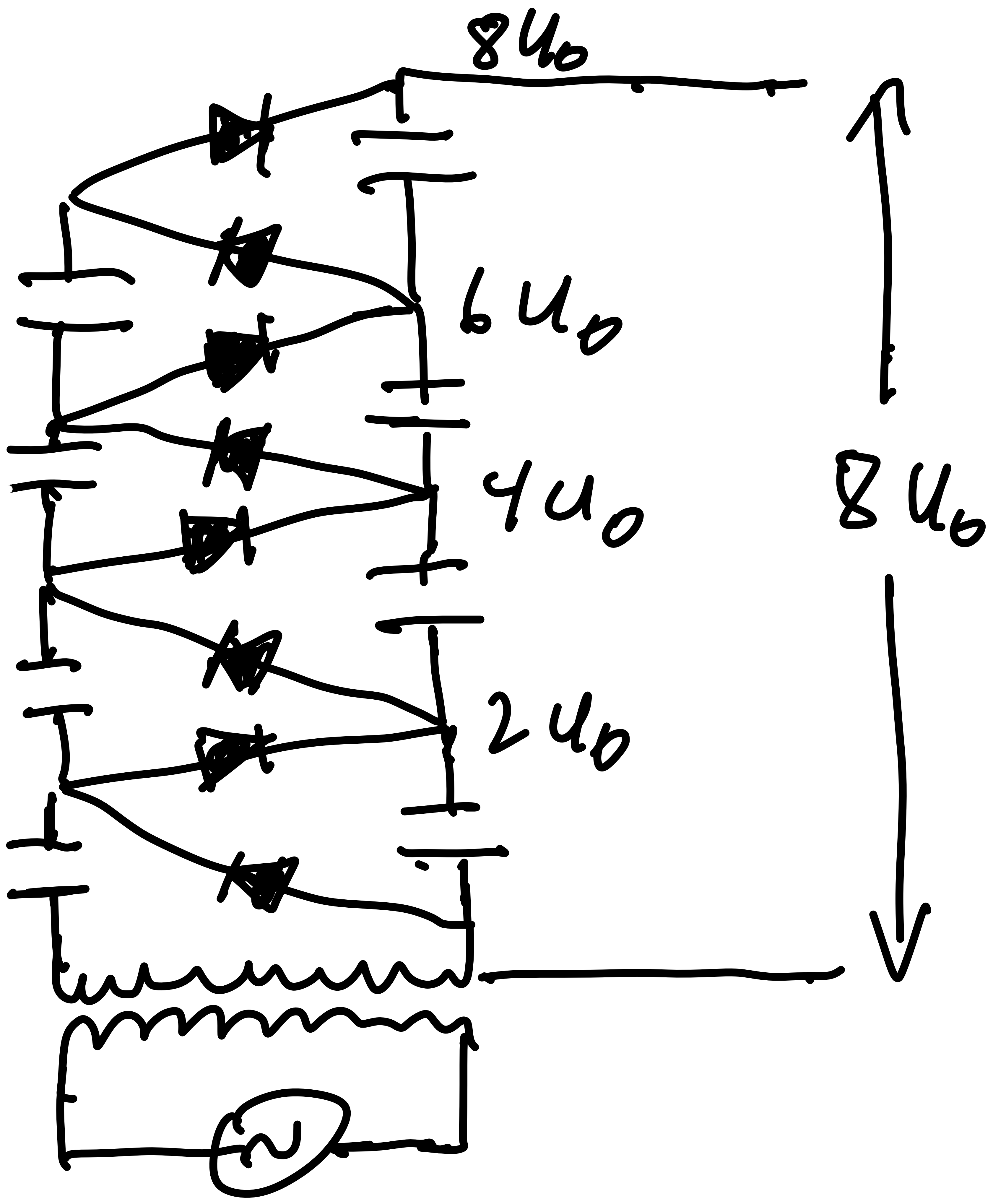




Cockroft-Walton Generator

Generation of High Voltage

- Cascade of Greinacher circuits:



CERN 600 kV Generator for pre-injector of a LINAC in the PS south hall (1964 - today an exhibit)

Voltage as a discovery tool

- The first artificial nuclear transmutation:

"Splitting the Atom"

$p + {}^{7}Li \rightarrow 2\,\alpha + 17$ MeV 400 kV voltage

Cockroft & Walton, 1932

Also the demonstration of a mass deficit:

Experimental proof of $E = mc^2$

Nobel Prize in physics for Cockroft & Walton 1951

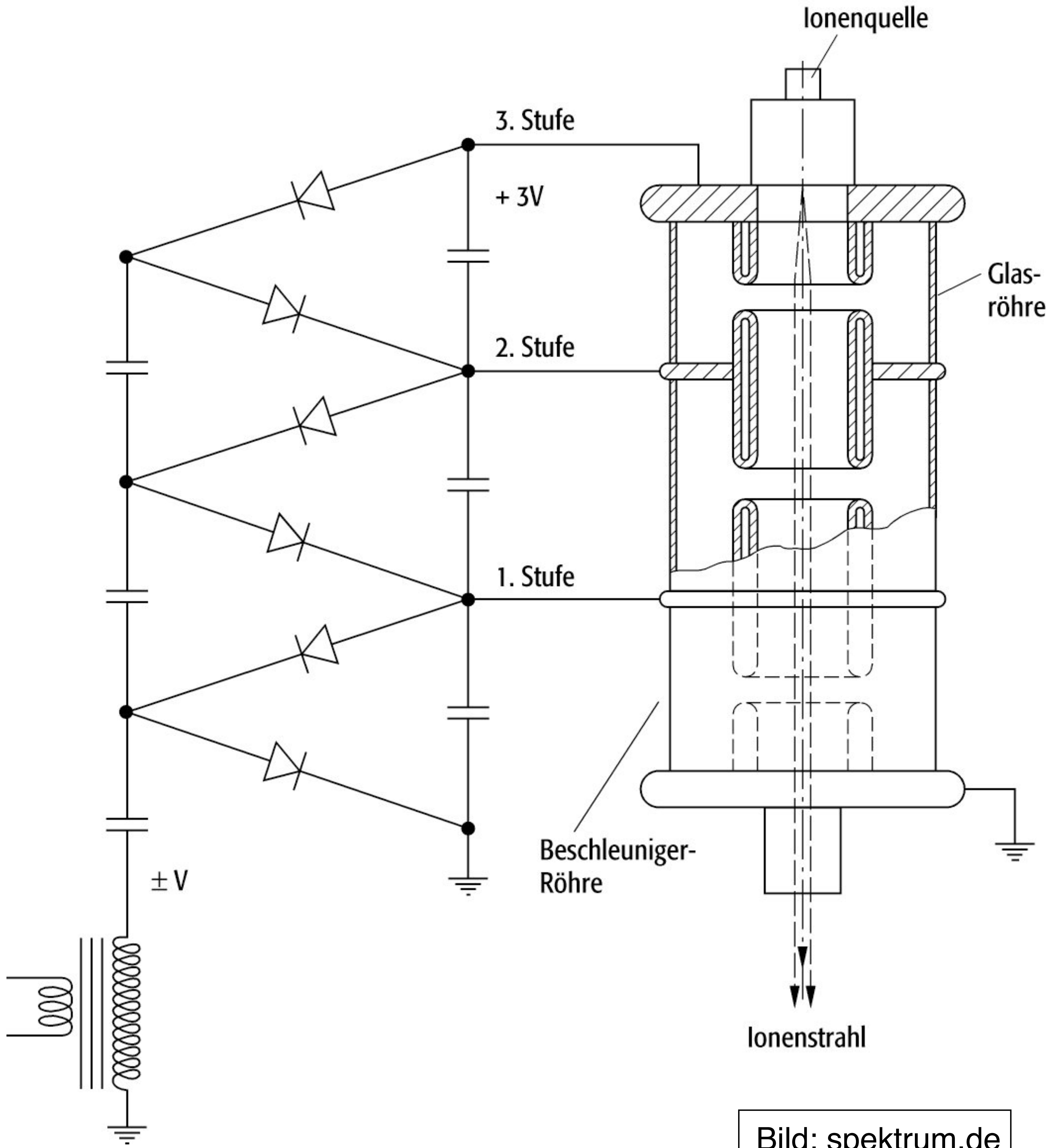


Bild: spektrum.de

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Chapter 4; Lecture 06 Part II

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Chapter 4

Operational Amplifiers

- OpAmp Basics
- Simple Circuits: Feedback etc.
- OpAmp Circuits I
- Realistic OpAmps
- OpAmp Circuits II

Overview

OpAmp Basics

In: Operational Amplifiers

Operational Amplifier (OpAmp)

Operationsverstärker

- Integrated circuit (IC) consisting of several transistors aTransistoren und anderen Komponenten.

- Wide range of applications:
  - Flexible amplifier for currents and voltages
  - Charge sensitive preamplifiers
  - Regulators
  - Comparators
  - Buffers
  - Active filters
  - As part of ADCs and DACs
  - …

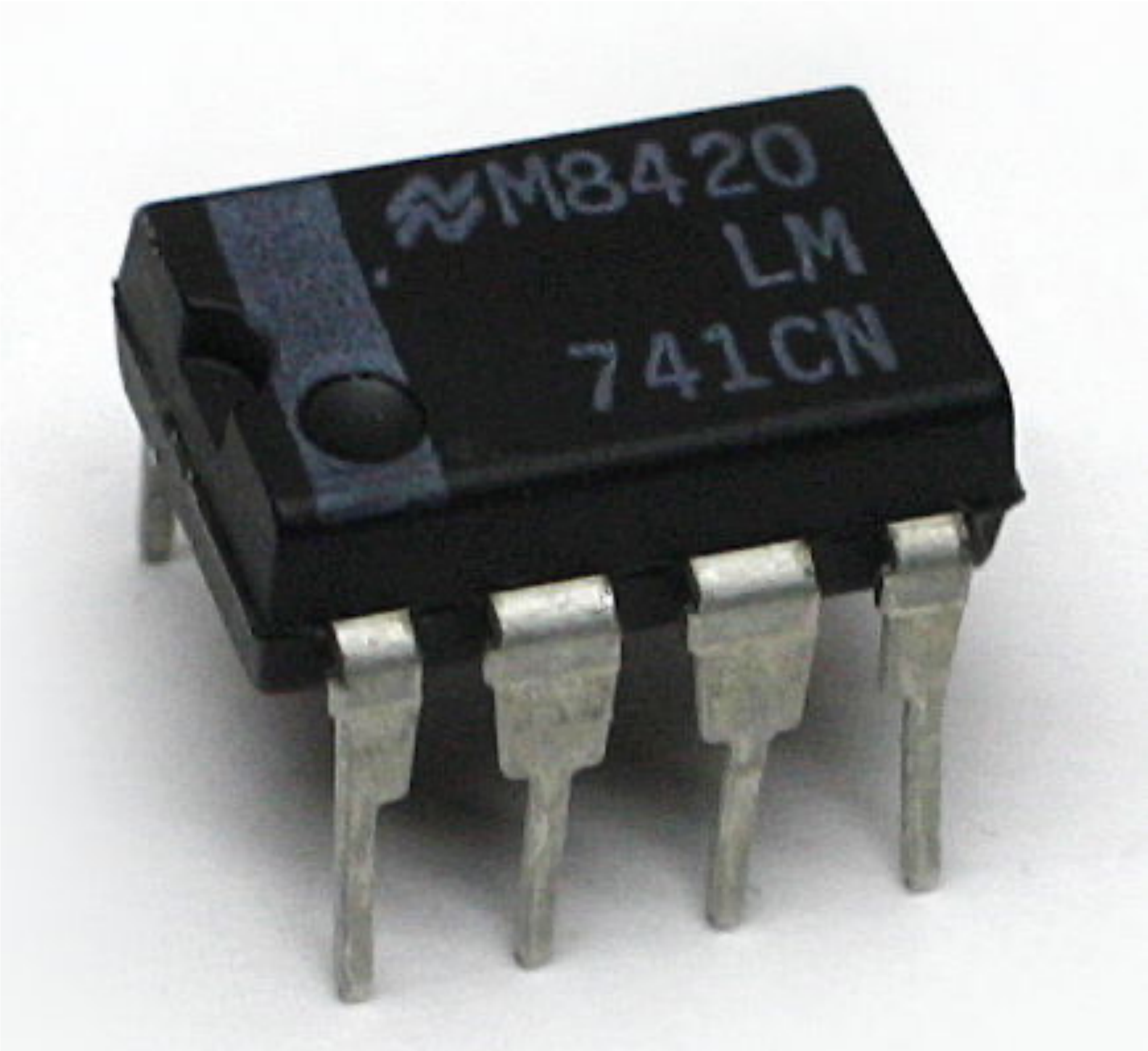
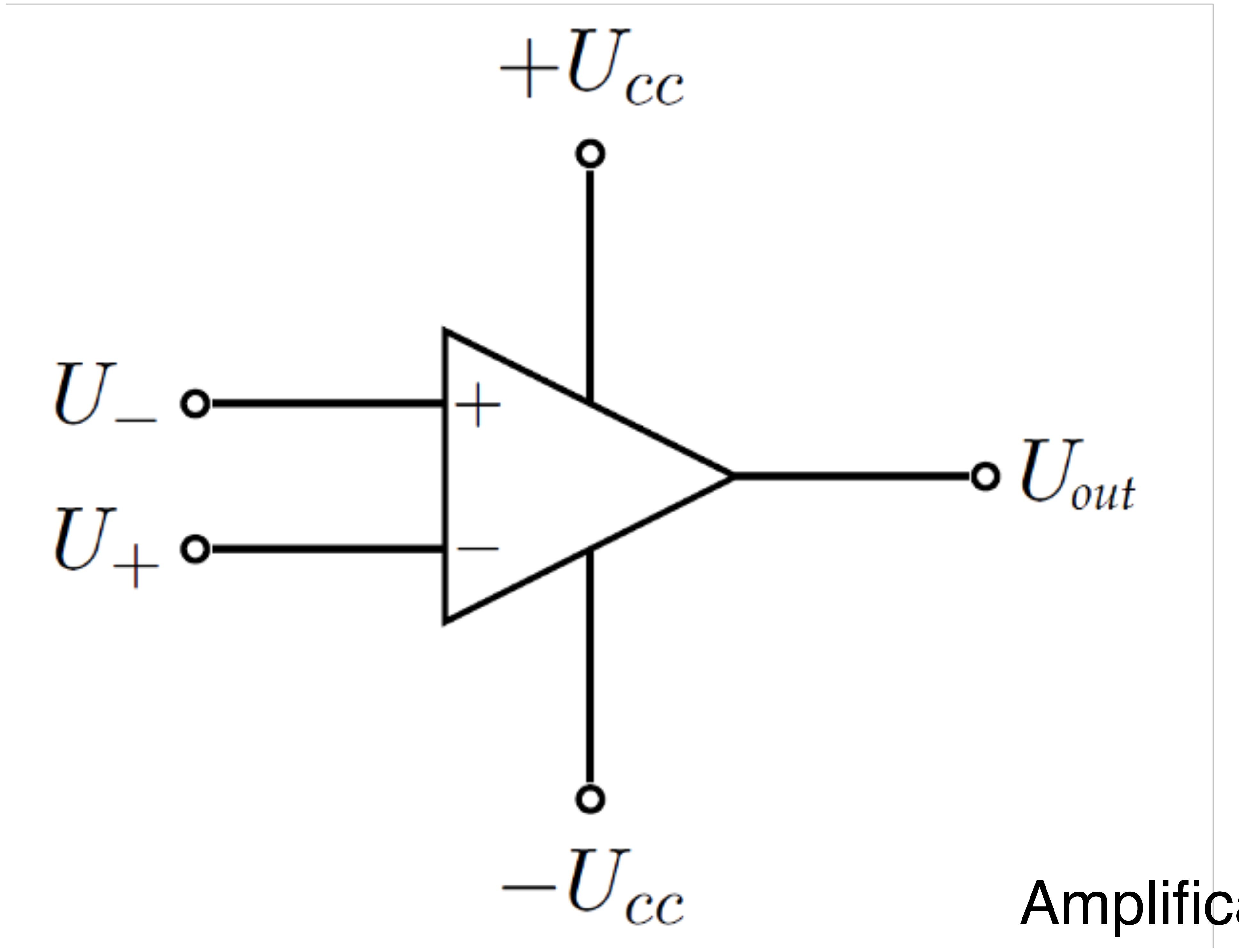


Bild Olli Niemitalo - Own work, CC0



- Active component: Needs a voltage supply! U_{cc}
- Two inputs:
  - non-inverting U_+
  - inverting U_-
- One output U_{out} ("single-ended output")

Why?

Differential input ('differentieller Eingang"):

- Suppression of noise
- Maximum flexibility (no predefined reference potential, …)

Amplification behavior:

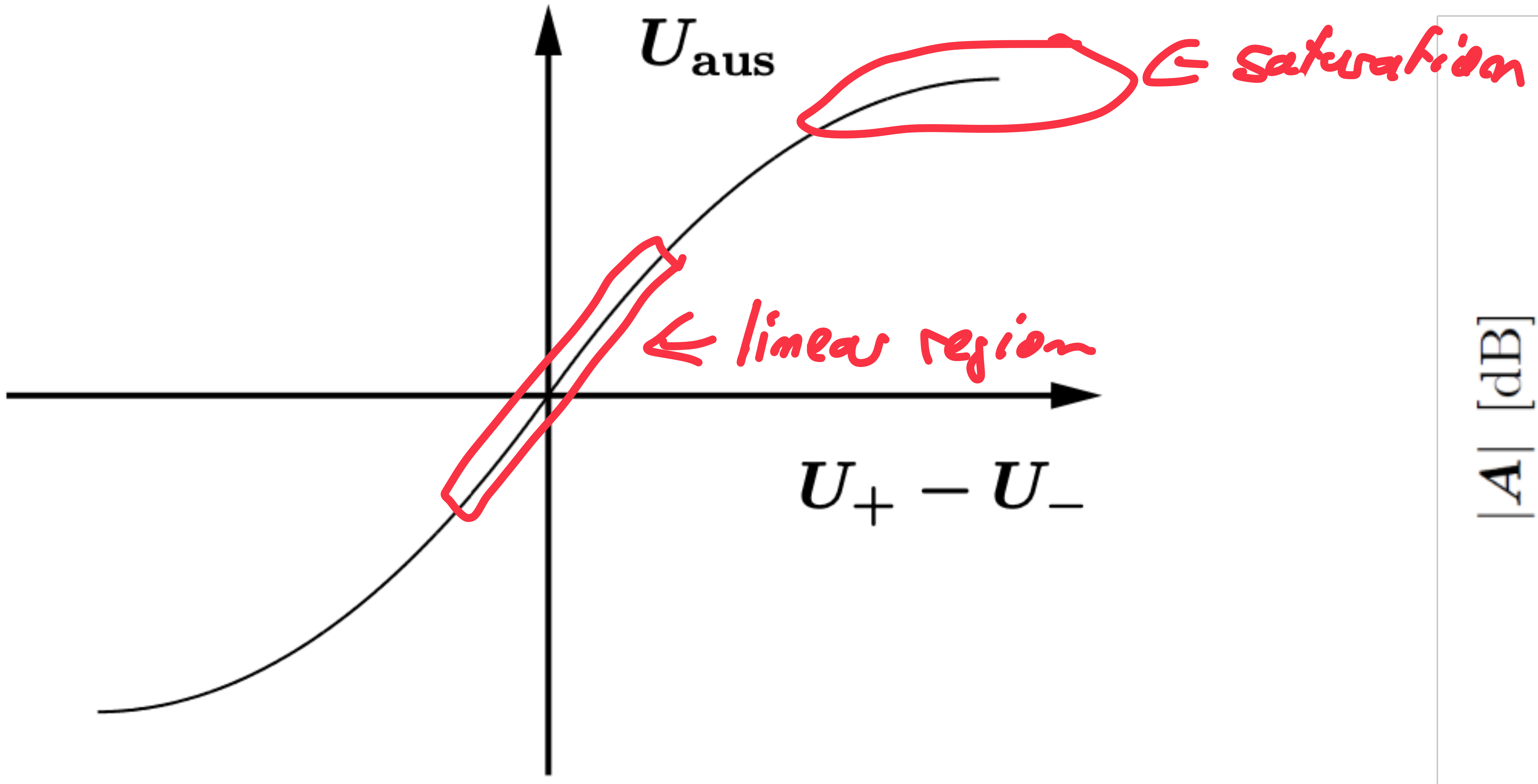
$$U_{out} = A_D (U_+ - U_-)$$

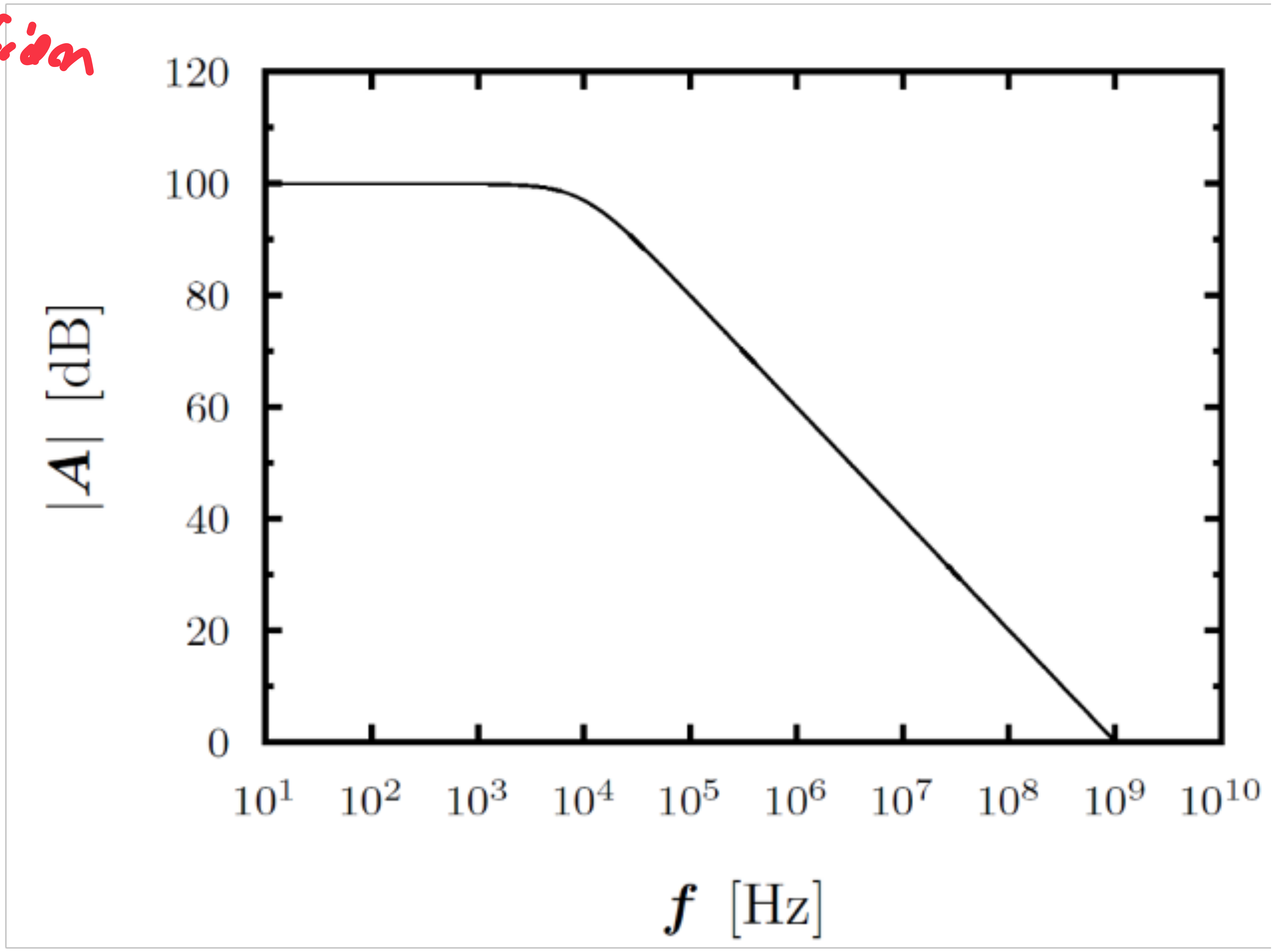
A_D : Gain ("Verstärkung")
- typically very large, ~ 10^5 or even more

Behavior

Amplification, Frequency Dependence

- Amplification of input signal - limited by voltage supply / saturation of amplifier



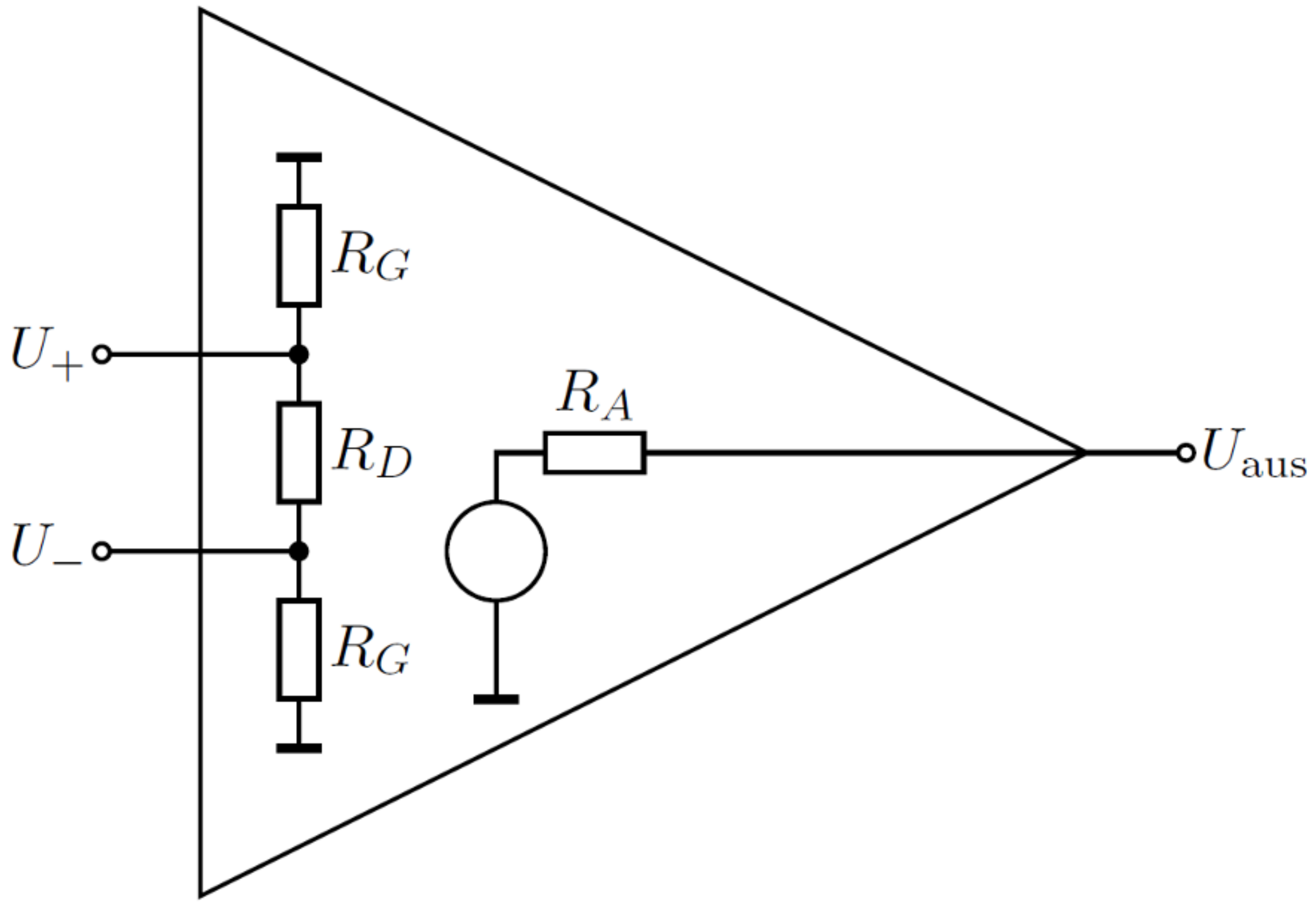


- Ideal behavior: Large and constant amplification
  In reality: dependence on input voltage, frequency temperature, …

low pass behavior of typical op amps

Simplified Circuit Diagram

The Op Amp as "Black Box"



- (Very) large input resistor R_G,
  Resistor between both inputs R_D
  (min MΩ, oft GΩ):
  Current at input negligible
- Small output resistance R_A:
  - Output current / voltage does not depend on circuitry behind the op amp. Can be used as voltage or current source.

NB: Supply voltage not shown

Under the Hood

An Example

- Circuit diagram of a typical op amp: ICL7621
  - $10^{12}\ \Omega$ input impedance,
  - 200 μW power,
  - ±1V to ±8 V supply voltage,
  - 75 db voltage gain,
  - 2 μs rise time,
  - 0.48 μs GBP (gain bandwidth product),
  - low-noise

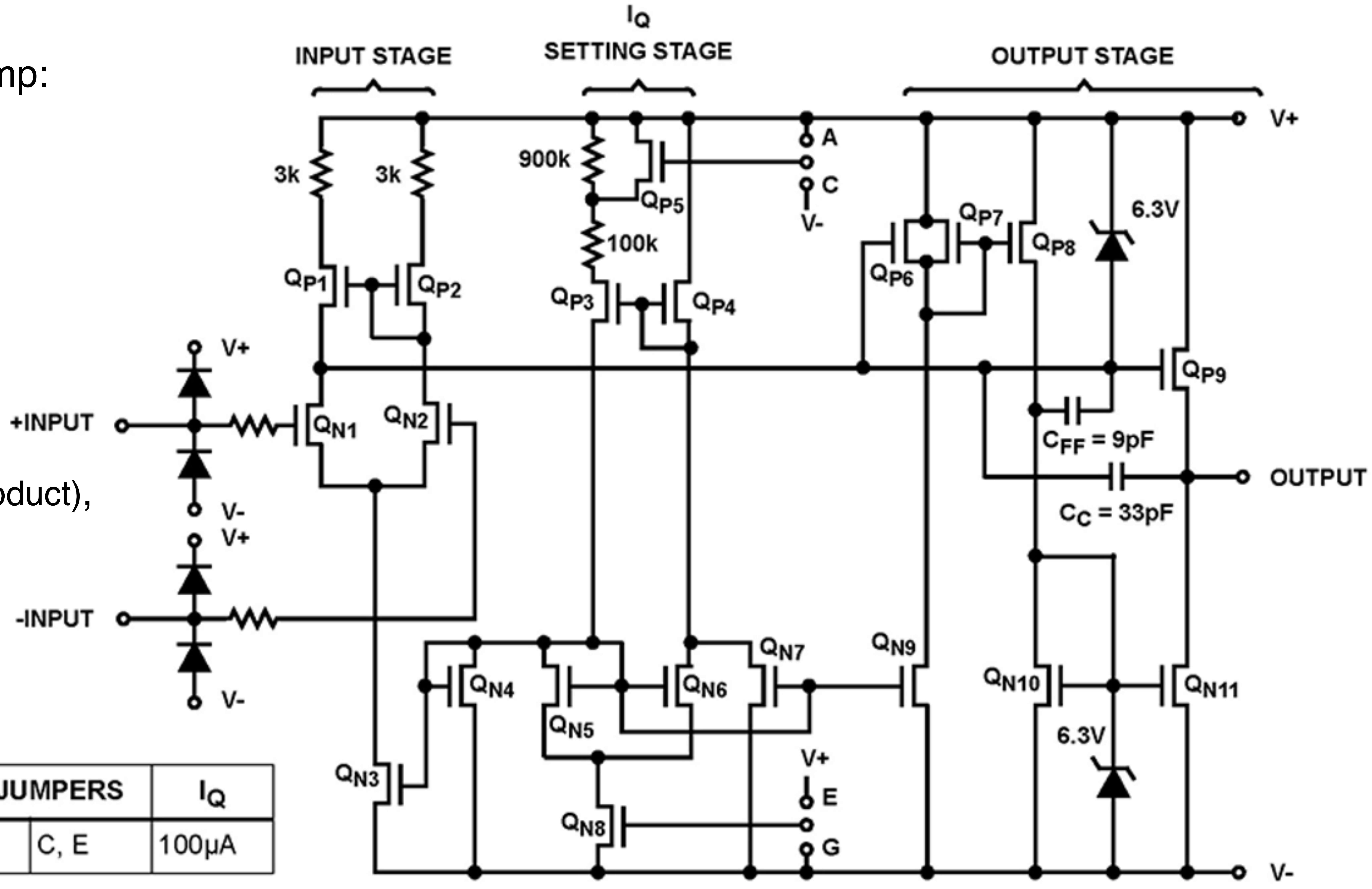


TABLE OF JUMPERS		IQ
ICL7621	C, E	100μA

Next Lectures:

Digital - Tuesday, November 28, Thursday Nov. 30 & Tuesday, Dec. 5

Analog 07 - Chapter 04 - Thursday, Dec. 7

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**