Battery Ageing • Battery Models • Battery Diagnostics • Battery Pack Design • Electromobility • Stationary Energy Storage • Energy System Analysis

Electrical Components and Their Nomenclature

21.04.2023
Dr. Florian Ringbeck

Chair for Electrochemical Energy Conversion and Storage Systems

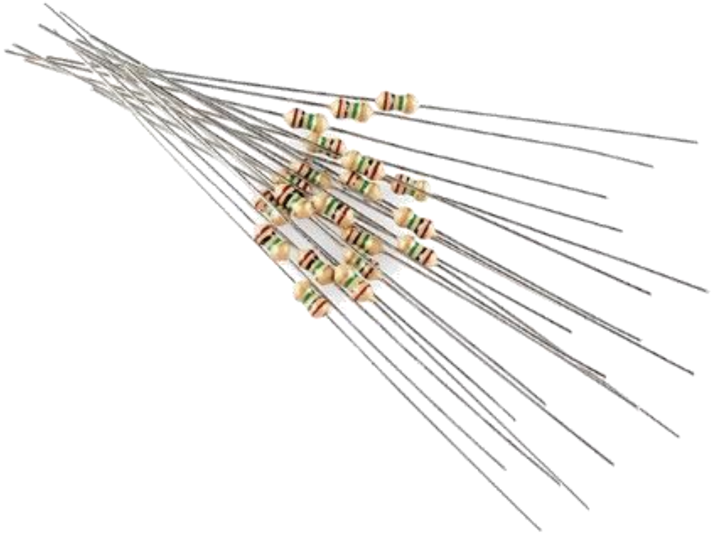
Power Electronics and Electrical Drives

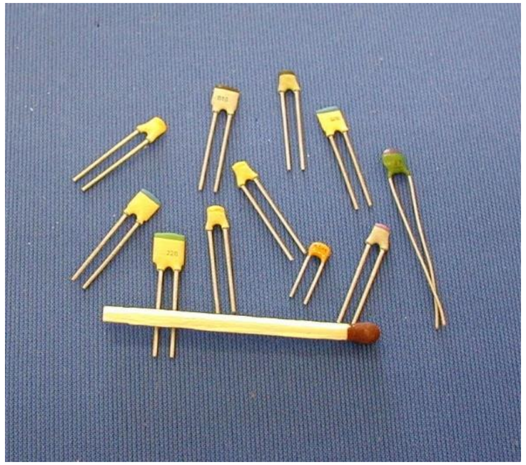
Agenda

1	**Basic Electrical Principles and their Terms**	08:30 – 09:30
	Break	*09:30 – 09:45*
2	**Electrical Components and their Nomenclature**	09:40 – 10:40
	Break	*10:45 – 11:00*
3	**Linear Electrical Networks and their Analysis**	11:00 – 12:00
	Lunch	*12:00 – 13:00*
4	**Introduction of Alternating Electrical Quantities**	13:00 – 14:00
	Break	*14:00 – 14:15*
5	**Optional Q&A**	14:15 – 15:15

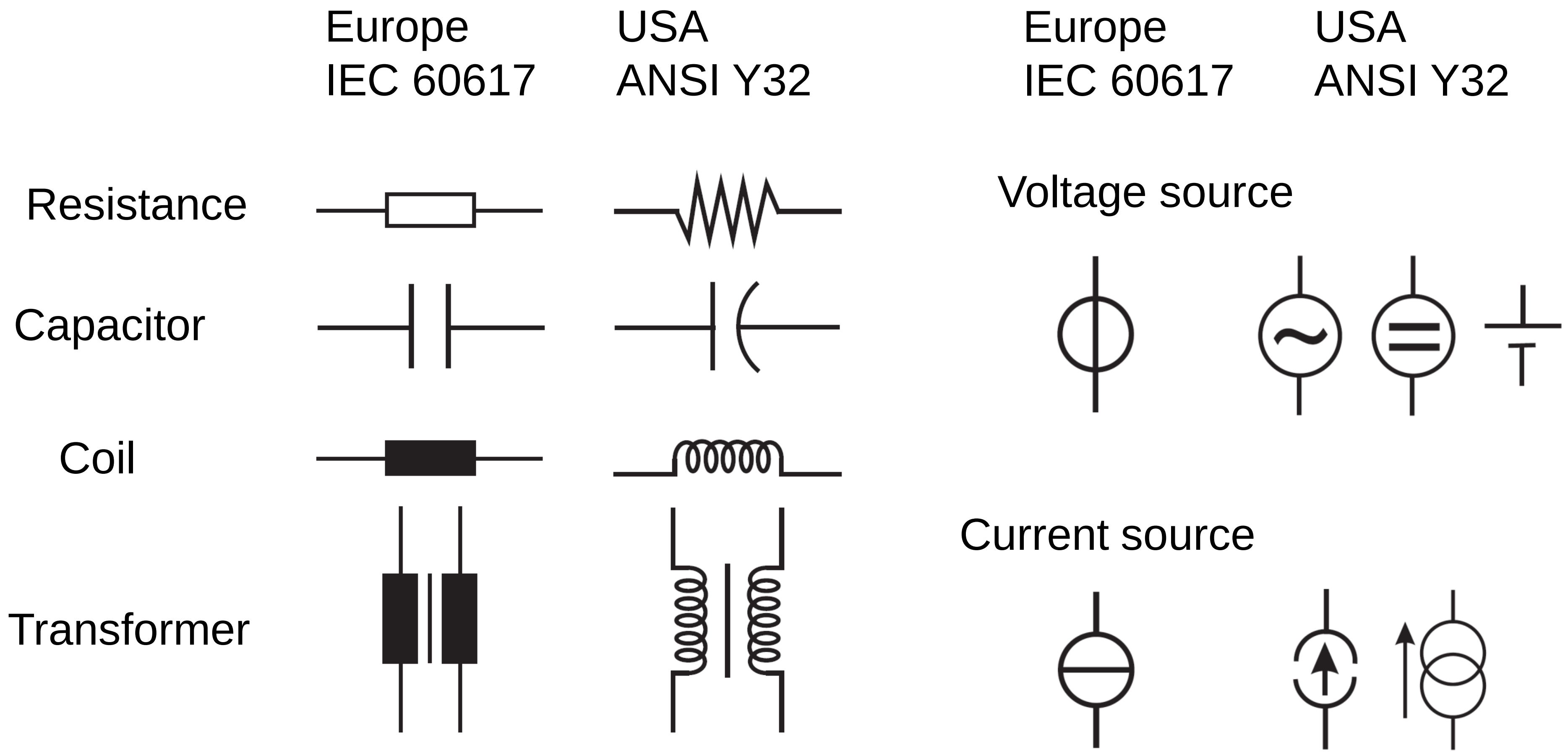
Outline

1. Currents and voltages in electrical networks
2. Resistor
   a. Designs and properties of resistors
   b. Energy conversion in the electrical resistance ("consumer")
3. Capacitor
   a. Principle structure
   b. Various designs
   c. Charging and discharging processes
   d. Application example: micromechanics



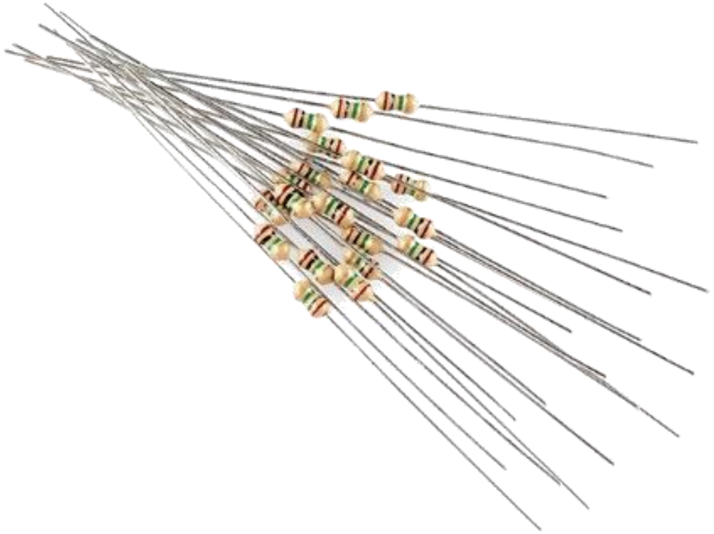


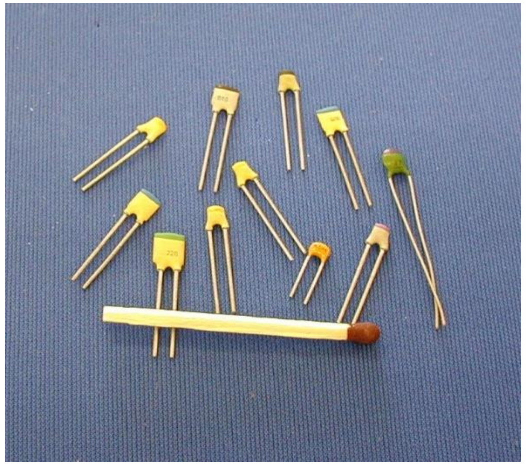
Representation of Circuit Elements



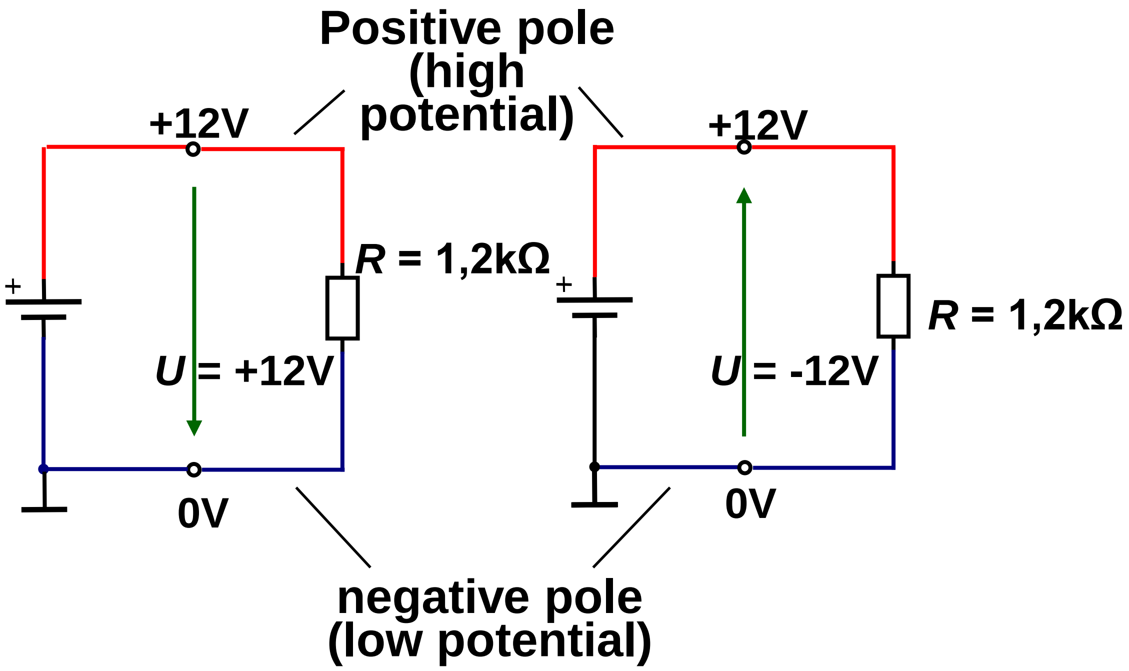
Outline

1. **Currents and voltages in electrical networks**
2. Resistor
   a. Designs and properties of resistors
   b. Energy conversion in the electrical resistance ("consumer")
3. Capacitor
   a. Principle structure
   b. Various designs
   c. Charging and discharging processes
   d. Application example: micromechanics

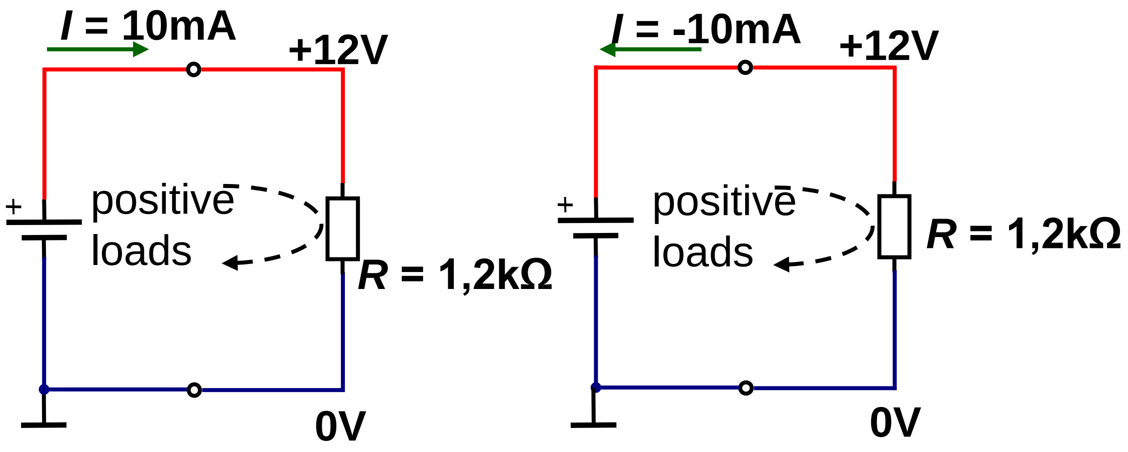




Passive Sign convention



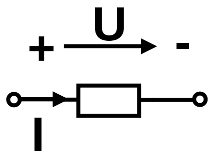
Possible counting
arrows for the <u>voltage</u>



Possible counting
arrows for the <u>current</u>

Counting Arrow Convention

Consumer counter arrow system

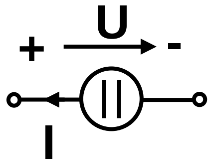


Current and voltage counter arrows point in the same direction

Analogy:

[www.wikipedia.de[1a]]

Generator counter arrow system



Current and voltage count arrows point in opposite directions

Analogy:

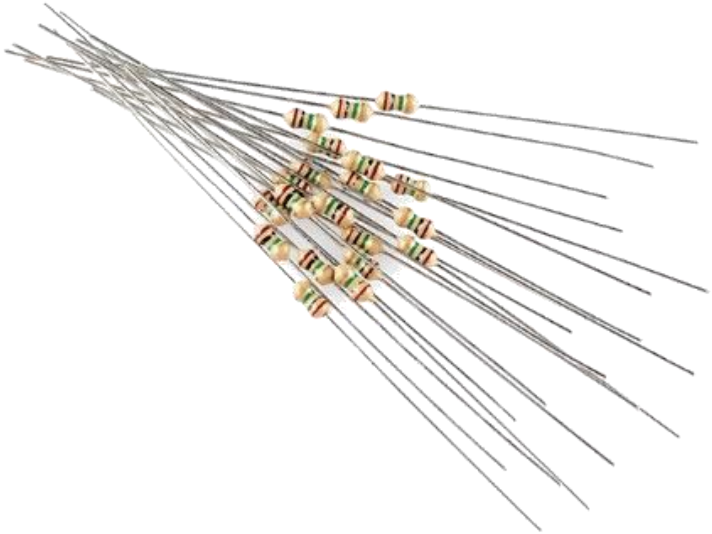
[www.wikipedia.de [2b]]

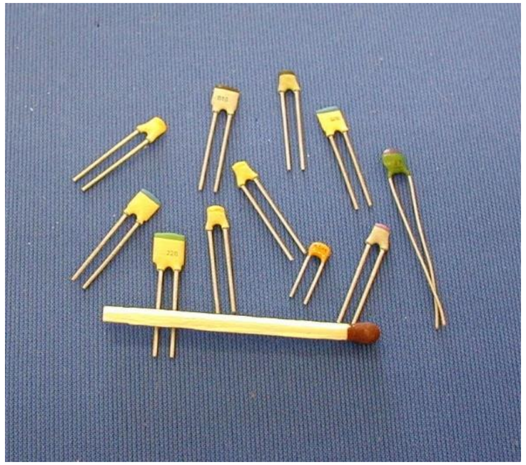
The technical direction of current flow corresponds to that of the consumer counter arrow system.

Note: The actual electron flow is then opposite to the current flow (electrons by definition have a negative charge).

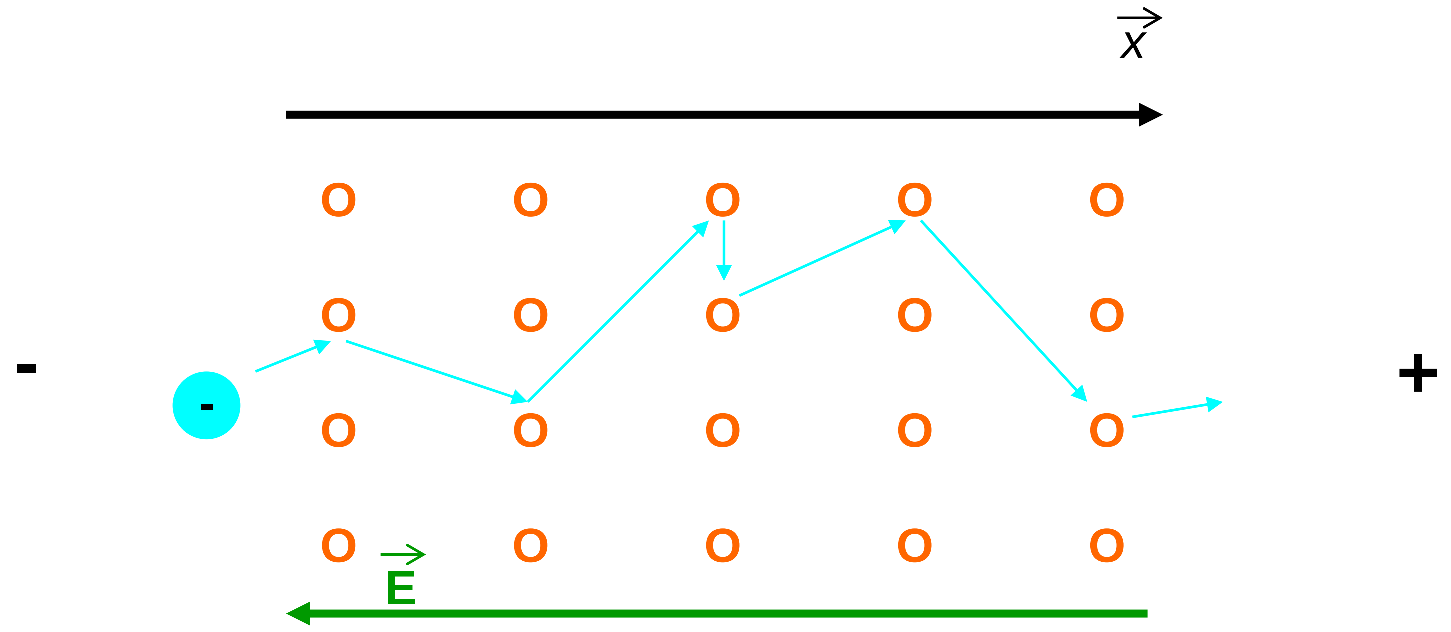
Outline and Objective

1. Currents and voltages in electrical networks
2. Resistor
   a. **Designs and properties of resistors**
   b. Energy conversion in the electrical resistance ("consumer")
3. Capacitor
   a. Principle structure
   b. Various designs
   c. Charging and discharging processes
   d. Application example: micromechanics





Current in Linear, Homogeneous Conductors: Ohm's Law

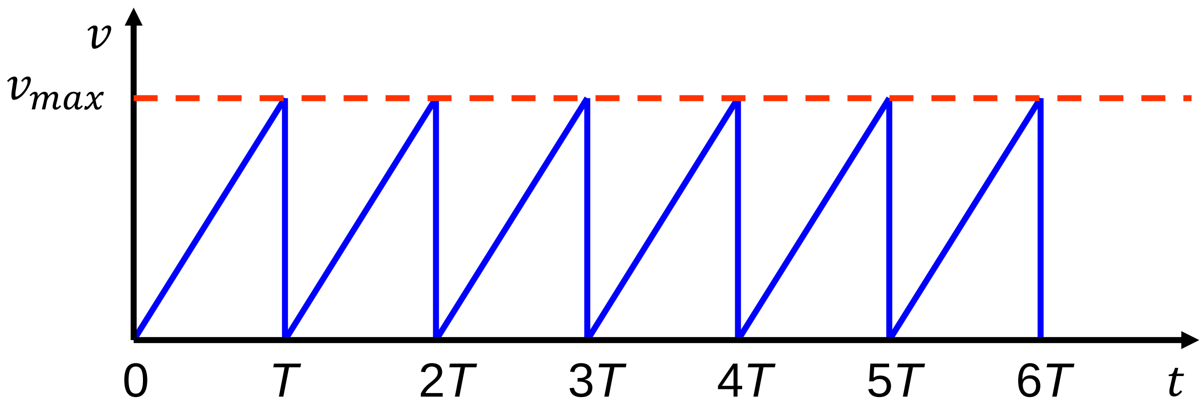


- Electrons are slowed down in the conductor by collisions with the crystal lattice.
- The material represents a resistance for the current flow.

Ohm's law - Acceleration and Collisions of Electrons

- Charge carriers are accelerated in the E-field: $|\vec{a}| = \frac{|q| \cdot |\vec{E}|}{m}$, because $|F| = m \cdot a = |q| \cdot |E|$

- Assumption:
  - The electron collides after passing through the so-called *mean free path* λ (runtime T) together with an atom of the crystal lattice.
  - In the process it loses all its kinetic energy.



$$\Rightarrow |\overrightarrow{v_{max}}| = \frac{|e_0| \cdot |\vec{E}|}{m_e} \cdot T$$

Ohm's Law

- **Constant drift speed**

$$|\overrightarrow{v_{max}}| = \frac{|e_0| \cdot |\vec{E}|}{m_e} \cdot T \;\; \Rightarrow \;\; \overrightarrow{v_D} = -\mu_e \cdot \vec{E}$$

μ_e: Mobility of the electron (material constant)

- Example: Drift speed of the conduction electrons in a copper conductor (only absolute values are considered)

$$I = q \cdot v_D \cdot \Delta y \cdot \Delta z = n \cdot |e_0| \cdot v_D \cdot \underbrace{\Delta y \cdot \Delta z}_{A} \Rightarrow v_D = \frac{I}{n \cdot e_0 \cdot A}$$

n: Electron concentration

- $I = 16$ A; $n = 10^{23}$ cm^{-3}; $A = 1$ mm^2; $e_0 = 1{,}6 \cdot 10^{-19}$ As → $v_D = 1$ mm / s = 10^{-3} m / s

- Electric field strength in the conductor: $E = v_D/\mu_e$ mit $\mu_{e,Cu}$ = 3 · 10^{-3} m^2 / Vs → $E = 0{,}33$ V / m

Fundamental definitions

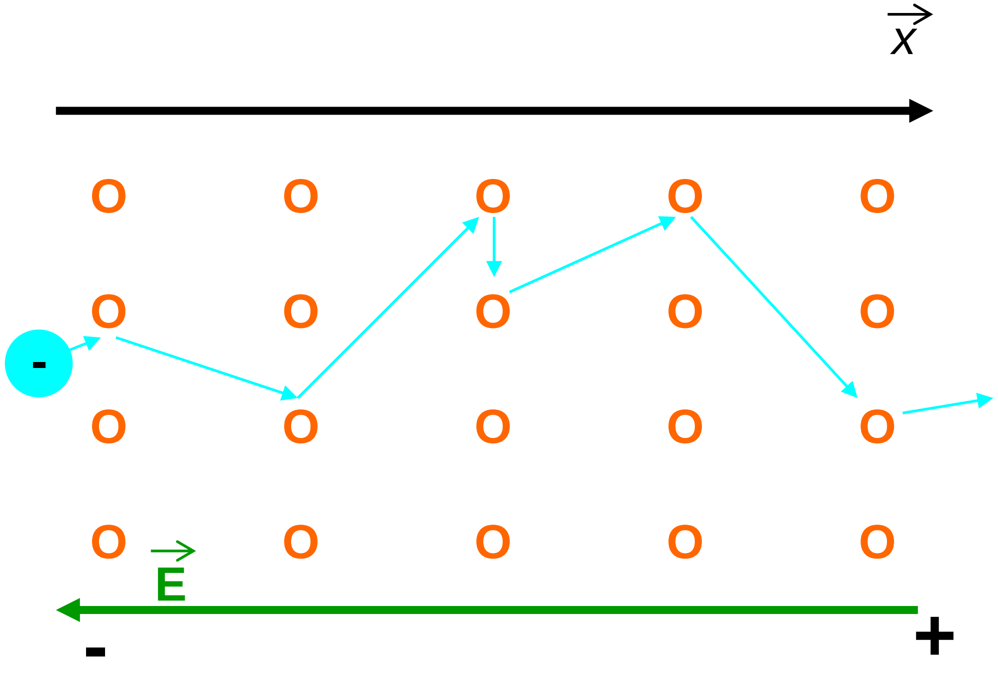
Movement of charge carriers: electric current *I*

$$I := \lim_{\Delta t \to 0} \frac{\Delta Q}{\Delta t} = \frac{\mathrm{d}Q}{\mathrm{d}t} \qquad [I] = \frac{[Q]}{[t]} = \frac{\mathrm{C}}{\mathrm{s}} = \mathrm{A}\ \ (\mathit{Ampere})$$

Ohm's law:

$$U = R \cdot I \qquad \text{with} \qquad R = \frac{L}{\sigma \cdot A} = \rho \frac{L}{A}$$

$$[R] = \frac{V}{A} = \Omega\ \ (\mathrm{Ohm})$$

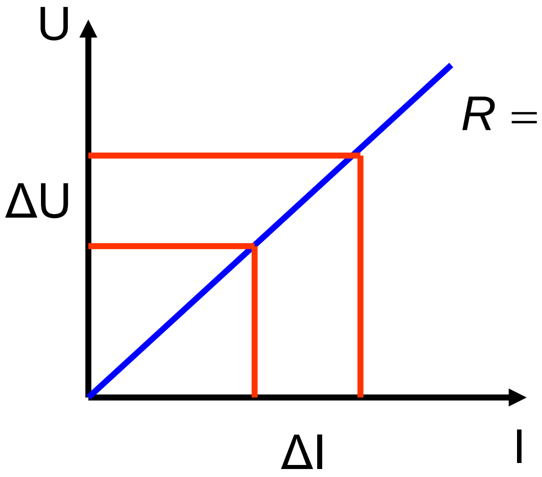


[ρ] = **specific resistance** $\rho = 1/\sigma$

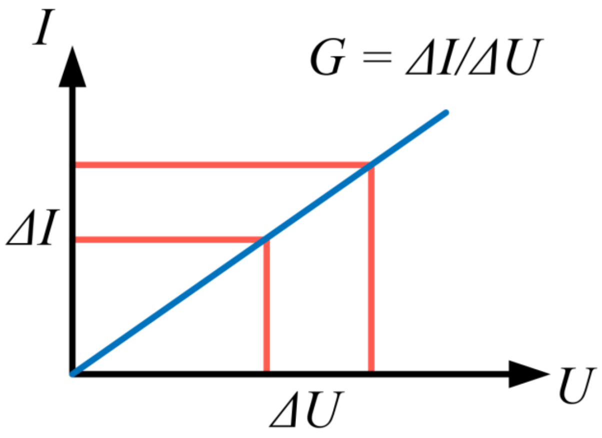
[σ] = **specific conductivity** $G := 1/R$ $[G] = 1/\Omega = \mathrm{S}$ (Siemens); $[\sigma] = \mathrm{S/cm} = 1/(\Omega\ \mathrm{cm})$

Ohm's Law

- **Ohmic resistance R and conductivity G**
- **Circuit symbol:**



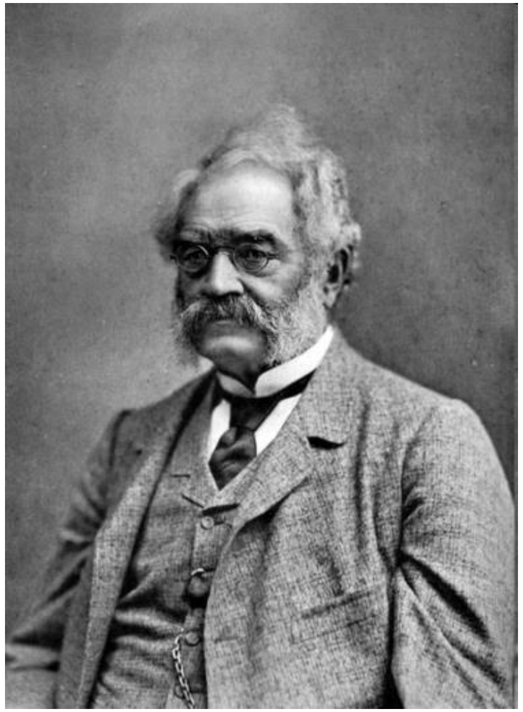
$$R = \frac{\Delta U}{\Delta I}$$



characteristic curve of an ohmic resistance

[www.wikipedia.de]

Georg Simon Ohm (1789 – 1854)

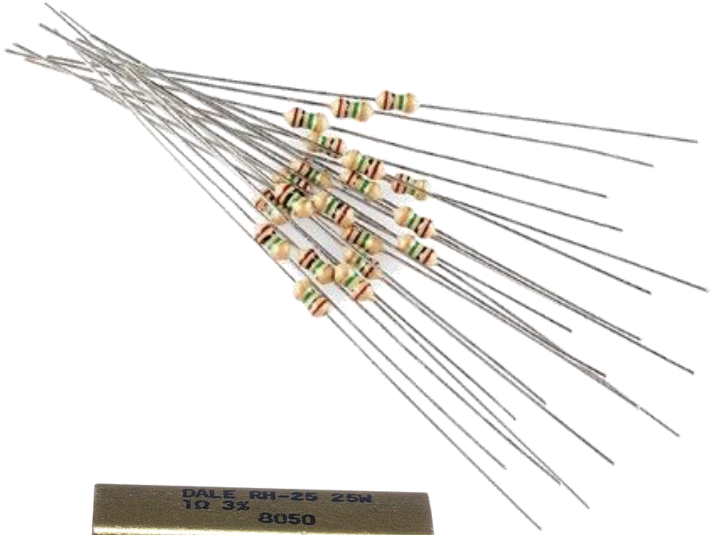


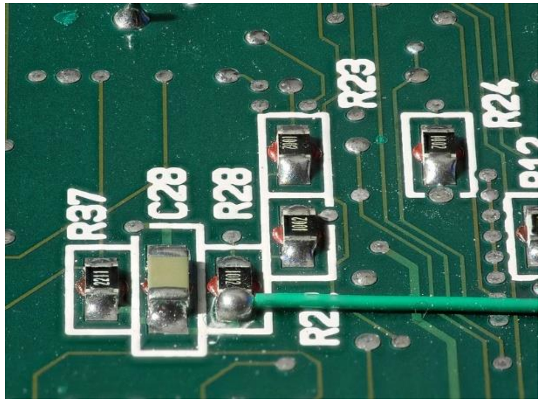
[www.wikipedia.de]

Werner von Siemens (1816 – 1892)

- The energy of the charge carriers is converted into heat by scattering in the solid.

Resistance: Typical Designs





- Metal or carbon film resistor:
  - Relatively low power (0.1 - 2 W)
  - formerly "typical" design
  - Resistance value in standardized color code on the component

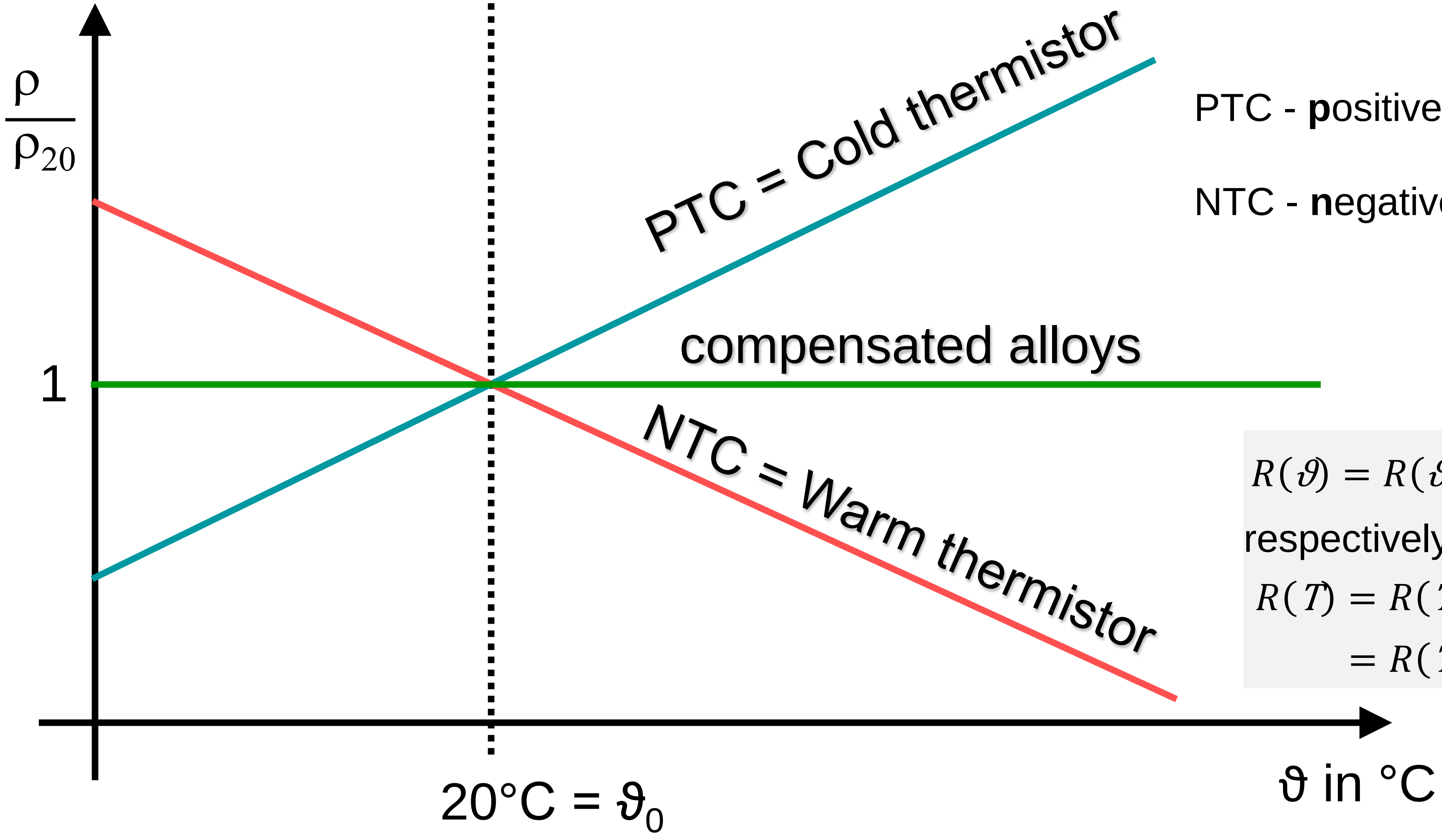
- Wire resistor:
  - High performance
  - Small resistance
  - High temperature resistance

- SMD (Surface Mounted Device)-resistor
  - Low output
  - Small dimensions enable high packing density
  - Well suited for high frequency technology

Resistance: Typical Properties of Various Materials

Conductor	σ in $10^4 \frac{S}{cm}$	ρ in $10^{-6} \Omega cm$	α_{298} in $\frac{1}{10^3 K}$ (temperature coefficient)
Silver	62,5	1,6	3,8
Copper	56	1,786	3,93
Gold	44	2,3	4,0
Aluminium	35	2,857	3,77
Tungsten	18	5,5	4,1
Brass (Cu, Zn)	14...11	7...9	1,5
Iron	10...7	10...15	4,5...6
Platinum	9…7	11…14	2…3
Nickel silver (Cu, Ni, Zn)	3,33	30	$3{,}5 \cdot 10^{-2}$
Constantan (Cu, Ni)	2,0	50	$-3{,}5 \cdot 10^{-3}$
Coal	$2 \cdot 10^{-2} \ldots 10^{-2}$	$5 \cdot 10^{3} \ldots 10^{4}$	$-2 \cdot 10^{-1} \ldots -8 \cdot 10^{-1}$
H2SO4 - Lsg. (10%)	$4 \cdot 10^{-5}$	$2{,}5 \cdot 10^{6}$	
ZrO2:CaO (1000°C)	$5{,}5 \cdot 10^{-6}$	$1{,}8 \cdot 10^{7}$	

Resistance: Temperature Dependence of the Specific Resistance
(linear range)



PTC - **p**ositive

NTC - **n**egative

Temperature coefficient

$$R(\vartheta) = R(\vartheta_0) \cdot \left(1 + \alpha_{\vartheta_0} \cdot (\vartheta - \vartheta_0)\right)$$

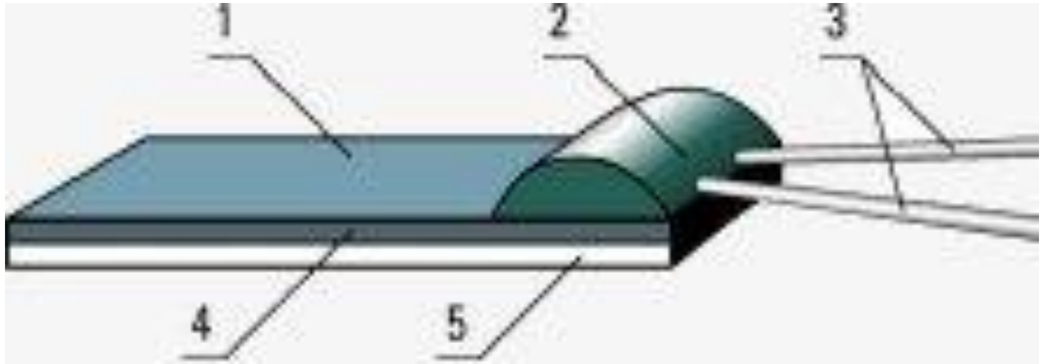
respectively

$$R(T) = R(T_0) \cdot \left(1 + \alpha_{T_0} \cdot (T - T_0)\right)$$
$$= R(T_0) \cdot \left(1 + \alpha_{T_0} \cdot \Delta T\right)$$

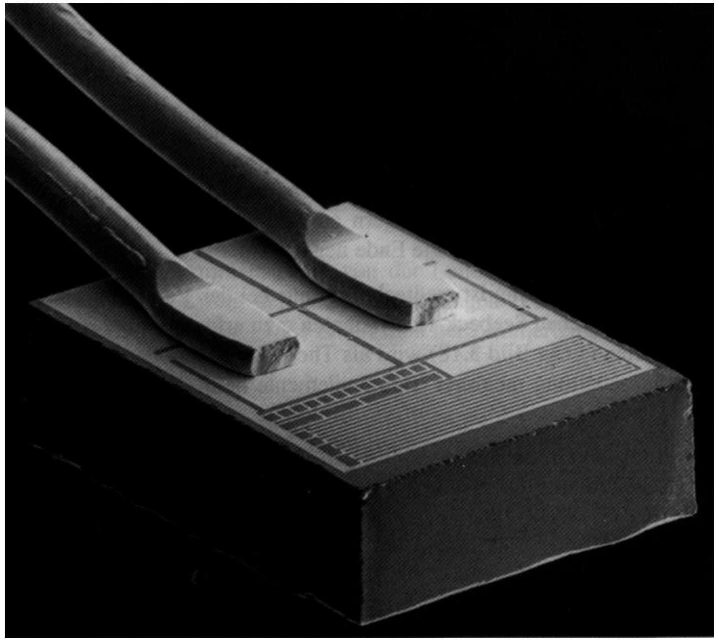
!

$$[\vartheta] = {}^\circ C$$
$$[1/\alpha] = [T] = K$$

Pt-100 Thin-Film Sensor - Designs



1. Passivation layer
2. Locking layer
3. Connection wires
4. Structured platinum layer
5. Al2O3 - carrier substrate

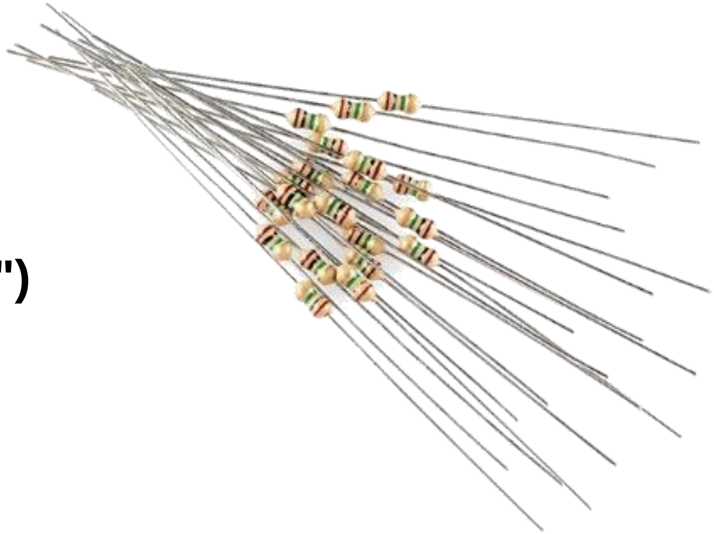


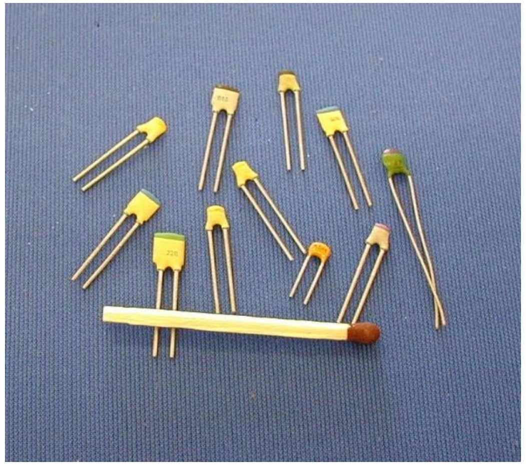
Product overview

Source: https://3.imimg.com/data3/MR/VP/MY-5168702/pt-500-temperature-sensors-250x250.jpg

Outline

1. Currents and voltages in electrical networks
2. Resistor
   a. Designs and properties of resistors
   b. **Energy conversion in the electrical resistance ("consumer")**
3. Capacitor
   a. Principle structure
   b. Various designs
   c. Charging and discharging processes
   d. Application example: micromechanics





Energy Conversion in Electrical Resistance

- Energy gain of a charge *Q* when passing through a voltage *V*: **dW = Q · *V***

- Total energy through integration: $W = \int V \cdot dQ \quad \text{with } I = \frac{dQ}{dt}$

$$\Rightarrow W = \int_{t1}^{t2} V(t) \cdot I(t)dt$$

[*W*] = [*V*] · [*I*] · [*t*] = V · A · s = J (Joule)

- **The following applies to constant current: *W* = *V* · *I* · *t***

- In electrical resistance: Conversion of electric energy into heat (hair dryer, soldering iron, etc.) with 100% efficiency

https://www.pkelektronik.com/media/catalog/product/0/0/0053230699.jpg

Energy Conversion in Electrical Resistance

- In electrical applications often more interesting: **Change of energy per time → Power:**

Definition: $$P = \frac{W}{t}$$

$$P(t) = \lim_{\Delta t \to 0} \frac{\Delta W}{\Delta t} = \frac{dW}{dt}$$

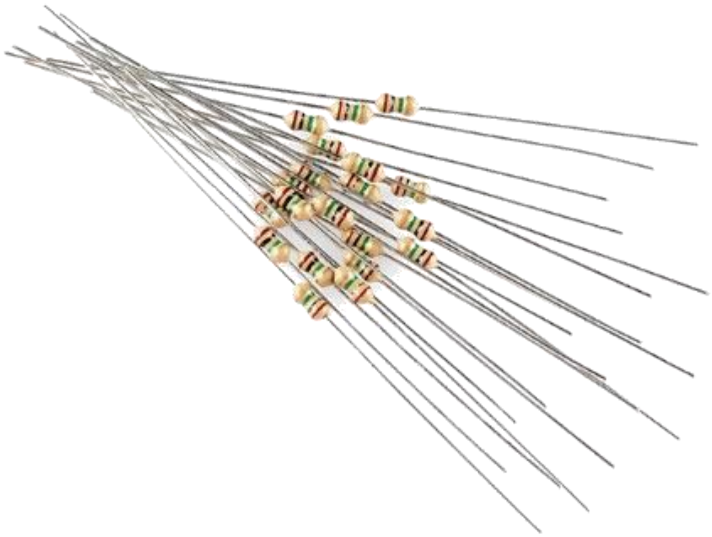
$$P(t) = V(t) \cdot I(t)$$

$$[P] = \mathrm{V} \cdot \mathrm{A} = \frac{\mathrm{J}}{\mathrm{s}} := \mathrm{W} \quad \text{(Watt)}$$

The following applies to direct current: $P = V \cdot I$

$$P = R \cdot I^2 = \frac{V^2}{R}$$

Energy Conversion in Electrical Resistance: Example



Electric load in resistors

- A resistor with R = 10 Ω is connected to a voltage V = 10 V

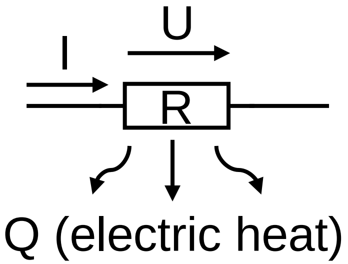
What happens?

- Ohm's law says: $I = \frac{V}{R} = \frac{10\ V}{10\ \Omega} = 1\ A$

- Furthermore, the power: $P = V \cdot I = 10\ \mathrm{V} \cdot 1\ \mathrm{A} = 10\ \mathrm{W}$

- **The usual metal or carbon film resistor "tolerates" only a power loss of 0.25 W!**

Load Capability of Resistors



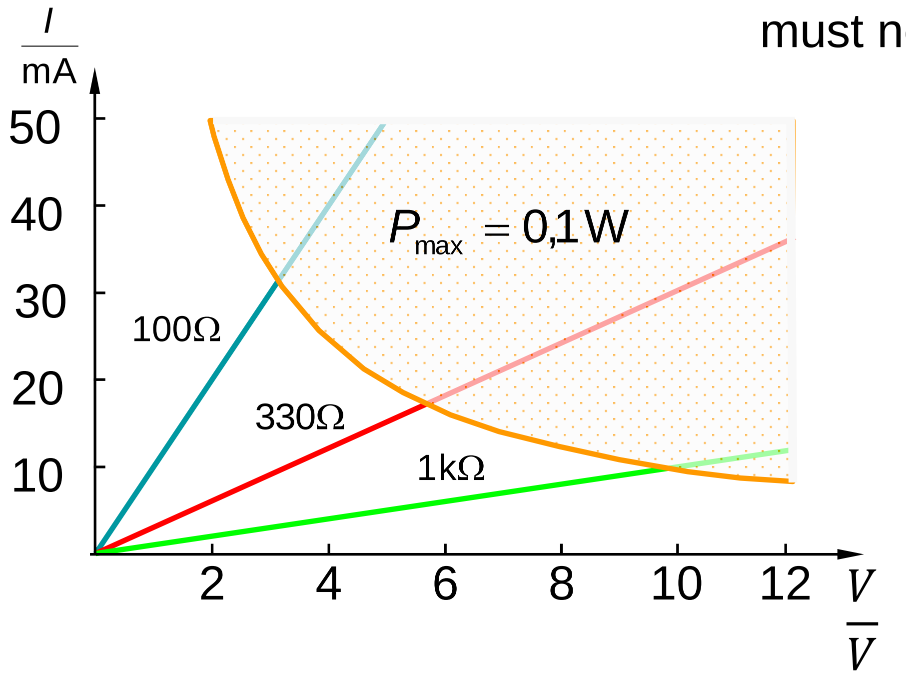
$$P = \frac{dQ}{dt}$$

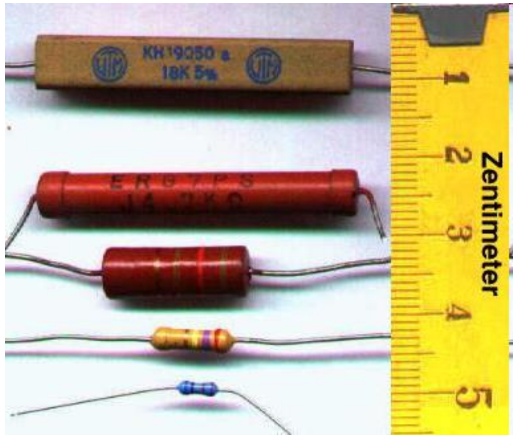
The electric power that is converted into a resistance can be expressed as follows:

$$P = V \cdot I = R \cdot I^2 = \frac{V^2}{R}$$

The nominal load capacity must not be exceeded!

$$\boxed{P \leq P_{max}}$$





Source: User:Honina [GFDL] https://commons.wikimedia.org/wiki/File:Widerst%C3%A4nde.JPG?uselang=de

Energy Conversion in Electrical Resistance - Example Power Grids

Why transmit power over long distances with high voltage?

- Power $P = V \cdot I = const.$, resistance cable $R_{cable} = const.$

- For maximum P two possibilities: U large or I large

- For high voltage, low current → low ohmic losses, because

- Voltage drop at the cable: $V_{cable} = R_{cable} \cdot I$

- Power loss: $P_{loss} = V_{cable} \cdot I = R_{cable} \cdot I^2$

→ Power should arrive at the consumer and not be lost through losses during transport

Example E-Vehicles

- Switching- copper & iron losses as an example: 400 W PM motor

- Changing electrical system voltage from 12 V to 48 V (Hybrid E-Vehicle) results in
  - Conductor current decreases from ~30 A to ~10 A
  - ~ 75 % decreased losses in electronics
  - Reduction of total losses

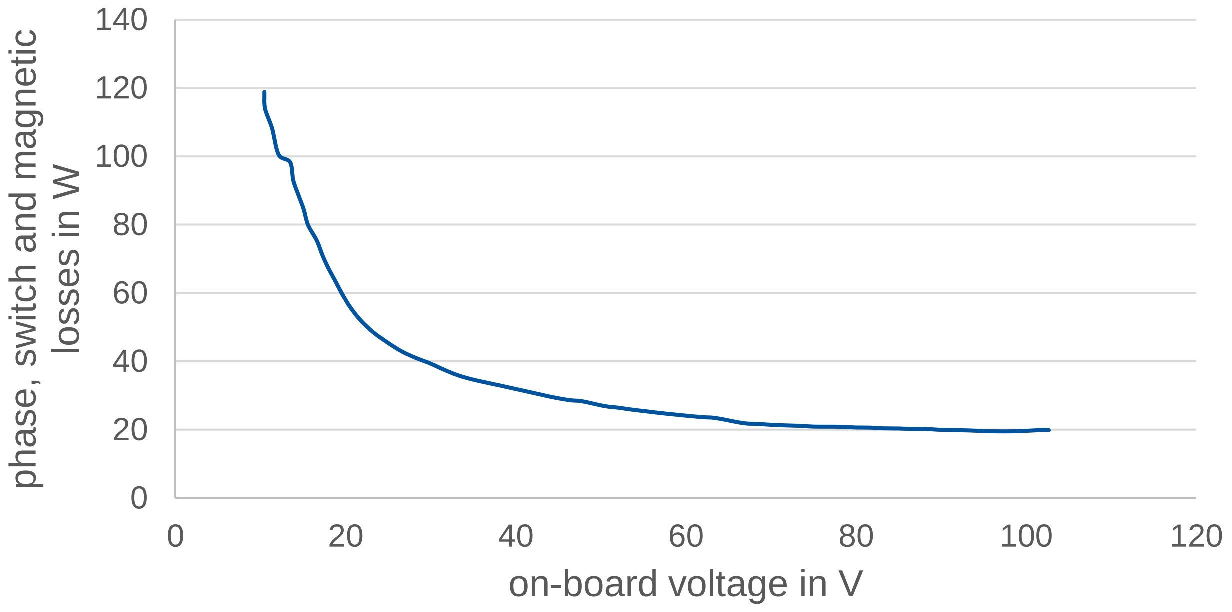


Figure based on: IEM RWTH 2016; Lecture: Elektrische Kfz-Bordnetzkomponenten

Typical voltage levels in the power supply system

Nominal voltage	Voltage level	Transmission distance	Application
230 / 380 V	Low voltage	Some 100 m	Local supply of household and business
10 kV	Medium voltage	Up to about 10 km	Energy distribution in large cities
20 kV	Medium voltage	Up to about 25 km	Energy distribution in rural areas including medium-sized towns
110 kV	High voltage	Up to about 100 km	Supply of the medium-voltage networks
220 kV, 380 kV	Maximum voltage	Some 100 km to over 1,000 km	Interconnection at national and European level

Voltage Levels in Battery Electric Vehicles

Mild Hybrid	12 – 48 V or HV
Full Hybrid / Plugin	250 – 450 V
Small Electric Vehicle	300 – 400 V
Medium Electric Vehicle	300 – 400 V
Sport Electric Vehicle	300 – 800 V

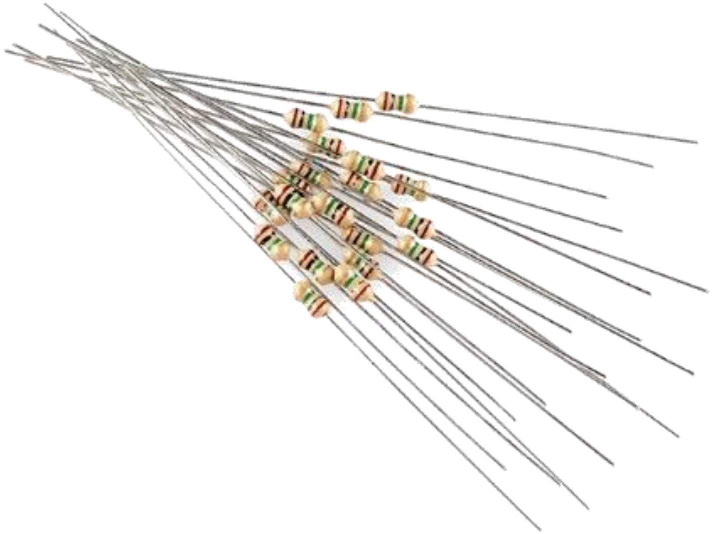
Table based on: https://www.zvei.org/

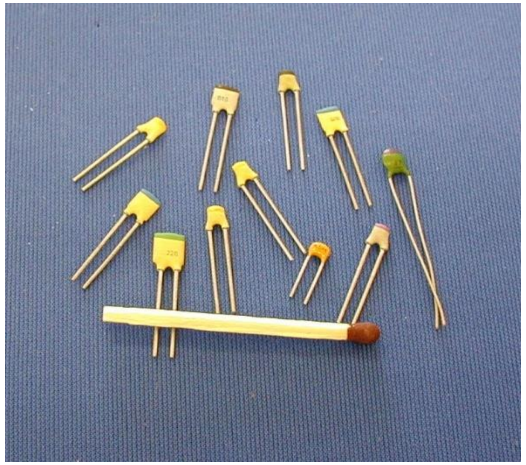
Forms of energy conversion

Electrical energy	→	Thermal energy via resistance (hair dryer, soldering iron, heating stove)
Electrical energy	→	Mechanical energy via electromagnetic field (electric motors)
Electrical energy	→	Chemical energy via electrochemical process (charging of a battery, electrolytic deposition of metals)
Electrical energy	→	Radiant energy via various processes (incandescent lamps, gas discharge lamps, light emitting diodes, laser diodes)

Outline

1. Currents and voltages in electrical networks
2. Resistor
   a. Designs and properties of resistors
   b. Energy conversion in the electrical resistance ("consumer")
3. Capacitor
   a. Principle structure
   b. Various designs
   c. Charging and discharging processes
   d. Application example: micromechanics



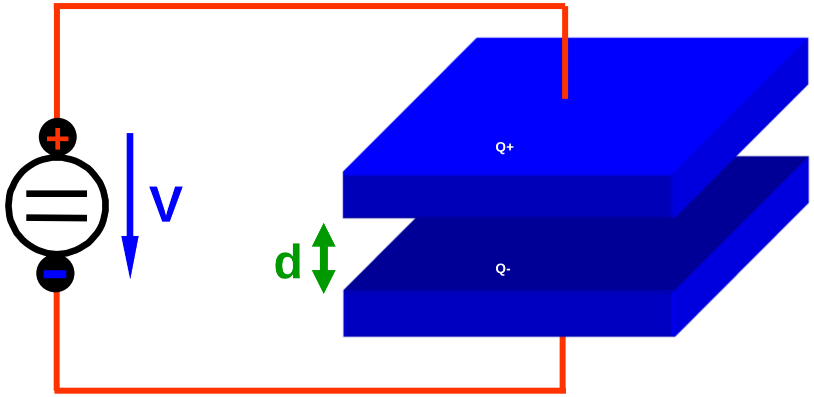


Capacitors

- A capacitor is a passive electrical component.
- A capacitor is a charge and energy storage device.
- Capacitors store the energy in an electrostatic field.
- The stored charge per voltage is called electrical capacitance.
- In an alternating current circuit, a capacitor acts as an alternating current resistor with a frequency-dependent impedance value.
- The name is derived from the Latin von *condensare* (to condense).

- The unit of capacitance is *Farad* $[C] = \frac{\mathrm{A} \cdot \mathrm{s}}{\mathrm{V}} = \mathrm{F}$ (Farad)
  - *Not to confuse with the „capacity“ of a battery (in Ah). Both are „Kapazität“ in German.*

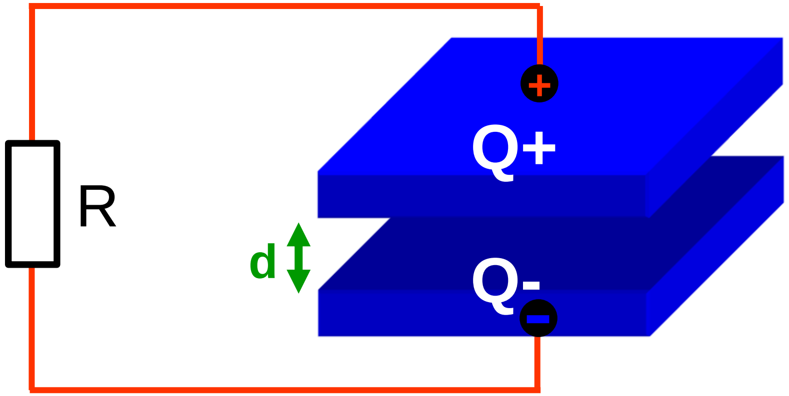
Capacitors - Function



Source: IWE1/RWTH Aachen

Charging the capacitor:
If the capacitor is connected to a DC voltage source, it charges.
More and more charges are brought onto the plates until the source no longer has enough voltage to continue charging the capacitor.

$$Q = C \cdot V$$



Source: IWE1/RWTH Aachen

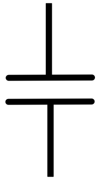
Discharge of the capacitor:
If now both plates of the charged capacitor are shorted via a resistor, a charge balance between positively and negatively charged plates takes place.

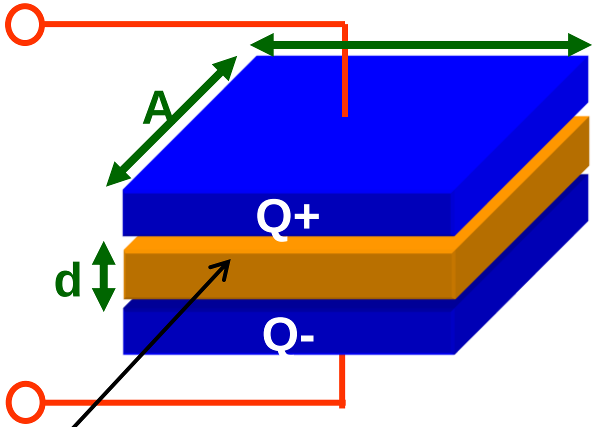
Definition of „Capacitance“

Plate capacitor

The characteristic size of a capacitor is its capacitance ***C***. It describes the amount of charge stored at a certain applied voltage *V*.

$$C = \frac{Q}{V} \qquad [C] = \frac{A \cdot s}{V} = F \ \text{(Farad)}$$

Circuit symbol: 



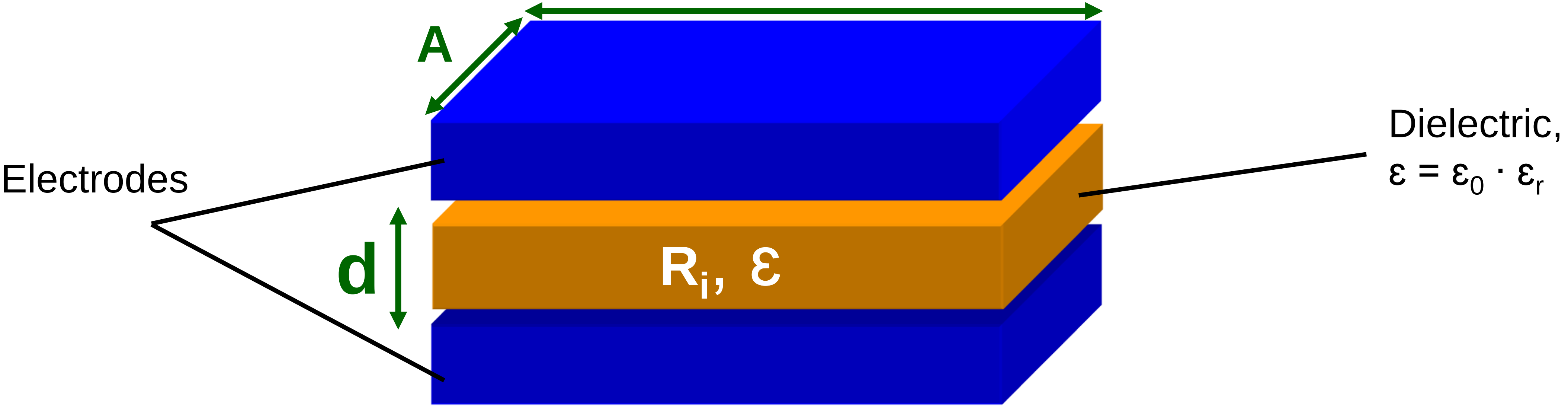
Source: modified according to IWE1/RWTH Aachen

- With plate capacitor *C* the capacitance increases due to the following factors:
  - larger plate surface A
  - smaller plate spacing d
  - higher dielectric constant ε

$$C = \frac{\varepsilon \cdot A}{d} \qquad \varepsilon = \varepsilon_0 \cdot \varepsilon_r \qquad \varepsilon_0 = 8{,}85 \cdot 10^{-12} \frac{As}{Vm}$$

- Increase of capacitance possible by inserting a **dielectric** (non-conductive material)

Schematic of a plate capacitor

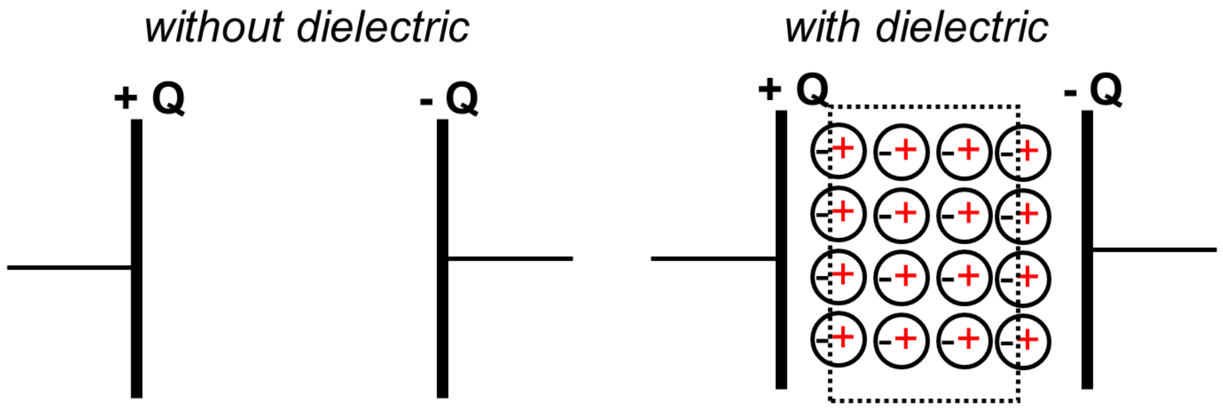


Source: modified according to IWE1/RWTH Aachen

Ideal: resistance of dielectric $R_i \rightarrow \infty$
$\Rightarrow$ no self-discharge

Real: resistance of the dielectric $R_i < 0$
$\Rightarrow$ Self-discharge depending on R_i

Capacitor with and without dielectric



- Electric field induces dipoles in the dielectric
- Inside the dielectric, pos. and neg. charges cancel each other out
- Surface charges are opposite the free charge carriers on the capacitor plates

$$\varepsilon = \varepsilon_0 \cdot \varepsilon_r \quad \text{mit} \quad \varepsilon_0 = 8{,}85 \cdot 10^{-12} \frac{\mathrm{As}}{\mathrm{Vm}}$$

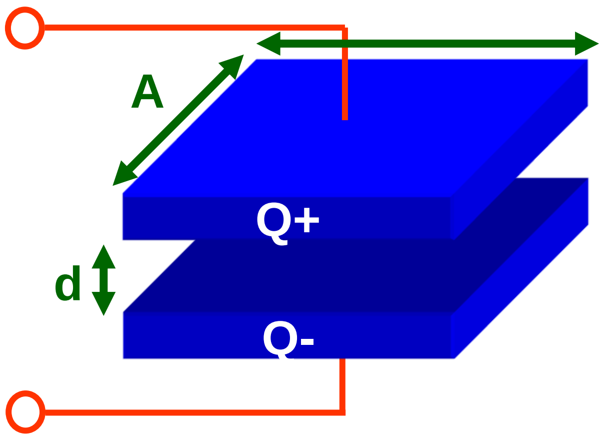
Material	ε_r
Quartz glass	3,75
Pyrex glass	4,3
Porcelain	6-7
Copper oxide CuO_2	18
TiO_2	≈ 80
$CaTiO_3$	≈ 160
$(SrBi)TiO_3$	≈ 1000
Water	81
Ethyl alcohol	25,8
Benzene	2,3
Nitrobenzene	37
Air	1,000576
H_2	1,000264
So_2	1,0099

Source: Demtröder 2

Storable energy

- In order to apply charges to a capacitor, energy is required.
  This is stored on the capacitor.

- $\Delta W = F \cdot \Delta s$ "Work is product of force and displacement" (Def. Work or energy)
- $F = \Delta Q \cdot E$ "Force is motion of charge in an electric field"
- $E = F \,/\, \Delta Q$ Def. of the electric field strength
- $V = E \cdot \Delta s$ „Difference in electric potential between two points"



Source: IWE1/RWTH Aachen

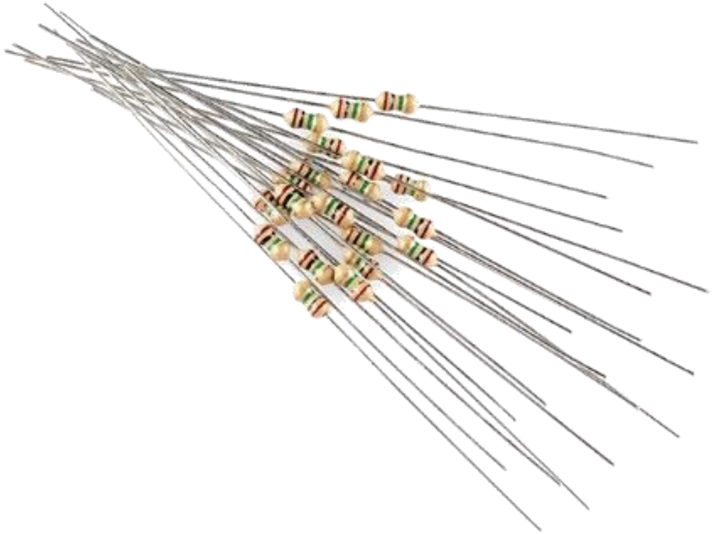
$$\Rightarrow \Delta W = \Delta Q \cdot E \cdot \Delta s = \Delta Q \cdot V$$

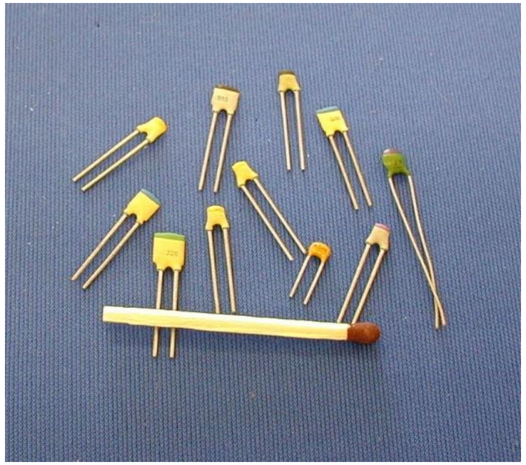
$$\text{with } Q = C \cdot V \Rightarrow V = Q / C$$

$$\Rightarrow W = \frac{1}{C} \int_0^Q Q \, dQ = \frac{1}{2 \cdot C} Q^2 \xRightarrow{Q = C \cdot V} \mathrm{W} = \frac{1}{2} \cdot C \cdot V^2$$

Outline

1. Currents and voltages in electrical networks
2. Resistor
   a. Designs and properties of resistors
   b. Energy conversion in the electrical resistance ("consumer")
3. Capacitor
   a. Principle structure
   b. **Various designs**
   c. Charging and discharging processes
   d. Application example: micromechanics

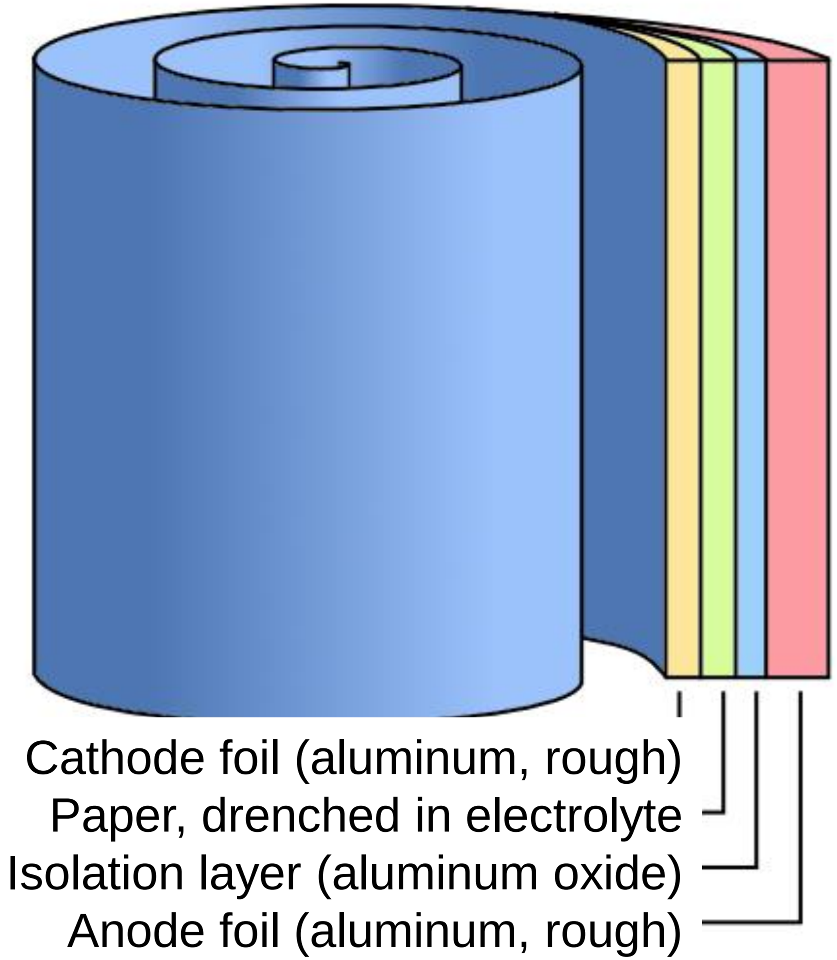




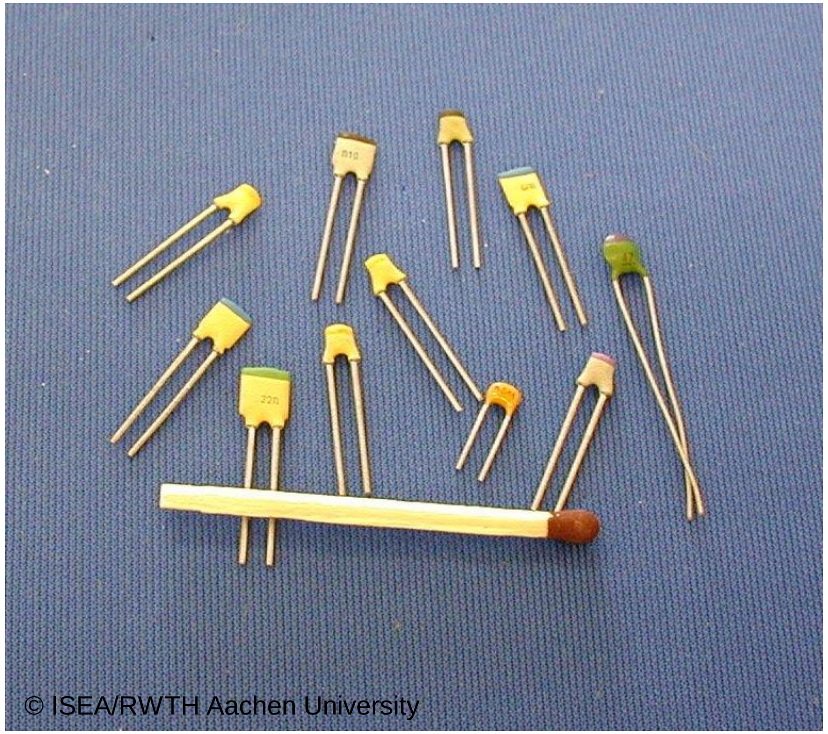
Electrolytic capacitors

Electrolytic capacitor:

- Liquid/solid interface
- High capacitance (> 10 mF)
- Poor frequency response
- Risk of leakage

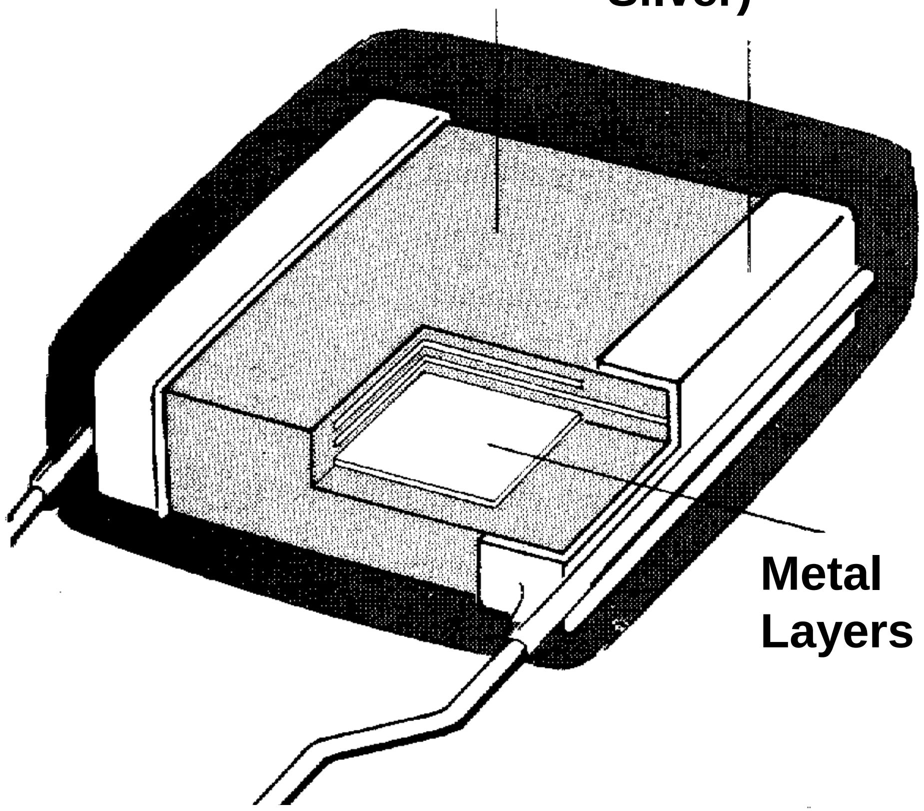


Ceramic Capacitor

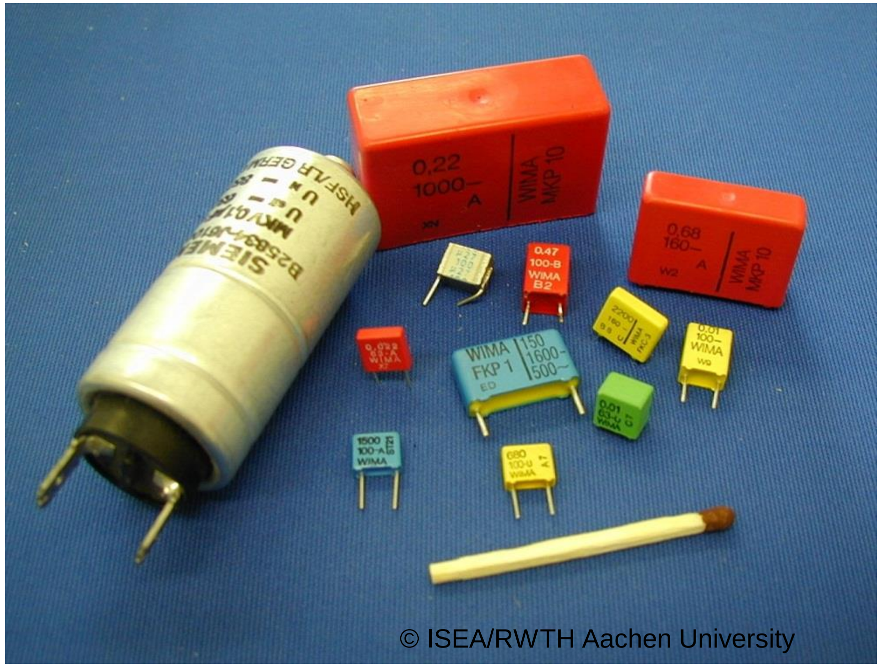


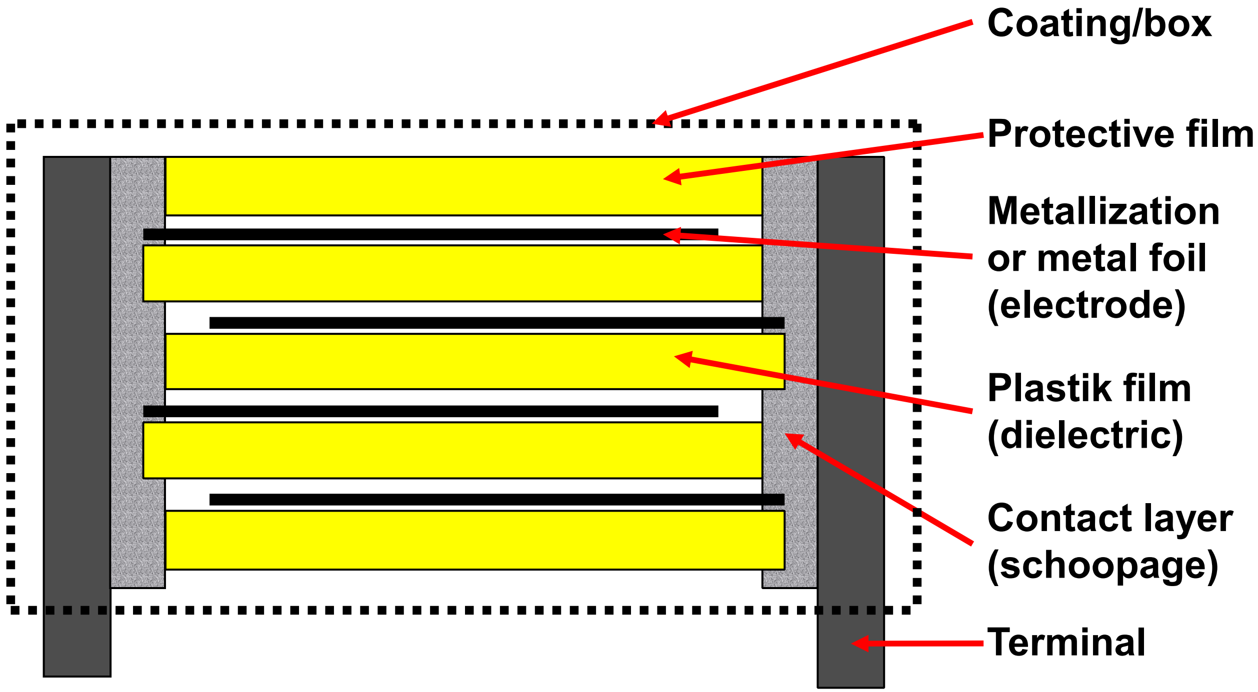
Ceramic capacitor:

- Value for money
- Low capacitances (< 10 µF)
- Poor frequency response



Film Capacitor





Film Capacitor:

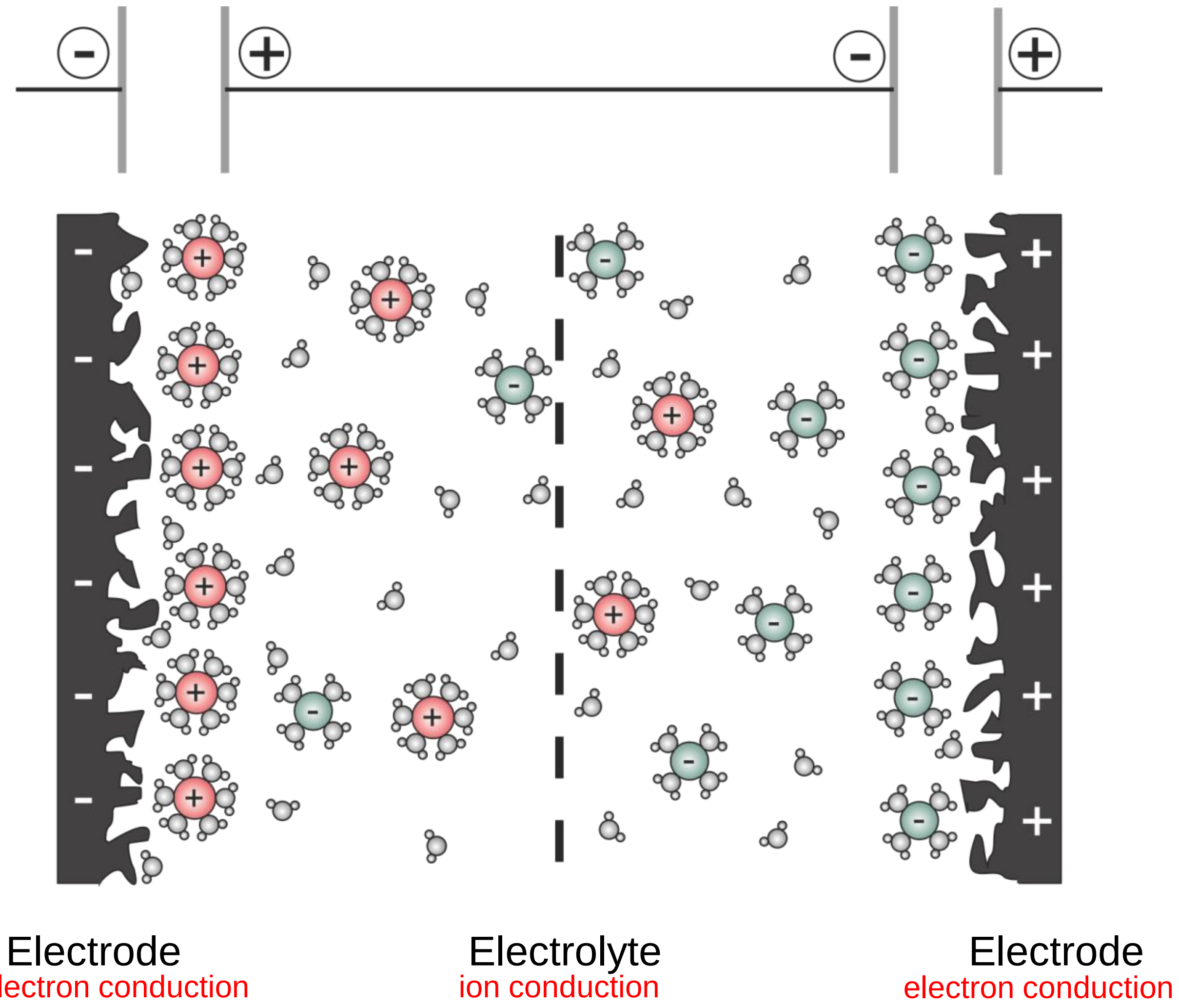
- HF suitable
- Nominal voltage: 50 V - 5 kV
- Capacitance range: 2 pF - 10 mF

Source: User:Elcap [CC0], https://commons.wikimedia.org/wiki/File:Folko-Aufbau-Metall-Metallisiert-engl.svg

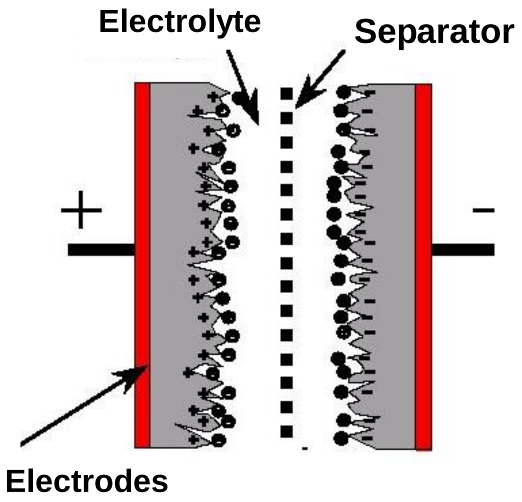
Structure of Electrochemical Double Layer Capacitor

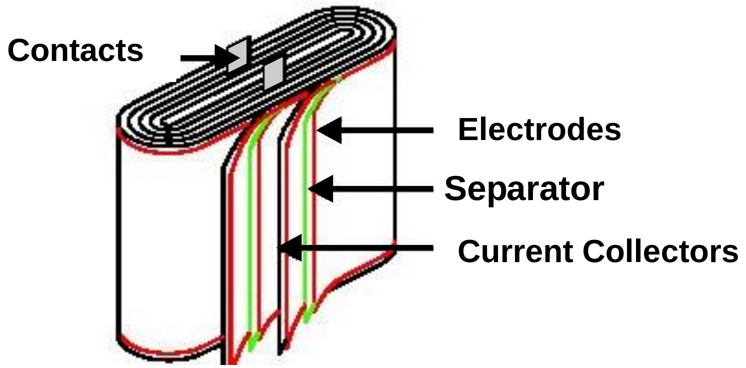
- Also called SuperCap or UltraCap
- Two capacitors in series
- One electrode consists of activated carbon, an electrode is formed by ions in the electrolyte
- Total capacitance is 50% of the capacitance of a single electrode
- Thickness of the double layer in the range of 0.5 - 1 nm
- Double layer capacitance : about 10-20 μF/cm²
- Typical maximum voltages: 2.7 - 3.0 V

$$C = \varepsilon_0 \cdot \varepsilon_r \cdot \frac{A}{d}$$



Designs of Electrochemical Double Layer Capacitor

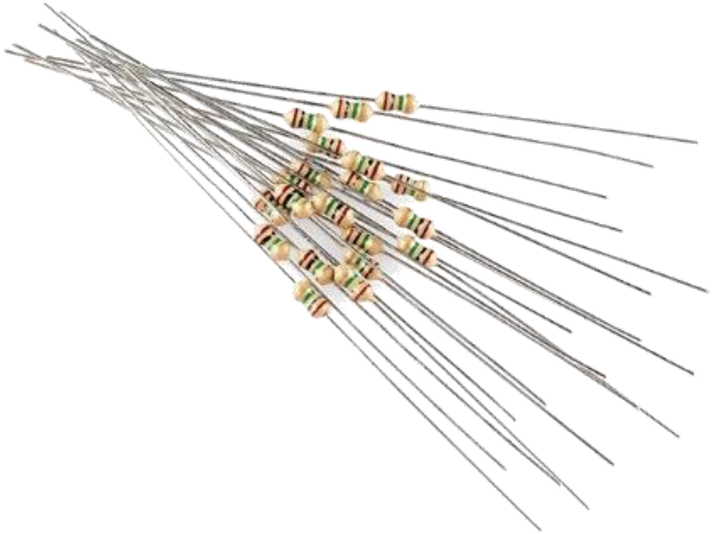


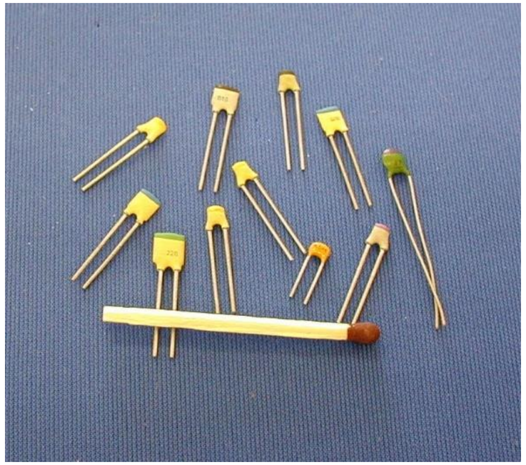


Capacity range: up to 2500 F
Application: High power energy storage with many cycles

Outline

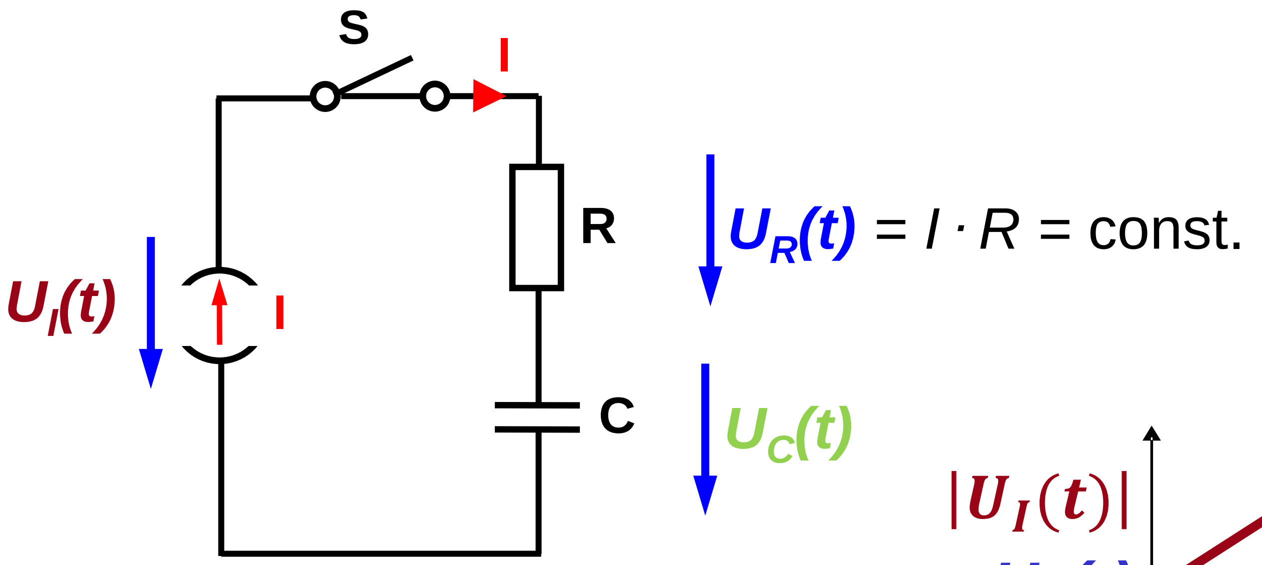
1. Currents and voltages in electrical networks
2. Resistor
   a. Designs and properties of resistors
   b. Energy conversion in the electrical resistance ("consumer")
3. Capacitor
   a. Principle structure
   b. Various designs
   c. **Charging and discharging processes**
   d. Application example: micromechanics



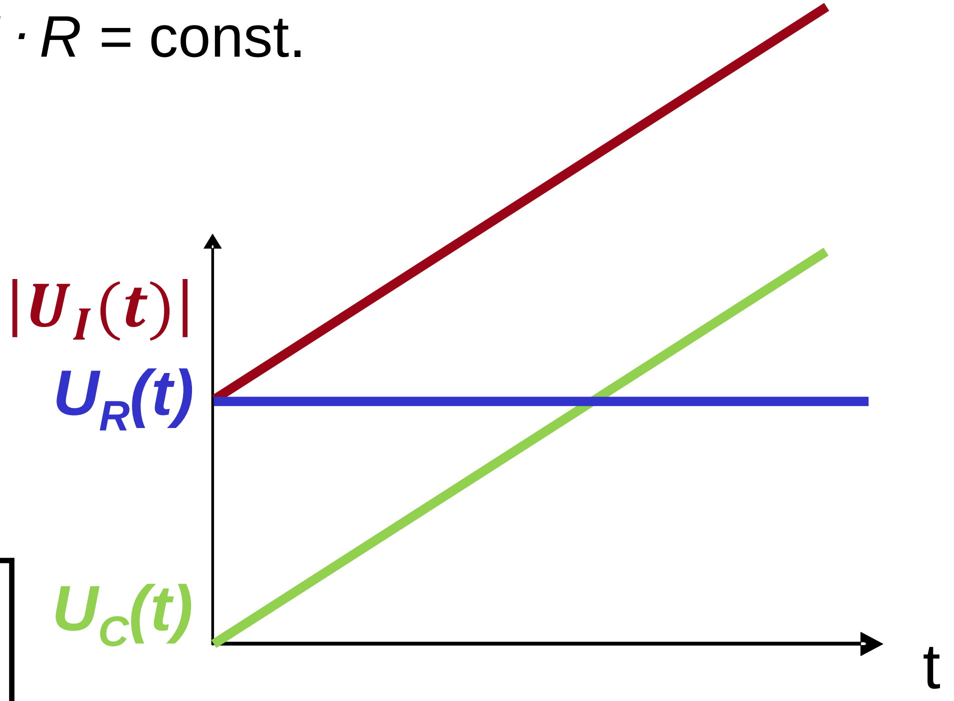


Capacitor in circuit with (ideal) direct current source

- What happens after closing the switch?

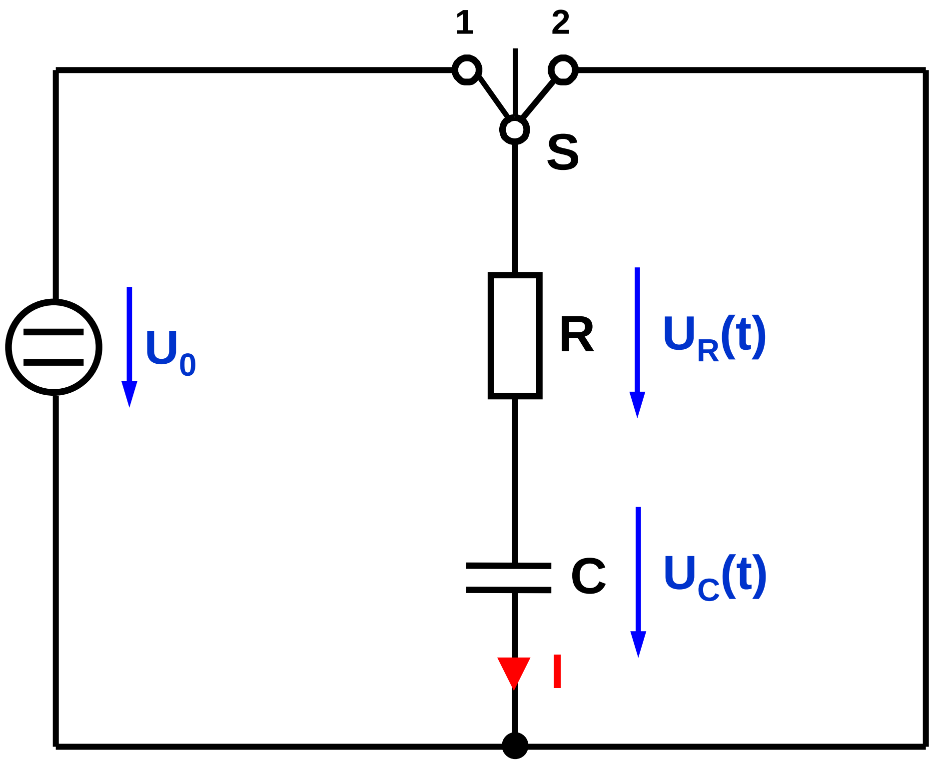


$$U_C(t) = \frac{Q(t)}{C} = \frac{I \cdot t}{C}$$



$$\boxed{u_C(t) - u_C(0) = \frac{1}{C}\int_0^t i_C(t)\mathrm{d}t \quad \Leftrightarrow \quad i_C(t) = C \cdot \frac{\mathrm{d}u_C(t)}{\mathrm{d}t} = \frac{\mathrm{d}q_C(t)}{\mathrm{d}t}}$$

Charging a capacitor



S in position 2
C discharged.

t = t_0: S is moved to position 1

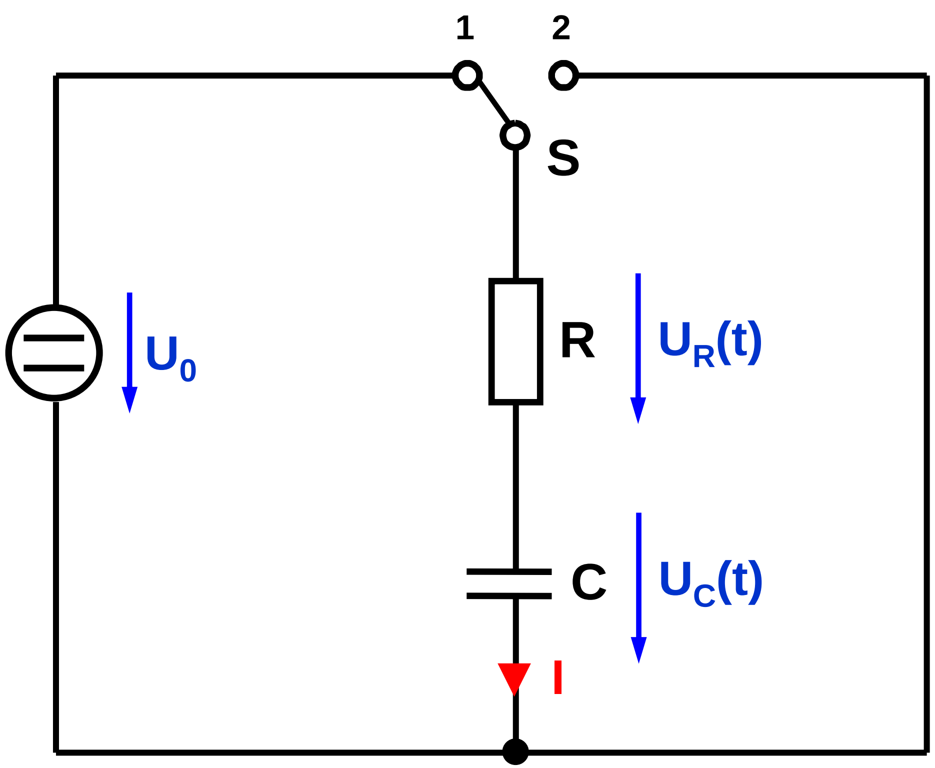
$$U_C(t_0) = 0;\ U_R(t_0) = U_0 \text{ und } I_C(t_0) = \frac{U_0}{R}$$

The capacitor is now being charged:

$$U_0 = U_R(t) + U_C(t)$$

$$U_0 = R \cdot I(t) + \frac{\int I(t)dt}{C}$$

Charging a capacitor



$$U_0 = R \cdot I(t) + \frac{\int I(t)dt}{C}$$

Differentiate by *t*

$$0 = R \cdot \frac{dI}{dt} + \frac{I(t)}{C} \Rightarrow \frac{dI(t)}{I(t)} = -\frac{dt}{R \cdot C}$$

Integration $\left[\int \frac{1}{x} dx = ln(x) + const.\right]$

$$\ln(I(t)) = -\frac{t}{R \cdot C} + \text{const.}$$

Initial conditions

$$U_R(t=0) = U_0 \Rightarrow I(t=0) = \frac{U_0}{R}$$

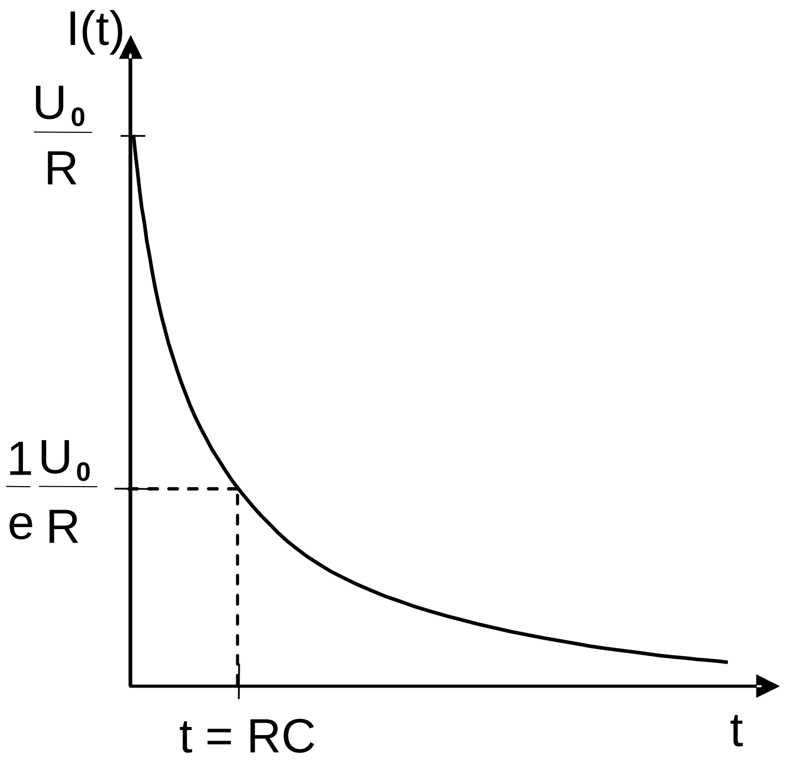
$$\ln(I(t)) = -\frac{t}{R \cdot C} + \ln\left(\frac{U_0}{R}\right) \quad \ln(a) - \ln(b) = ln\frac{a}{b}$$

$$\boxed{I(t) = \frac{U_0}{R} \cdot e^{\frac{-t}{R \cdot C}}}$$

Charging a capacitor

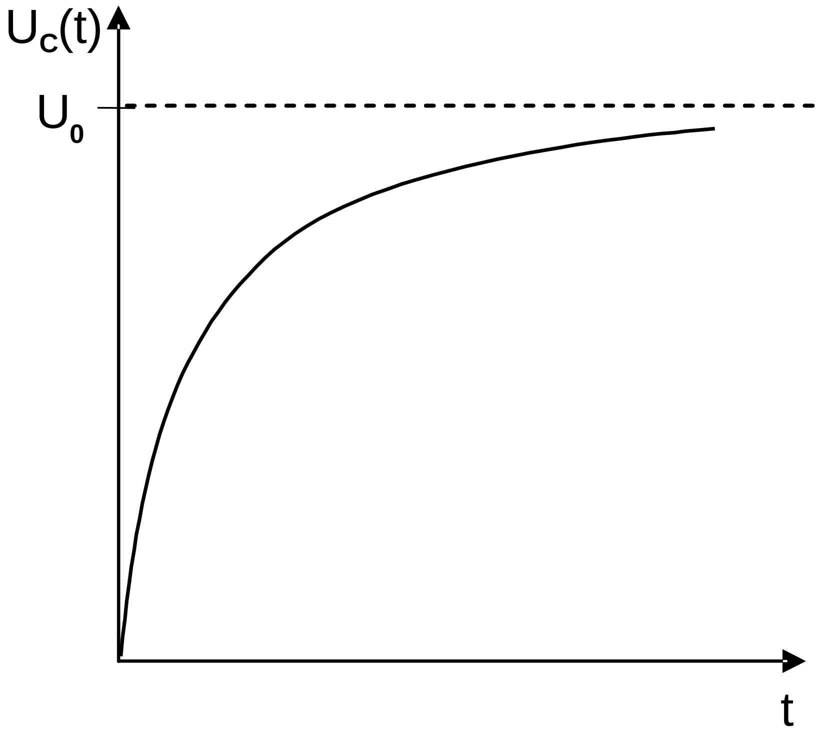
- Current and voltage at resistor and capacitor are time-dependent
- The current through the resistor decreases exponentially
- When the capacitor is charged, no more current flows
- Uncharged capacitor: Short circuit
- Charged capacitor: open terminals

Current flow through R:



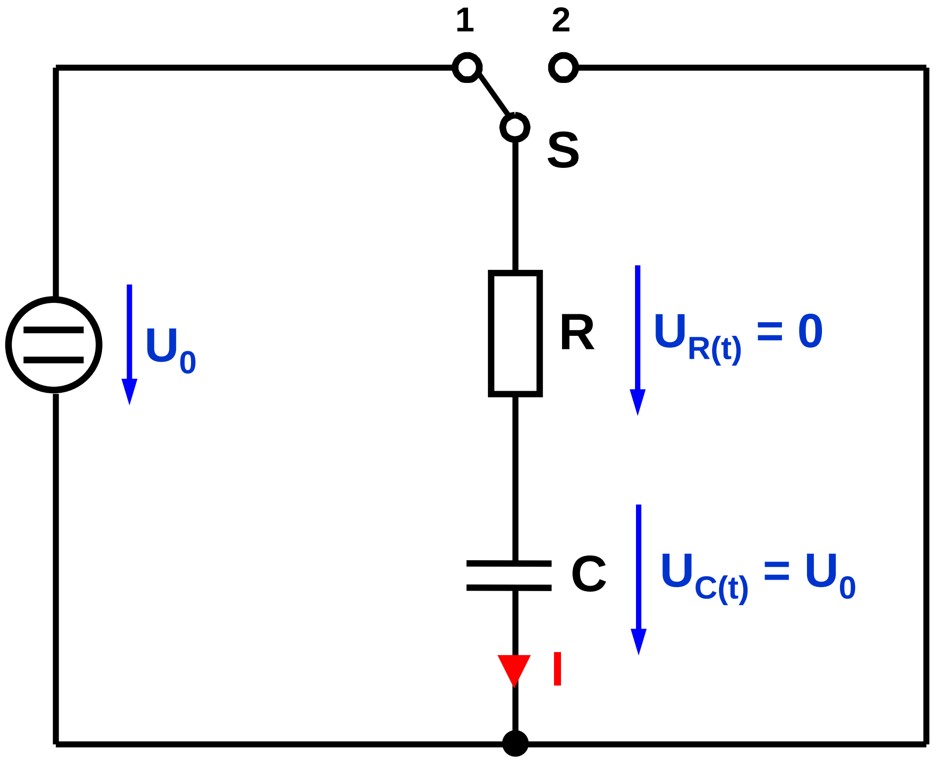
$$I(t) = \frac{U_0}{R} \cdot e^{\frac{-t}{R \cdot C}}$$

Voltage curve at C:



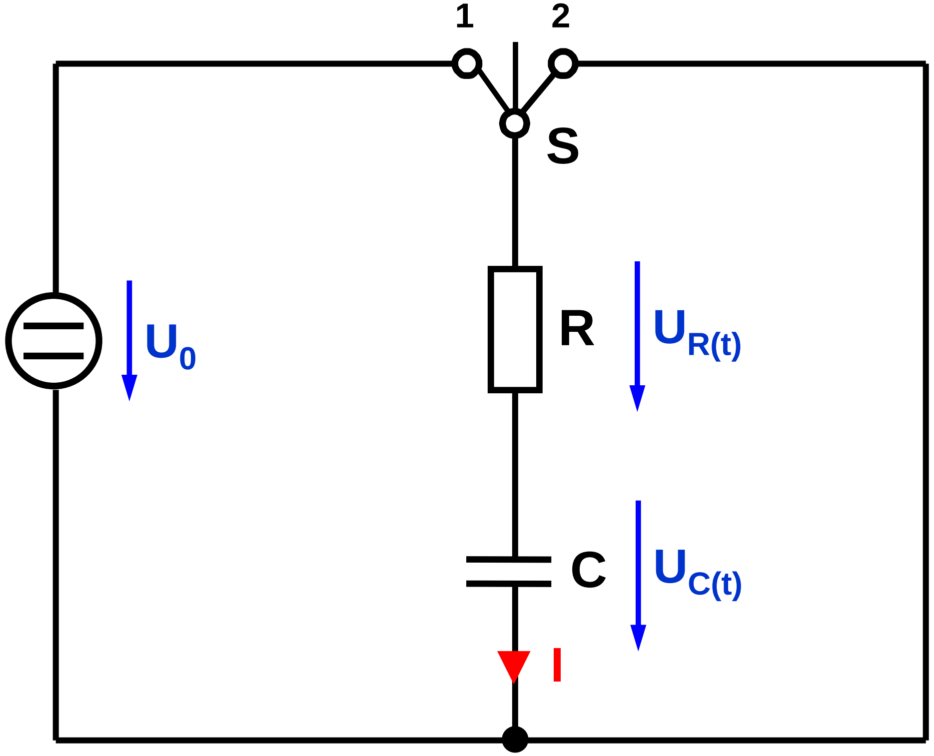
$$U_C(t) = U_0 (1 - e^{\frac{-t}{R \cdot C}})$$

Discharging a Capacitor



S at position 1 → C loaded.

Discharging a Capacitor



S at position 1 → C is charged.

$t = t_0$: S is moved to position 2

The capacitor is now discharged:

$$U_R(t) = -U_C(t)$$

$$U_C(t_0) = U_0$$

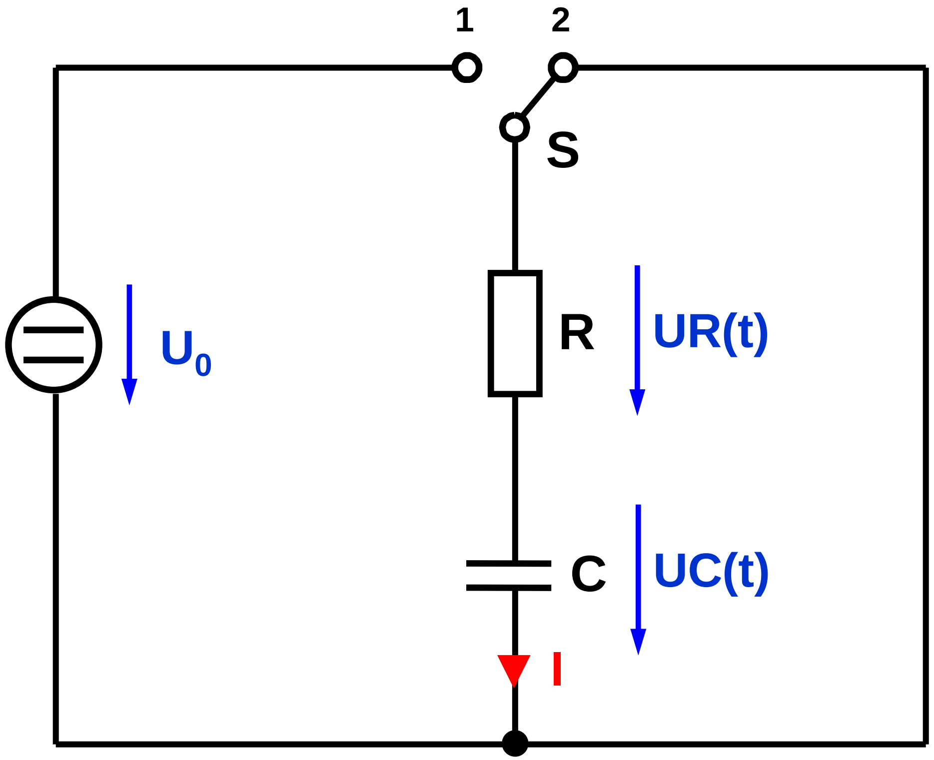
$$U_R(t_0) = -U_0$$

$$I_C(t_0) = -\frac{U_o}{R}$$

Integral equation

$$R \cdot I_R(t) = -\frac{\int I(t)dt}{C}$$

Discharging a Capacitor



$$R \cdot I(t) = -\frac{\int I(t)dt}{C}$$

Differentiate by *t*

$$R \cdot \frac{dI(t)}{dt} = -\frac{I(t)}{C}$$

$$\frac{dI(t)}{I(t)} = -\frac{dt}{R \cdot C}$$

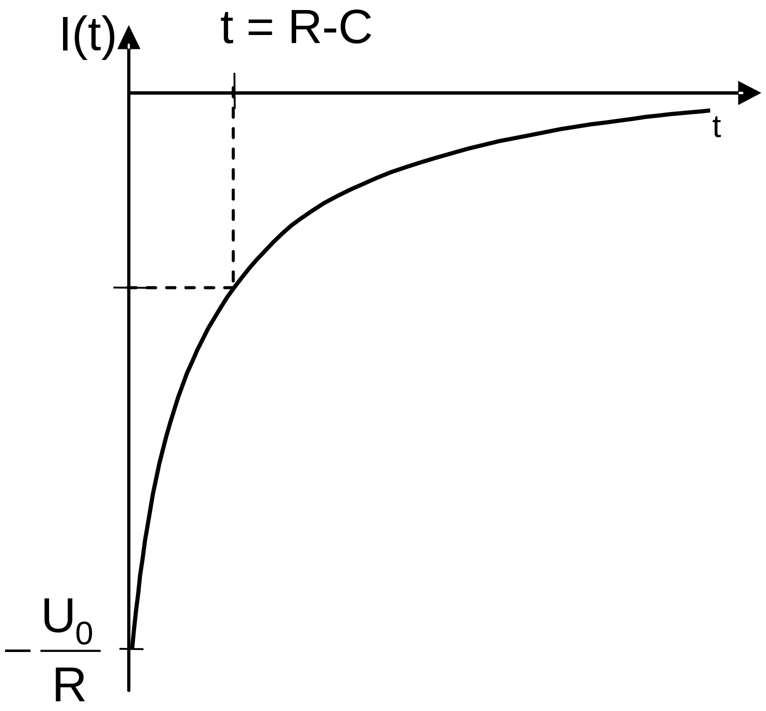
$$\ln(I(t)) + const. = -\frac{t}{R \cdot C}$$

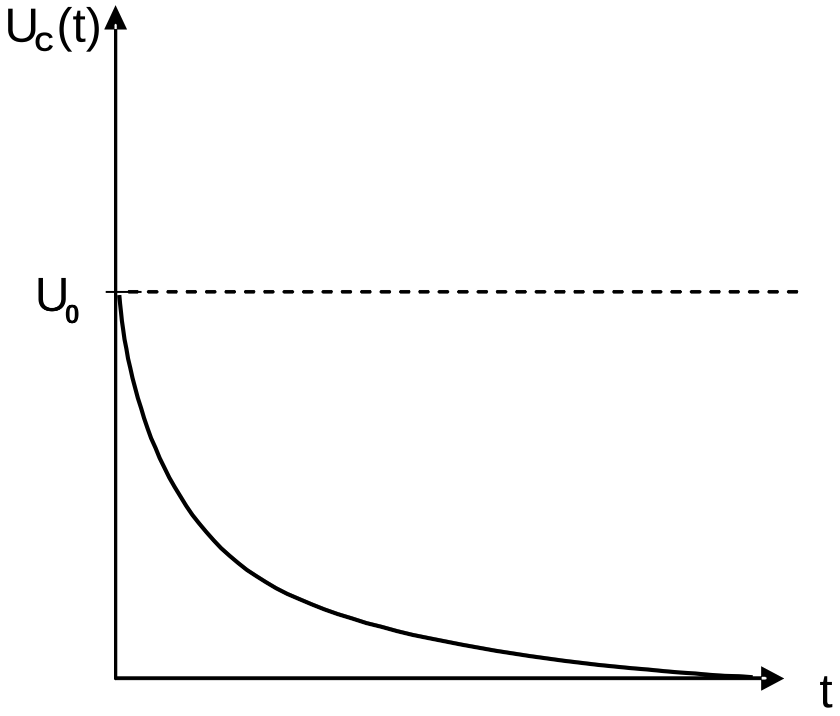
$$\boxed{I(t) = -\frac{U_o}{R} \cdot e^{-\frac{t}{R \cdot C}}}$$

Discharging a Capacitor

- Current and voltage at resistor and capacitor are time-dependent
- The current through the resistor decreases exponentially
- If the capacitor is discharged, no more current flows
- Uncharged capacitor: Short circuit

At time $t = R \cdot C$ the current through R has dropped to $\frac{1}{e}$ = 36.8% of the initial current.





$$I(t) = -\frac{U_o}{R} \cdot e^{-\frac{t}{R \cdot C}}$$

$$U_C(t) = U_0(e^{\frac{-t}{R \cdot C}})$$

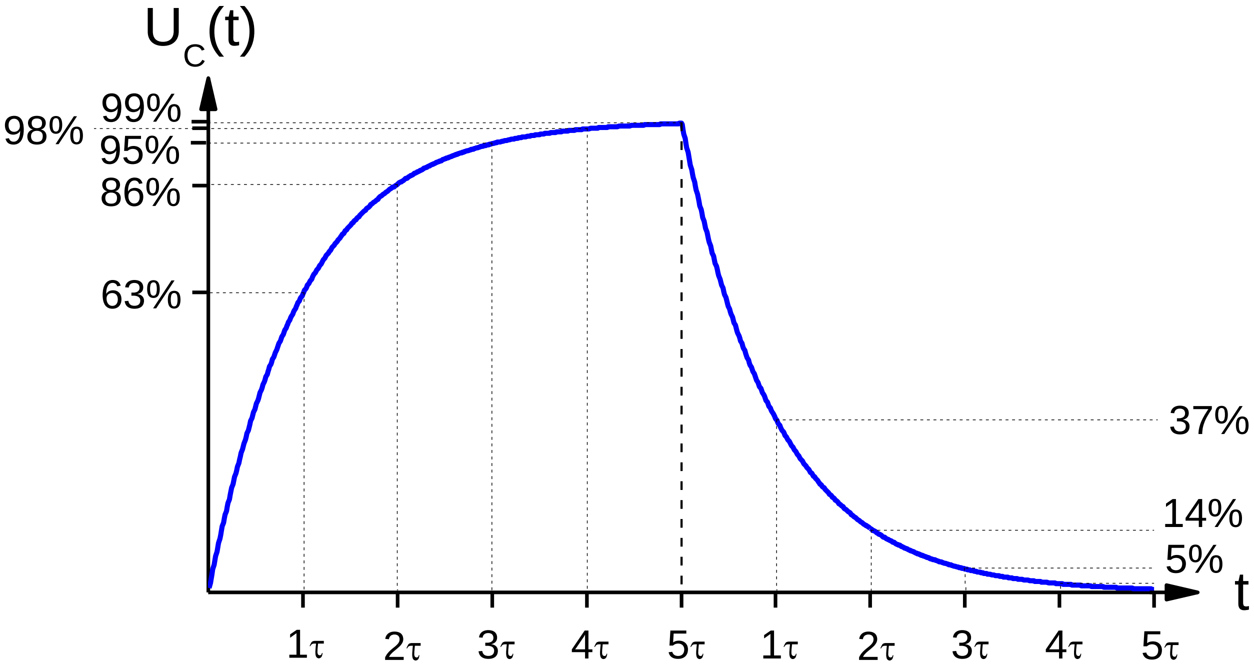
Charging and discharging time of the capacitor

The time constant serves to describe the charging and discharging time $\tau = R \cdot C$.

- Charging / discharging therefore faster at
  - Smaller capacitance C
  - Smaller resistance R

$$U_C(t) = U_0 \left(e^{\frac{-t}{R \cdot C}}\right)$$

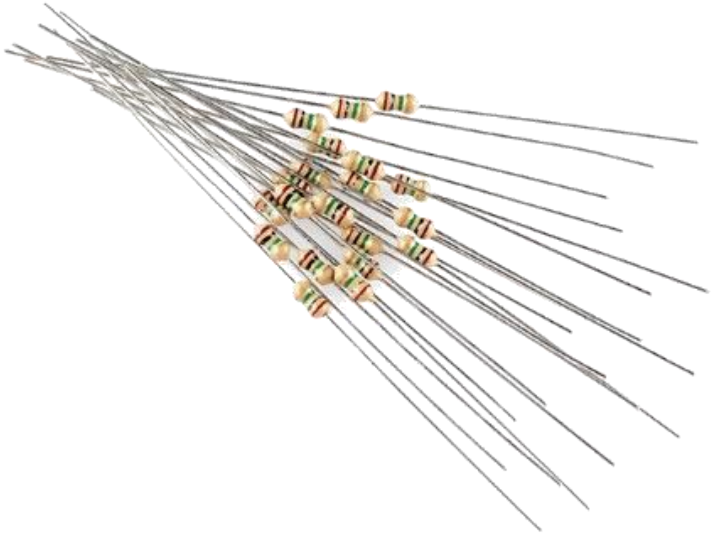
$$U_C(t) = U_0 \left(1 - e^{\frac{-t}{R \cdot C}}\right)$$

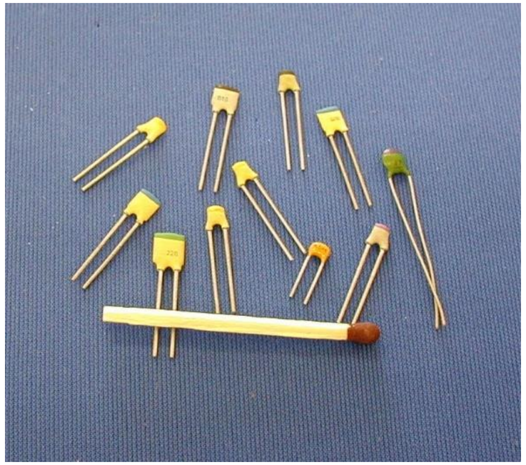


Date	Charge voltage at the capacitor	$\%U_0$
1τ	$U_{C1\tau} = 0{,}63 \cdot U_0$	63
2τ	$U_{C2\tau} = 0{,}86 \cdot U_0$	86
3τ	$U_{C3\tau} = 0{,}95 \cdot U_0$	95
4τ	$U_{C4\tau} = 0{,}98 \cdot U_0$	98
5τ	$U_{C5\tau} = 0{,}99 \cdot U_0$	99 ~ 100

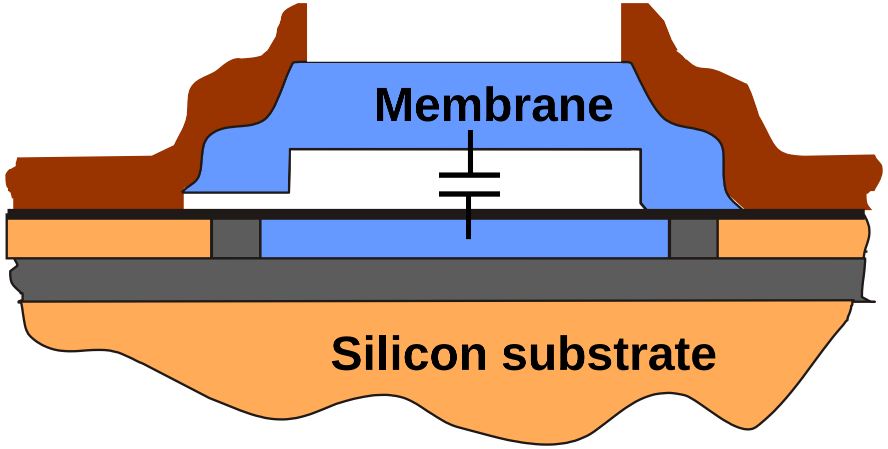
Outline

1. Currents and voltages in electrical networks
2. Resistor
   a. Designs and properties of resistors
   b. Energy conversion in the electrical resistance ("consumer")
3. Capacitor
   a. Principle structure
   b. Various designs
   c. Charging and discharging processes
   d. **Application example: micromechanics**

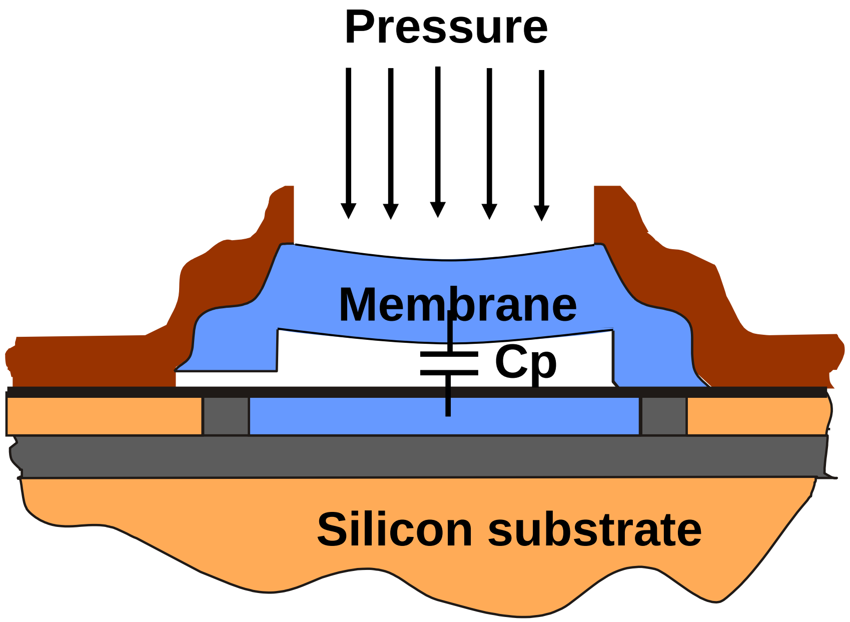




Application example: Pressure sensor membranes



Pressure sensor diaphragms in unloaded condition

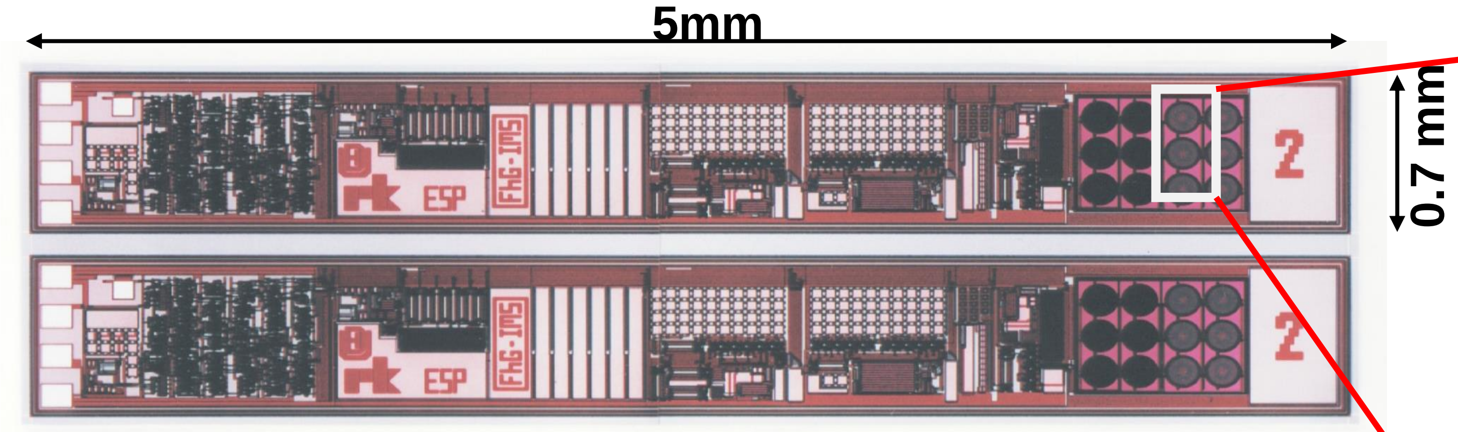


Pressure sensor diaphragms in loaded condition

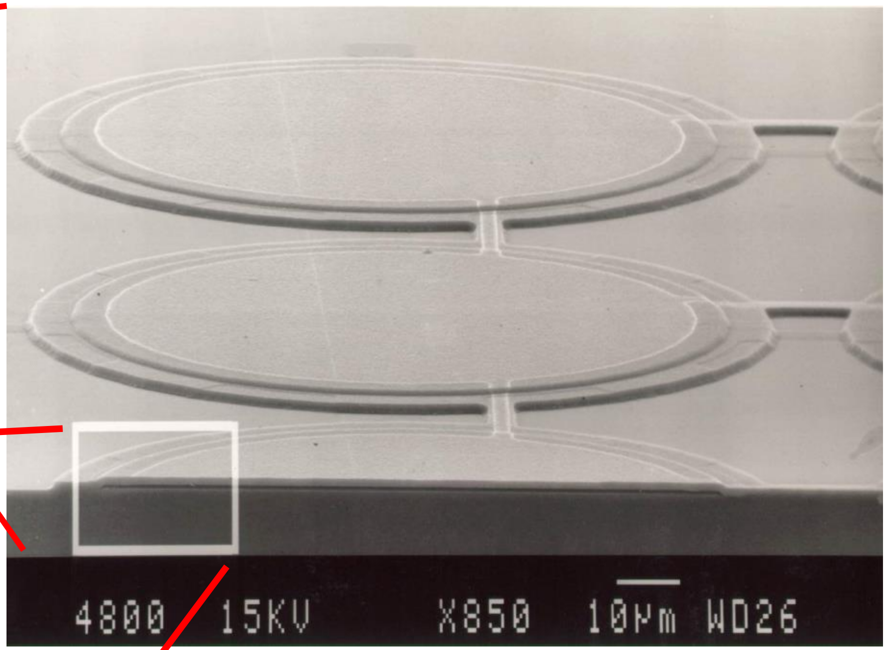
- Pressure changes the capacitance of the capacitor
- Capacitance change leads to voltage change, e.g. with $Q = \text{const.}$ ➔ $= Q / \Delta C$
- Various applications, e.g. in microphones

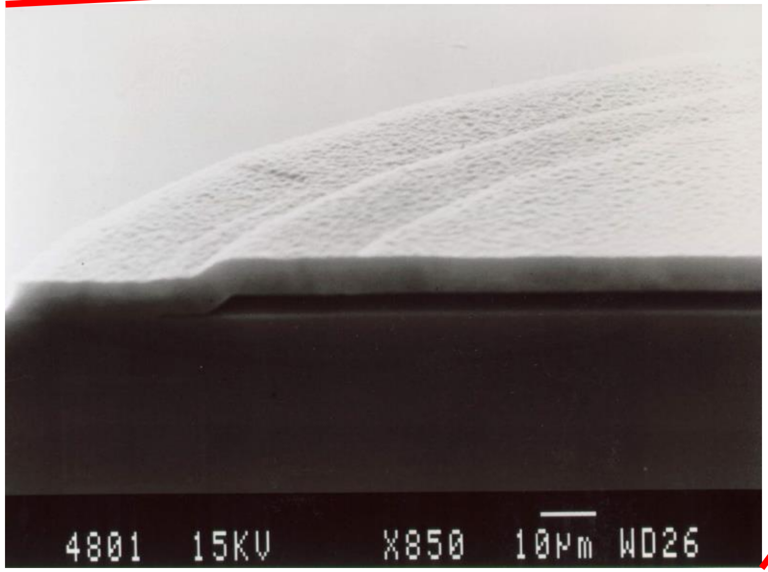
Surface micromechanical pressure sensors

Source: FhG IMS Duisburg



Monolithically integrated capacitive pressure sensor chips





Close-ups of
Pressure sensor membranes

Numerical example: Micromechanically Manufactured Pressure Sensor

- Assumption: Electrode surface A = (100 µm)**²** ; distance between both electrodes 1 µm

$$C = 8{,}854 \cdot 10^{-12}\,\frac{\mathrm{As}}{\mathrm{Vm}} \cdot \frac{100 \cdot 100 \cdot 10^{-6} \cdot 10^{-6}\,\mathrm{m}^2}{10^{-6}\,\mathrm{m}}$$

$$= 8{,}854 \cdot 10^{-14}\,\mathrm{F} \cong 88\,\mathrm{fF}$$

- At a voltage of U = 1 V, how many electrons are on one electrode of the pressure sensor?
- The following applies: $Q = 8{,}8 \cdot 10^{\mathbf{-14}}$ As with $e_0 = 1{,}6 \cdot 10^{\mathbf{-19}}$ As

  ⇒ $\mathbf{N_{Electrons}} = Q / e_0 = 5{,}5 \cdot 10^{\mathbf{5}}$

- Assumption: The capacitor plates are discharged linearly in one second.

  ⇒ $I = Q / t = 8{,}8 \cdot 10^{\mathbf{-14}}$ A

Properties of the capacitor

- Acts like a short circuit at the moment of switch-on
  - ➔ therefore acts as if it were not present at very high frequencies
  - ➔ if a capacitor is connected to a very strong current source (e.g. a battery), the electronics are destroyed by the large current flow

- Can store electrical charge and thus also energy

- Blocks the direct current, thus acting as an infinitely large resistance at frequency 0 Hz

- Charges and discharges in an exponential function

Summary Capacitors

- Electrical charges and energy can be stored in a capacitor
- Capacitance: $C = Q / V$ or $Q = C \cdot V$
- The following applies to plate capacitors: $C = \frac{\varepsilon \cdot A}{d}$ with $\varepsilon = \varepsilon_0 \cdot \varepsilon_r$
- Stored energy: $W = \frac{1}{2} \cdot C \cdot \mathrm{V}^2$
- Charging process of a capacitor: $I(t) = \frac{\mathrm{V}_0}{R} \cdot e^{-\frac{t}{R \cdot C}}$
- Discharge process of a capacitor: $I(t) = -\frac{\mathrm{V}_0}{R} \cdot e^{-\frac{t}{R \cdot C}}$

Batteriealterung • Batteriemodelle • Batteriediagnostik • Batteriepackdesign • Elektromobilität • Stationäre Energiespeicher • Energiesystemanalyse

Electrical Components and Their Nomenclature

21.04.2023
Dr. Florian Ringbeck

Lehrstuhl für Elektrochemische Energiewandlung und Speichersystemtechnik

Stromrichtertechnik und Elektrische Antriebe
RWTH AACHEN UNIVERSITY