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The Fundamentals of Electrical Engineering

Felix Hüning

ISBN: 978-3-11-034991-7

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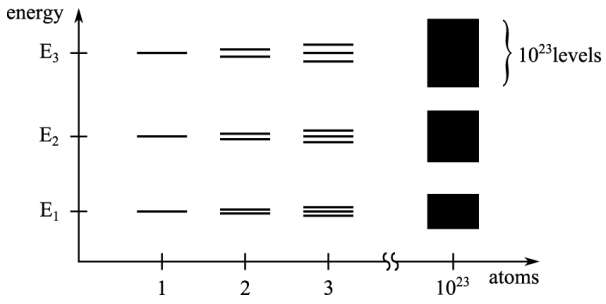

Fig. 1.1: Splitting of discrete energy levels into energy bands for increasing number of atoms.

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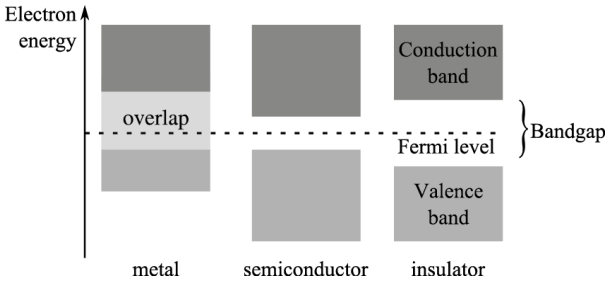

Fig. 1.2: The electronic band structure of solids: metal (left); semiconductor (center); insulator (right).

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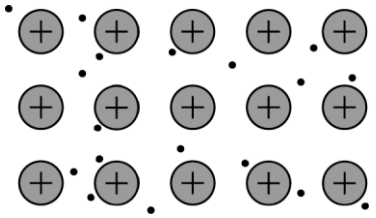

Fig. 1.3: The crystal structure of a metal: positively charged atomic cores surrounded by delocalized free electrons.

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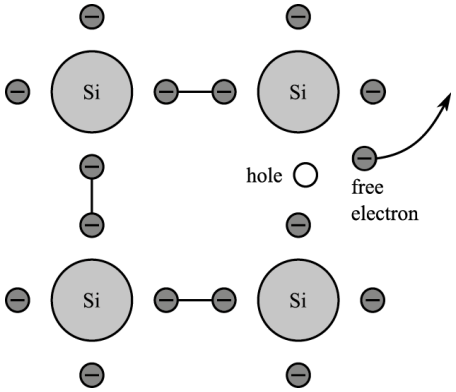

Fig. 1.4: The crystal structure of silicon.

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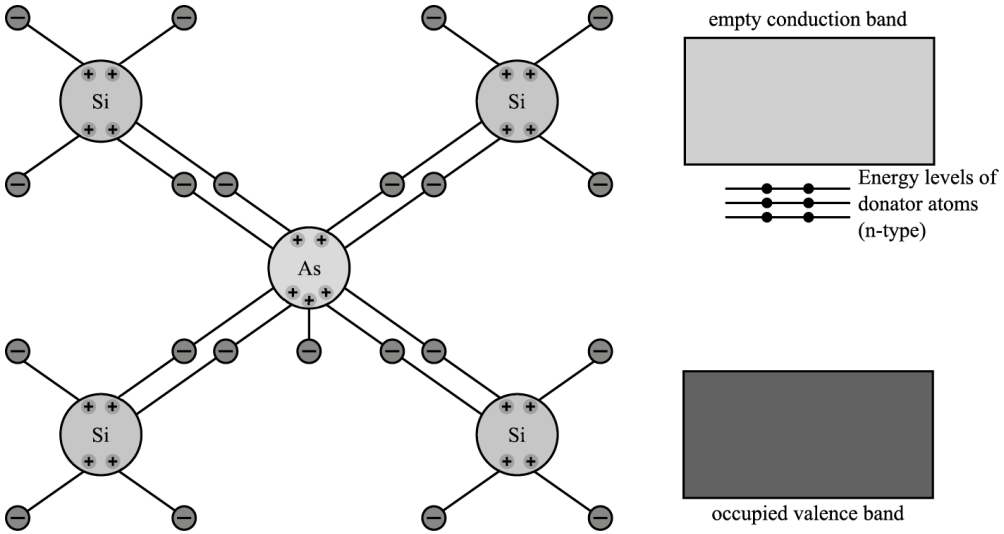

Fig. 1.5: The crystal structure of arsenic-doped silicon, n-type semiconductor (left) and the band structure of a n-type semiconductor showing the donator's energy levels within the band gap (right).

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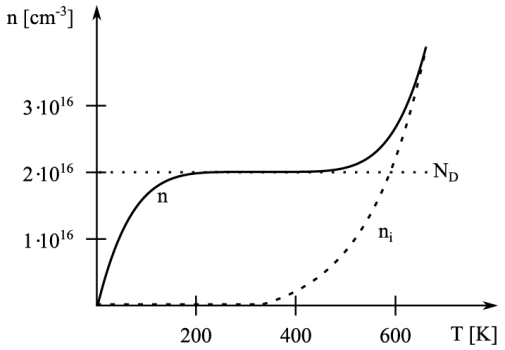

Fig. 1.6: The carrier density n of an n-type semiconductor as a function of temperature: solid line = total carrier density n, dotted line = intrinsic carrier density n_i; N_D is the density of impurity atoms.

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Classification	Material	Specific conductivity σ [S/m]
Metal	Silver	$61 \cdot 10^6$
	Copper	$58 \cdot 10^6$
	Iron	$10 \cdot 10^6$
Semiconductor	Germanium	1.45
	Silicon (pure)	$252 \cdot 10^{-6}$
Insulator	Plastic material	$< 10^{-9}$
	Glas	$< 10^{-9}$
	Diamond	$< 10^{-9}$

Tab. 1.1: The conductivity values and electrical classification for certain materials.

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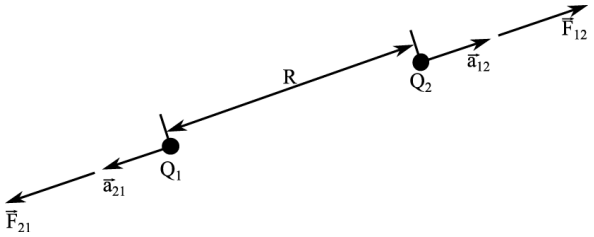

Fig. 2.1: An illustration of Coulomb's law.

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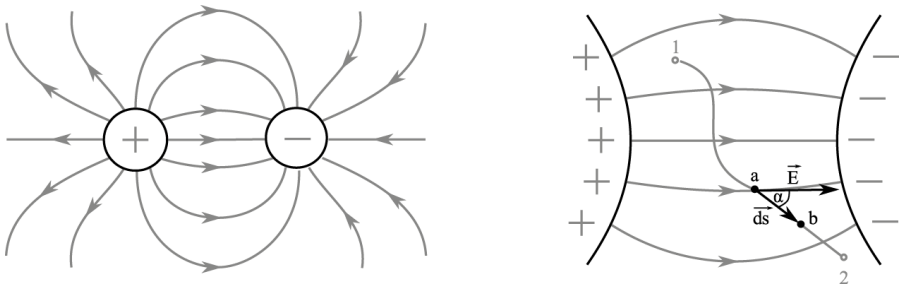

Fig. 2.2: Electric field lines for two charges (left) and the voltage in an inhomogeneous electric field (right).

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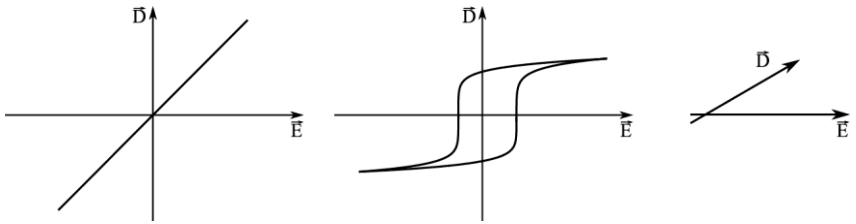

Fig. 2.3: The relationship between electric and displacement field : linear with constant ε_r (left); non-linear with hysteresis shape (center); anisotropic (right).

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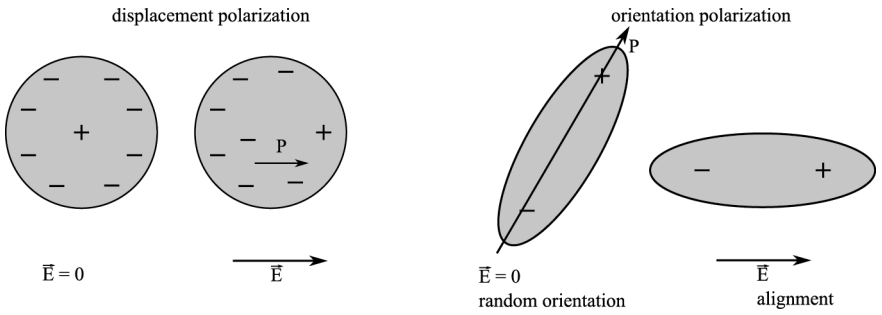

Fig. 2.4: The displacement polarization (left) and orientation polarization (right).

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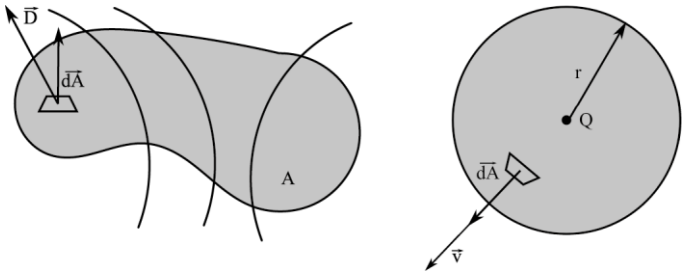

Fig. 2.5: Electric flux $\vec{D}$ through a surface $\vec{A}$ with surface element d $\vec{A}$

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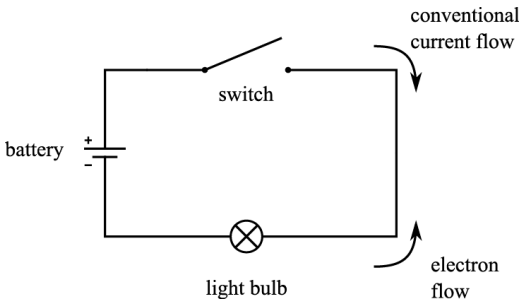

Fig. 2.6: The definition of conventional (technical) current flow (flow of positive charge carriers) and the direction of electron flow.

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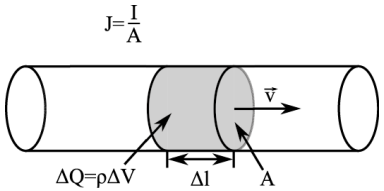

Fig. 2.7: The current density J for a current flowing in a wire with cross-section A

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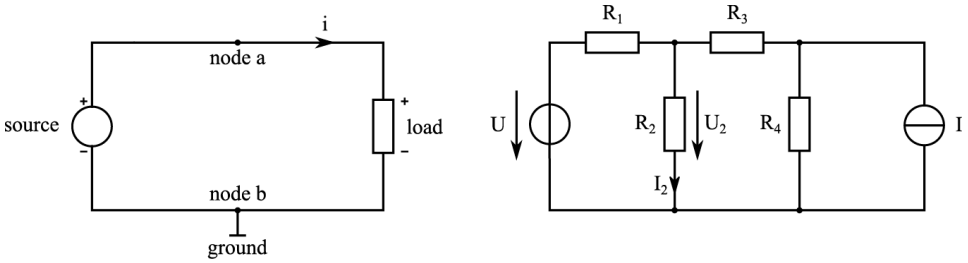

Fig. 3.1: Simple electric circuits or networks.

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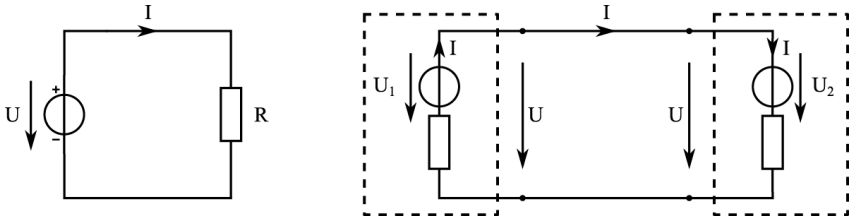

Fig. 3.2: The direction of current and voltage.

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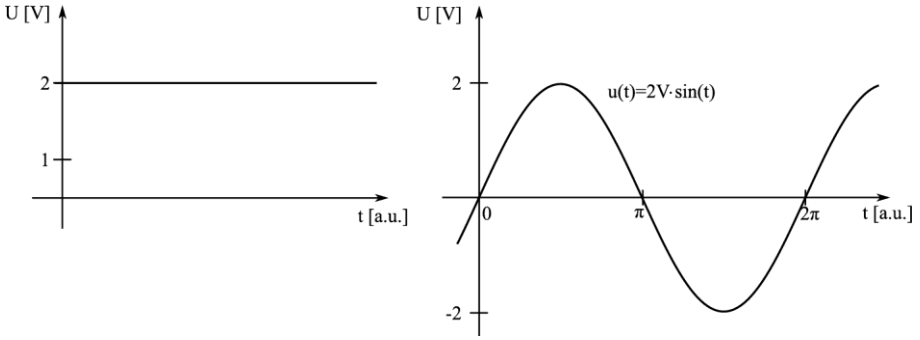

Fig. 3.3: Constant (left) and time-dependent (right) voltage source.

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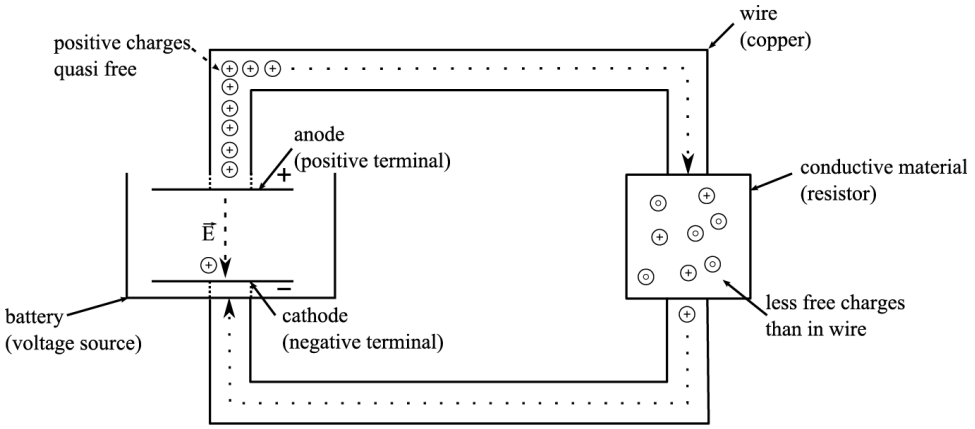

Fig. 3.4: A simple electric circuit with an ideal voltage source.

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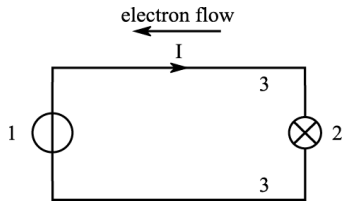

Fig. 3.5: A simple electric circuit indicating the direction of current flow I and the direction of electrons.

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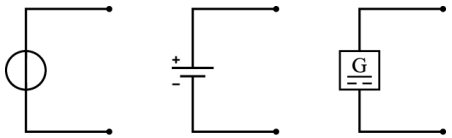

Fig. 3.6: A simple notation of voltage sources: general symbol (left), electrochemical symbol (battery, center), DC generator (right).

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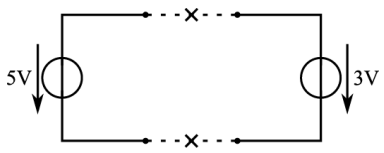

Fig. 3.7: Do not connect ideal voltage sources in parallel.

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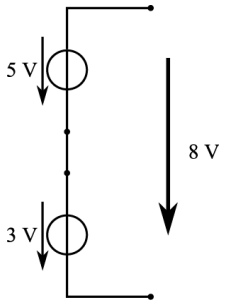

Fig. 3.8: The permitted connection of two ideal voltage sources in series.

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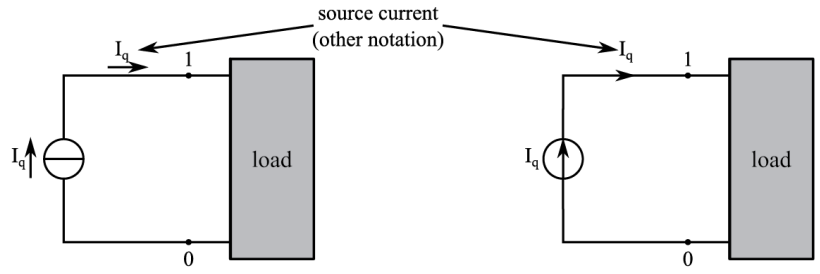

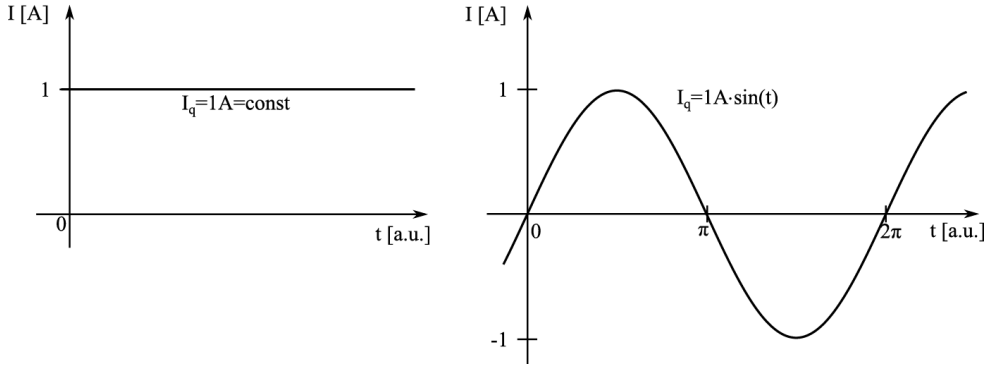

Fig. 3.9: Models of ideal current sources (top) and current waveforms (bottom).

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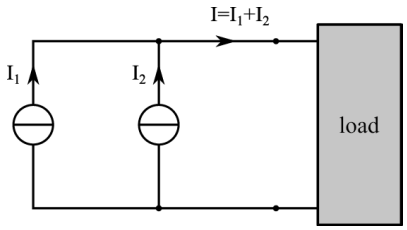

Fig. 3.10: Two ideal current sources connected in parallel.

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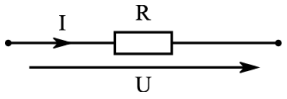

Fig. 3.11: Current I and voltage U for a resistor R.

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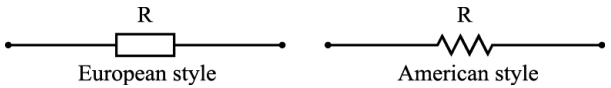

Fig. 3.12: Different models for resistors used in electric circuits: European style (left) and American style (right).

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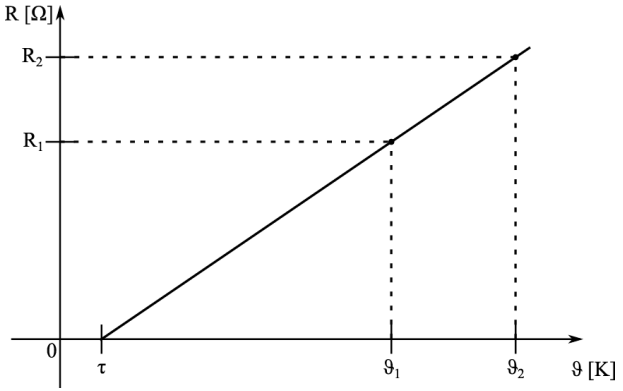

Fig. 3.13: Temperature dependence of the resistance of a conductor.

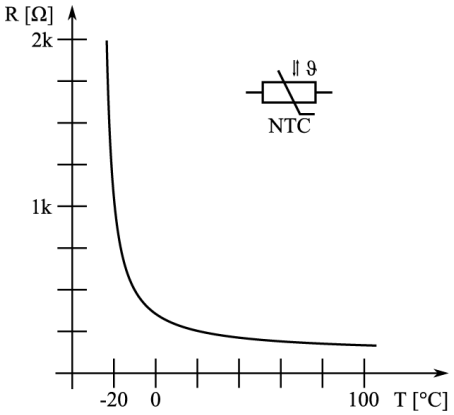

Fig. 3.14: Typical characteristic of a NTC and circuit symbol.

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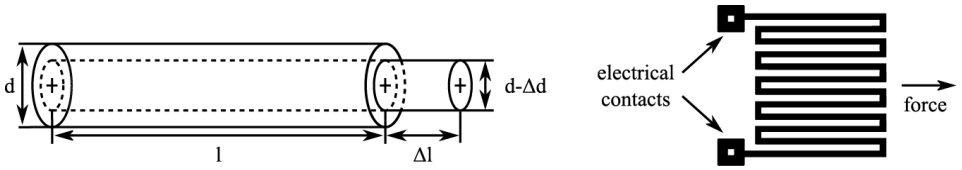

Fig. 3.15: Geometric changes of a bar of material in case of lengthening (left); resistance strain gauge with a meander like structure.

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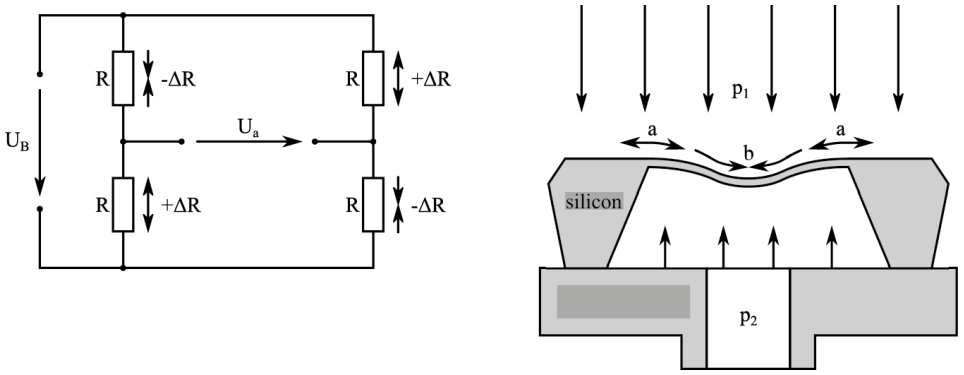

Fig. 3.16: A Wheatstone bridge (left) with four strain gauges; pressure sensor for differential pressure measurement (right).

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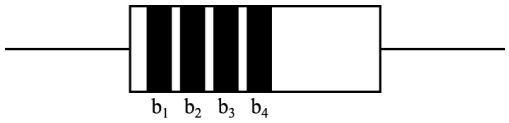

Fig. 3.17: Color-coding of resistors.

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Color of the band	Value of the band b_1, b_2	Multiplier b_3	Tolerance value [%]
Black	0	10^0	
Brown	1	10^1	1
Red	2	10^2	2
Orange	3	10^3	
Yellow	4	10^4	
Green	5	10^5	0.5
Blue	6	10^6	0.25
Violet	7	10^7	0.1
Grey	8		0.05
White	9		–
Gold		10^{-1}	5
Silver		10^{-2}	10
Black/no color			

Tab. 3.1: Color coding of resistors.

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1.0	1.8	3.3	5.6
1.1	2.0	3.6	6.2
1.2	2.2	3.9	6.8
1.3	2.4	4.3	7.5
1.5	2.7	4.7	8.2
1.6	3.0	5.1	9.1

Tab. 3.2: Resistance values in Ω for the E24 series of resistors.

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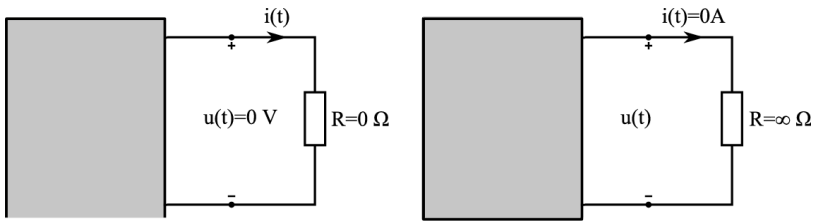

Fig. 3.18: Simple electric circuit: short circuit (left) and open load (right).

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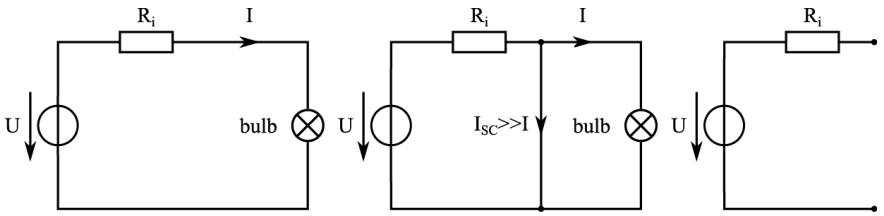

Fig. 3.19: A simple circuit with voltage source and internal resistance to drive a bulb (left); short circuit (center); open load by broken filament of the bulb (right).

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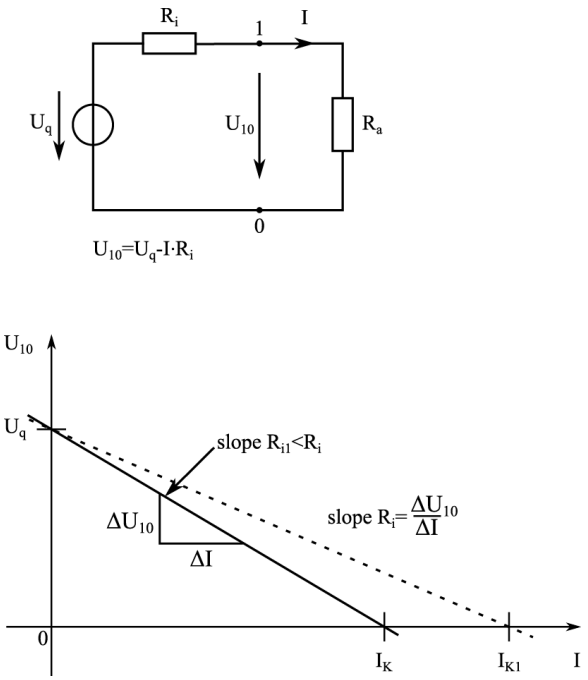

Fig. 3.20: A simple schematic for a real voltage source with internal resistance R_i and voltage vs current characteristic.

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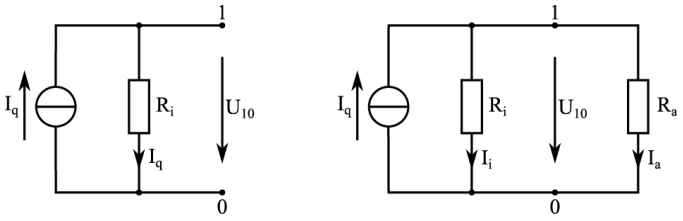

Fig. 3.21: A real current source without (left) and with load (right).

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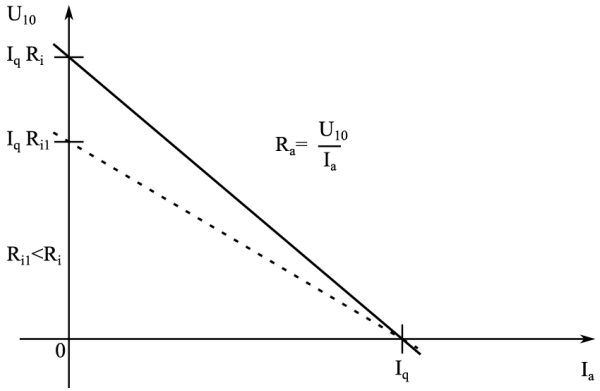

Fig. 3.22: Voltage as a function of load current for different external loads.

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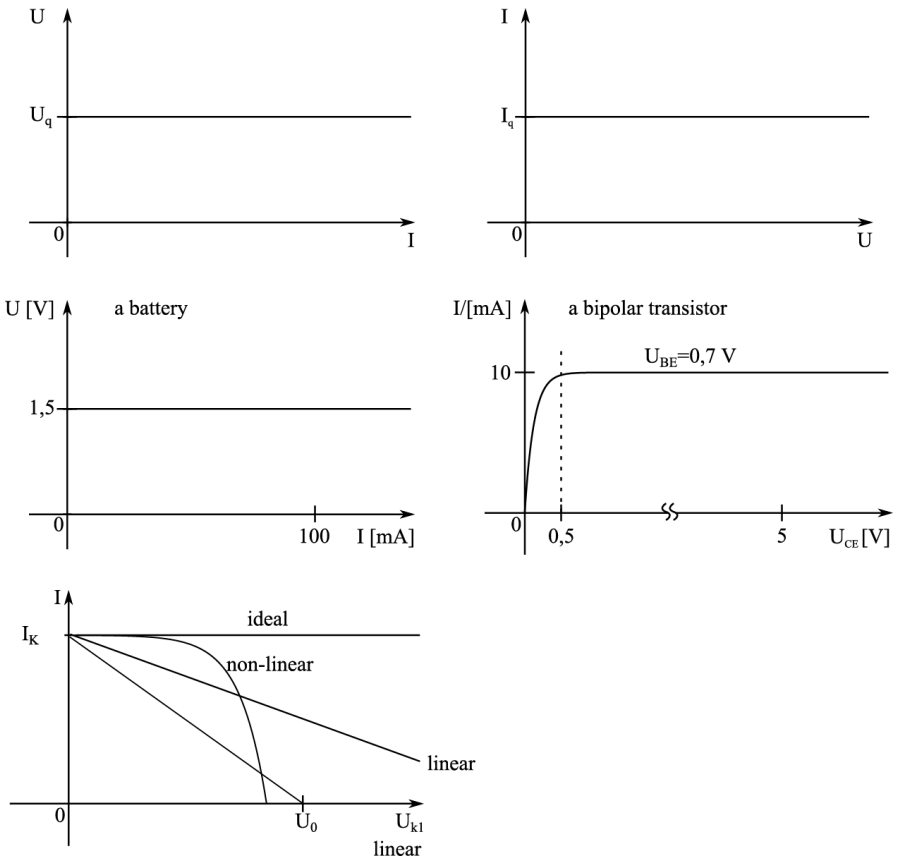

Fig. 3.23: Examples of sources: An ideal voltage source (top left); an ideal current source (top right); a battery (center left); a bipolar transistor (center right); ideal, linear and non-linear current source of a solar cell (bottom).

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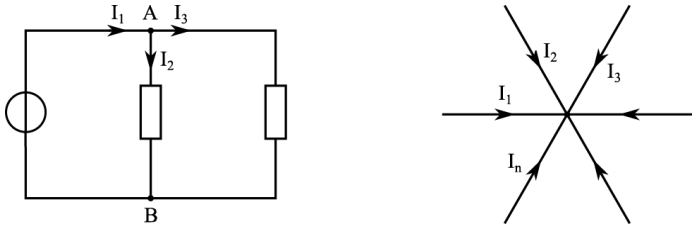

Fig. 4.1: An electric circuit with one voltage source, two resistors and corresponding current vectors (left); one node as part of a circuit with six elements connected to the node and corresponding currents (right).

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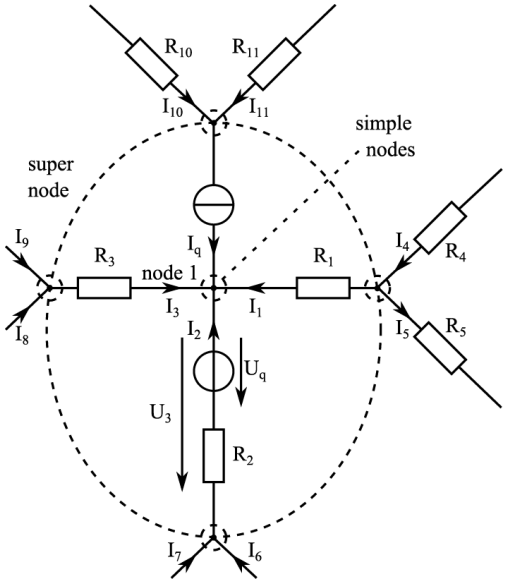

Fig. 4.2: A more complex part of a circuit with a closed region (dotted line) for which KCL also applies.

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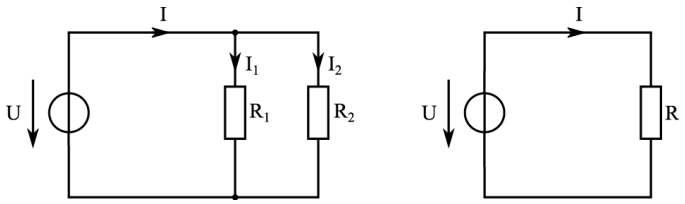

Fig. 4.3: Parallel connection of two resistors (left) and equivalent circuit with one equivalent resistor (right).

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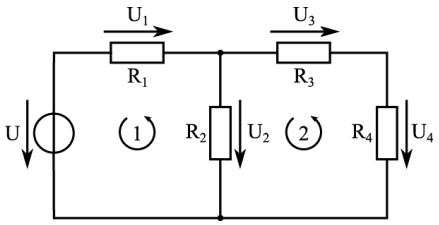

Fig. 4.4: A simple circuit with a voltage source and 4 resistors, two loops (meshes) are marked with I and II.

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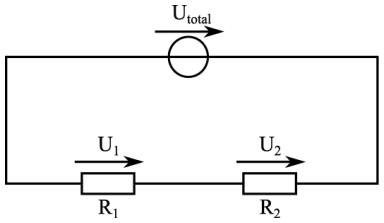

Fig. 4.5: Series connection of two resistors.

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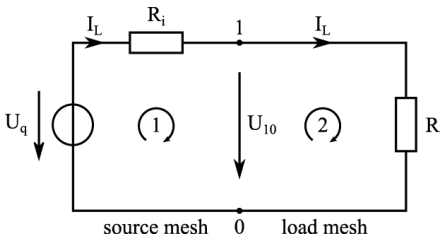

Fig. 4.6: A simple electric circuit with a source and a load mesh.

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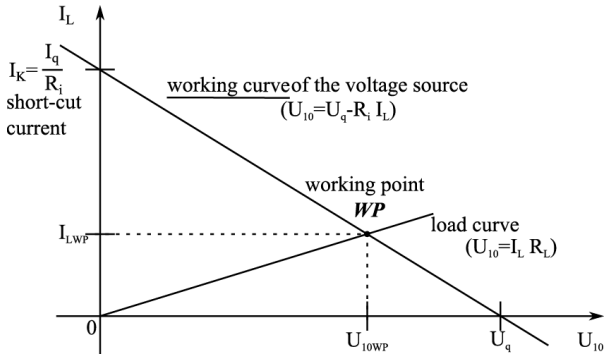

Fig. 4.7: Characteristic curves of the voltage source and the load. WP indicates the working point of the circuit.

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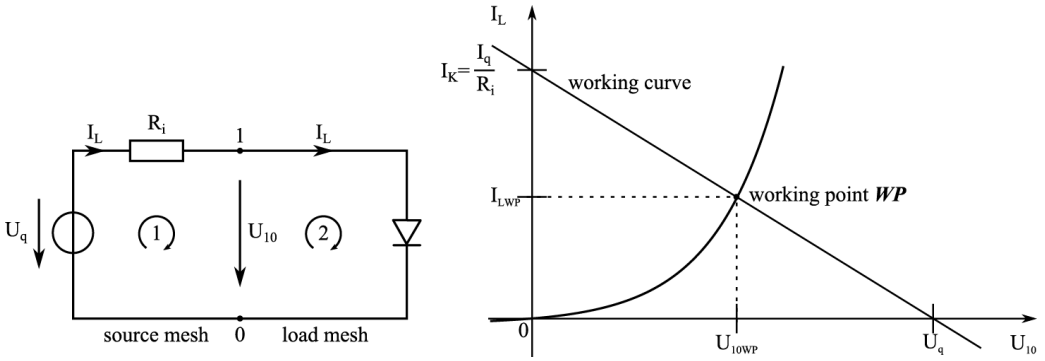

Fig. 4.8: A simple circuit with a diode as load (left); Characteristic curves for the source and the diode; diode current is a non-linear function of the voltage (right).

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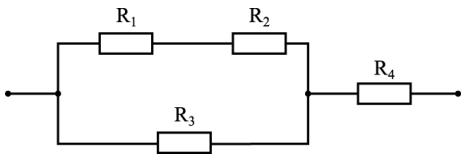

Fig. 4.9: A circuit with series and parallel connections for the demonstration of simplification.

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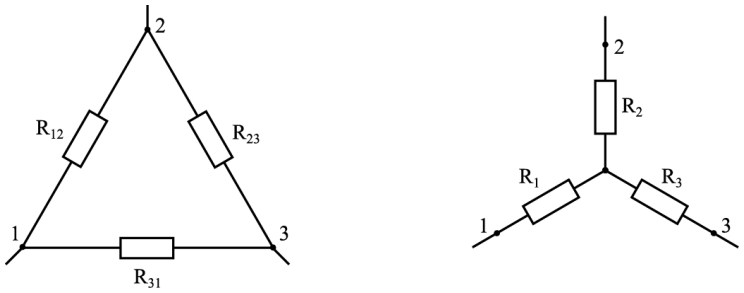

Fig. 4.10: Delta configuration (left) and Wye configuration (right).

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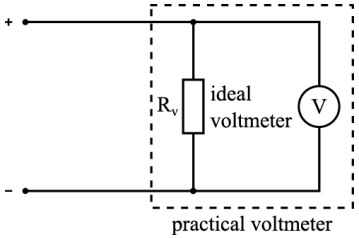

Fig. 4.11: The connection of a voltmeter to measure the voltage across the shunt resistor R_V.

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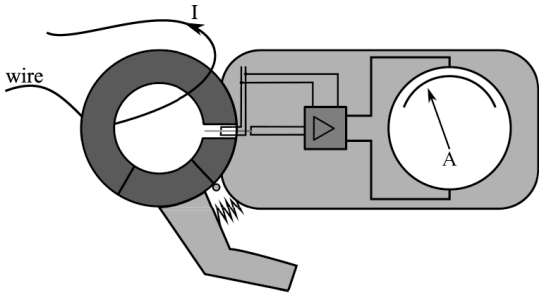

Fig. 4.12: A current probe or measuring caliper.

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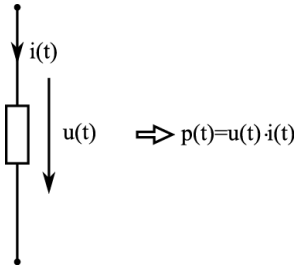

Fig. 4.13: Power at a resistor with current i(t) and voltage drop u(t).

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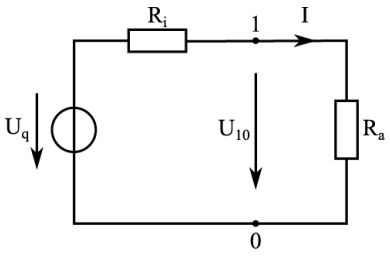

Fig. 4.14: A simple circuit for the investigation of power transfer, R_i is the internal series resistor of the voltage source, R_a the load resistor.

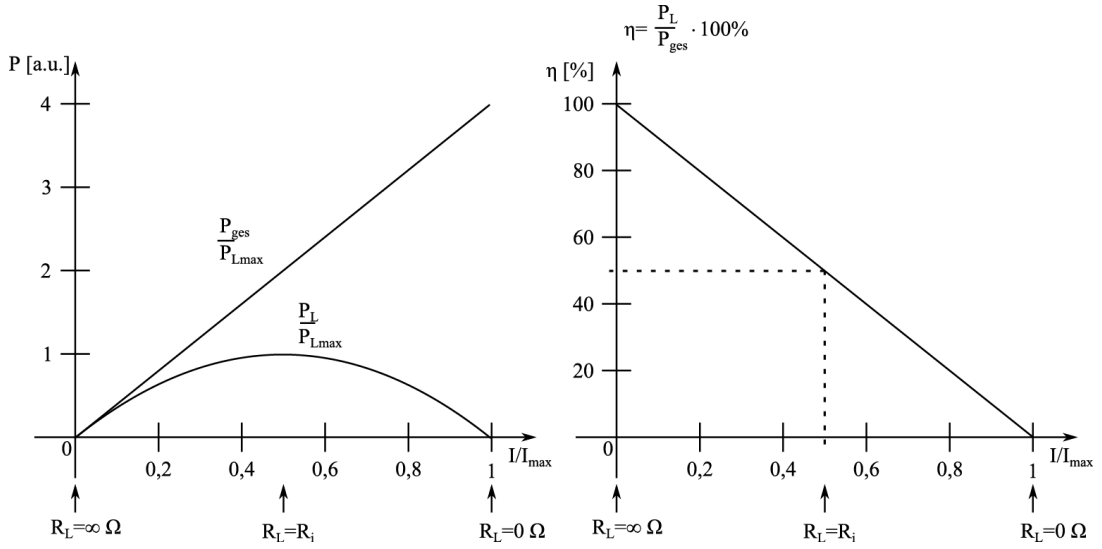

Fig. 4.15: Power transfer to the load (P_L) and total power provided by the source (P_{ges}) in units of the maximum power transfer (P_{Lmax}) (left); efficiency (right).

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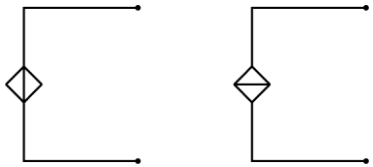

Fig. 4.16: Symbols of a dependent voltage source (left) and a dependent current source (right).

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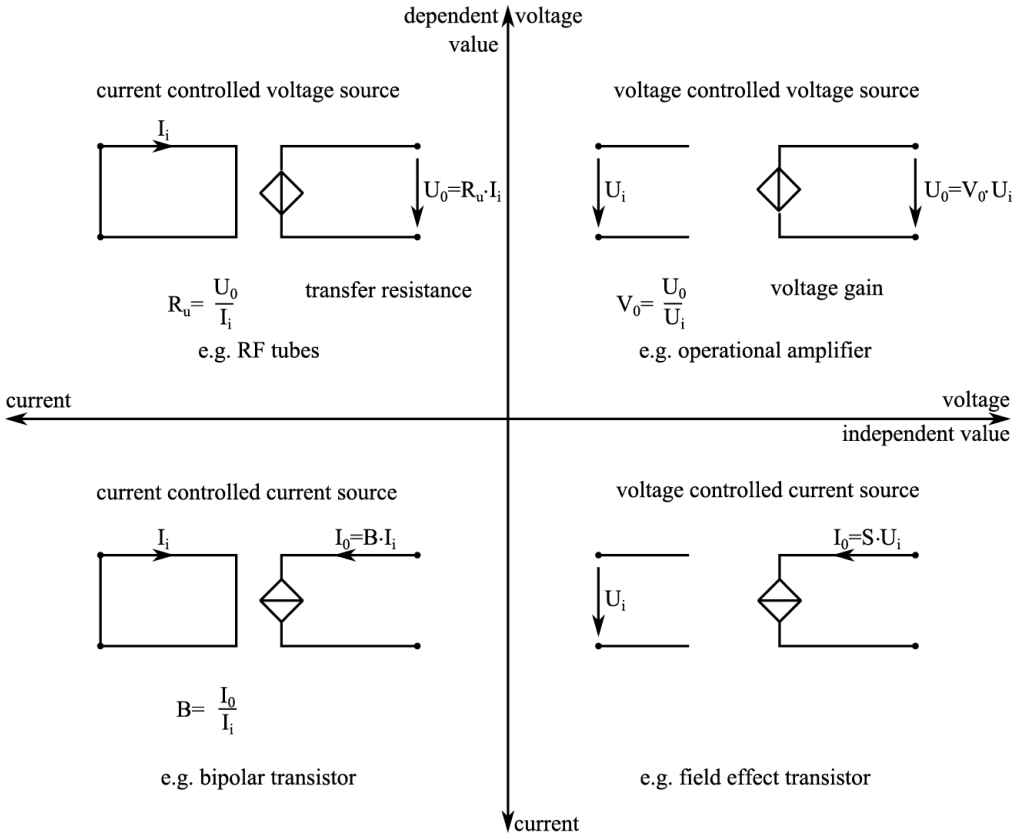

Fig. 4.17: Examples for dependent sources.

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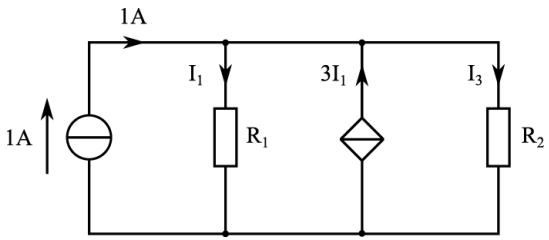

Fig. 4.18: An example of a circuit with a current controlled current source.

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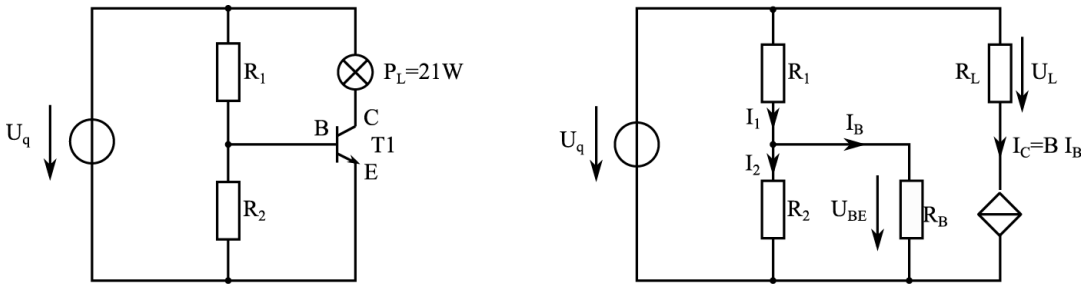

Fig. 4.19: A circuit with a biploar transistor acting as a current controlled current source (left); an equivalent circuit showing the current controlled current source (right).

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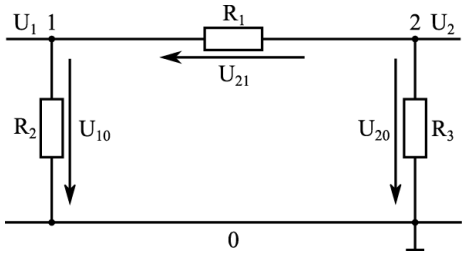

Fig. 5.1: Voltages (including a reference potential U_0) in an electric circuit.

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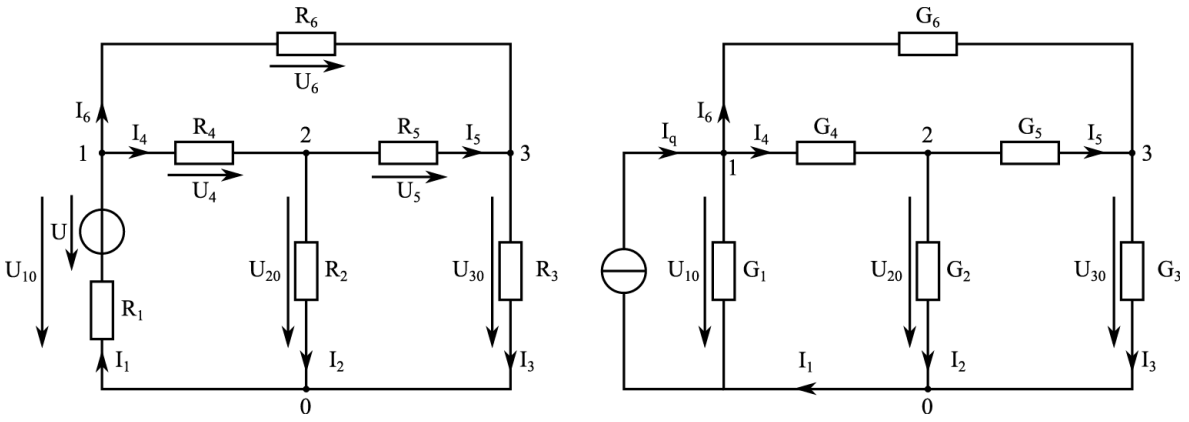

Fig. 5.2: An electric circuit with corresponding currents and voltages as an example of nodal analysis (left); node 0 is defined as ground potential; equivalent circuit with the voltage source and resistance R_1 transformed into a current source (right).

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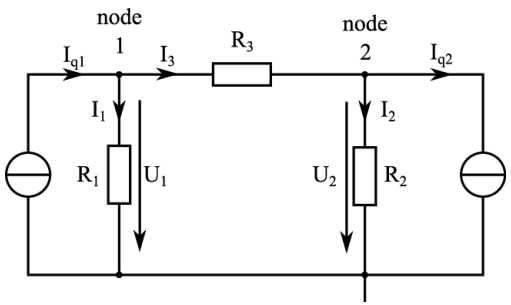

Fig. 5.3: Electric circuit with two ideal current sources and three nodes.

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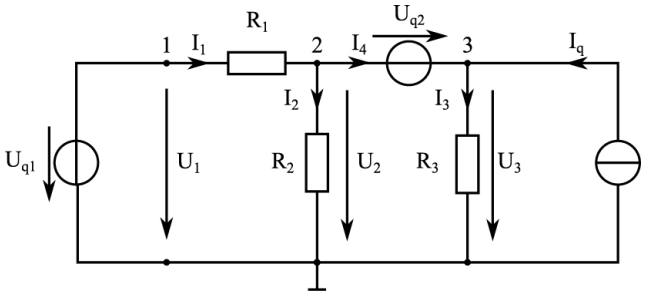

Fig. 5.4: Circuit for nodal analysis with an ideal voltage source between two reference nodes.

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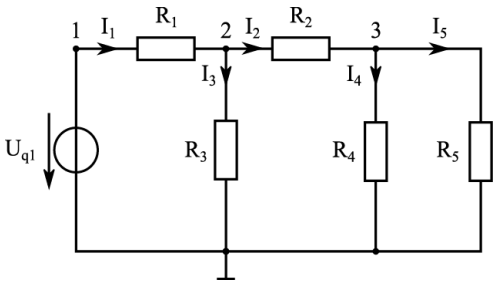

Fig. 5.5: Circuit with three nodes and the reference node for the application of Cramer's rule.

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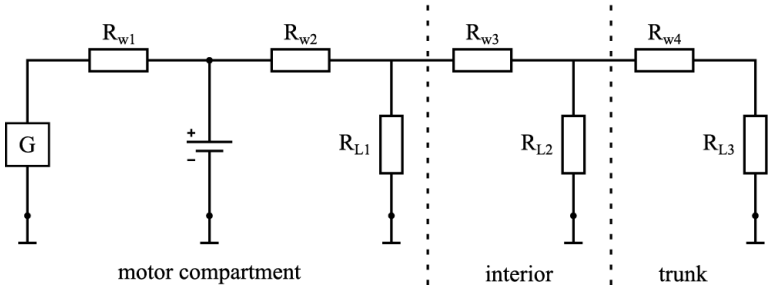

Fig. 5.6: Automotive electrical system with the battery in the engine compartment.

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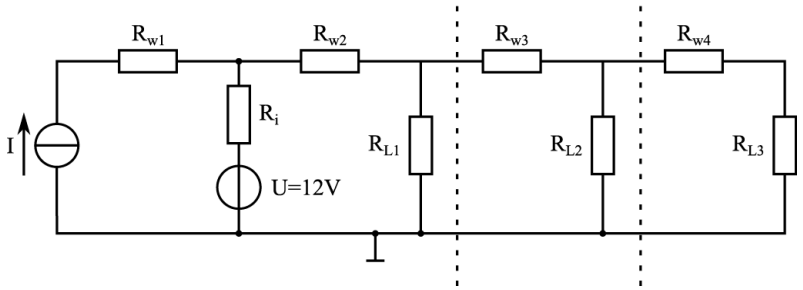

Fig. 5.7: The corresponding electric circuit, alternator modeled by a current source.

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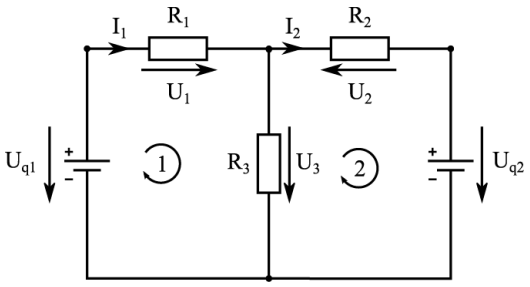

Fig. 5.8: An example for mesh analysis.

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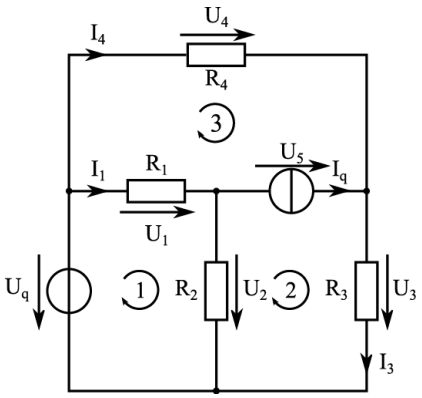

Fig. 5.9: Circuit for mesh analysis, mesh currents indicated clockwise by arrows.

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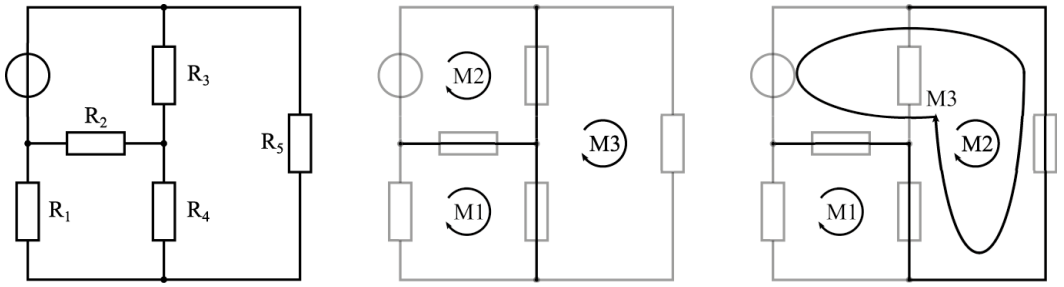

Fig. 5.10: Electric circuit with examples of two complete trees for the definition of meshes M1-M3.

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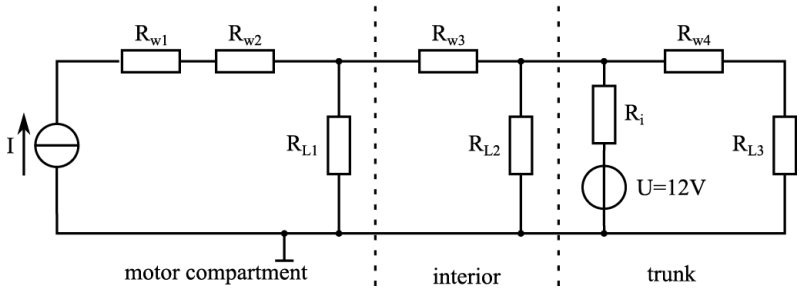

Fig. 5.11: Electric circuit with the battery located inside the trunk.

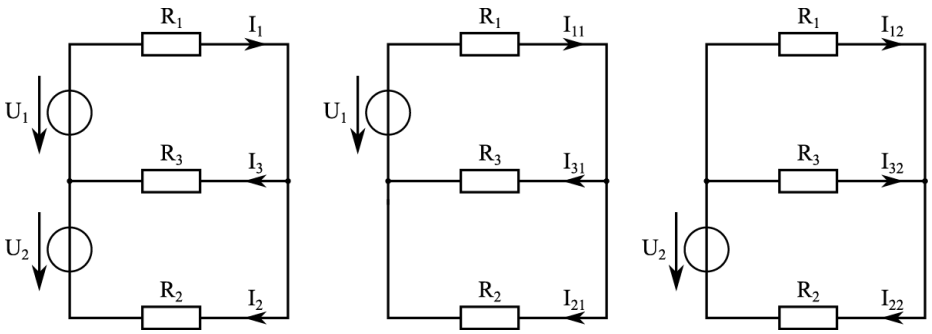

Fig. 5.12: An example for the application of superposition.

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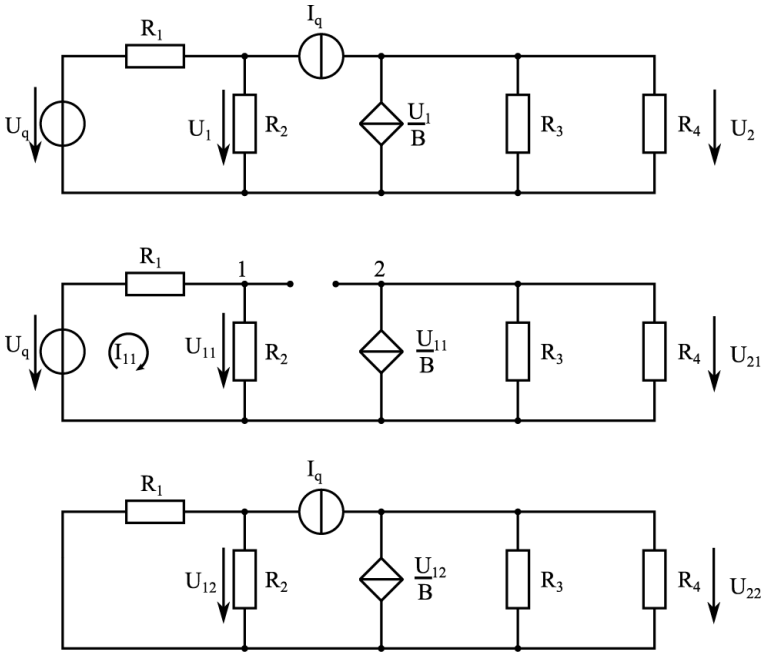

Fig. 5.13: An example for superposition for a circuit with a dependent current source; complete circuit (top); circuit with suppressed current source (open circuit, middle); circuit with suppressed voltage source (short circuit, bottom).

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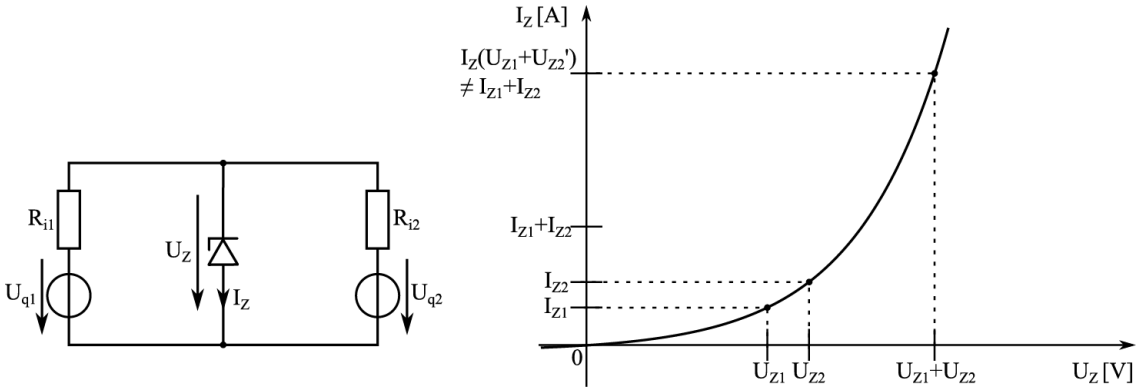

Fig. 5.14: An example for a non-linear network with a Zener diode; the method of superpopsition fails in this case.

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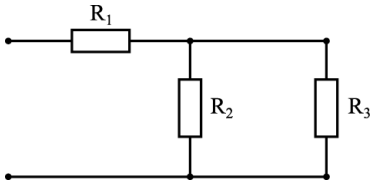

Fig. 5.15: A passive two-terminal circuit composed of resistors.

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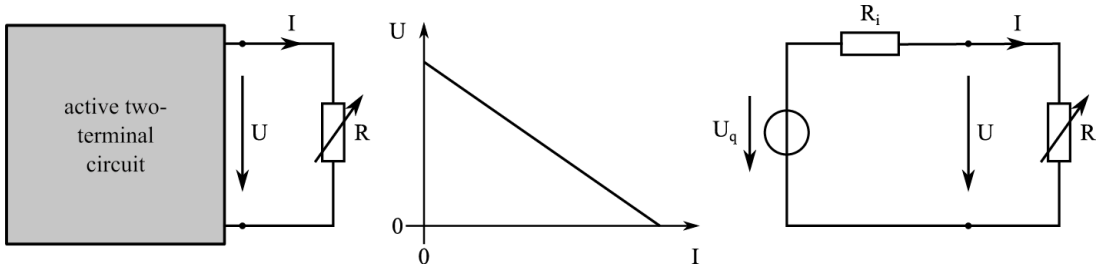

Fig. 5.16: Active two-terminal circuit with arbitrary internal configuration (left); corresponding voltage vs current diagram (middle); Thevenin equivalent circuit (right).

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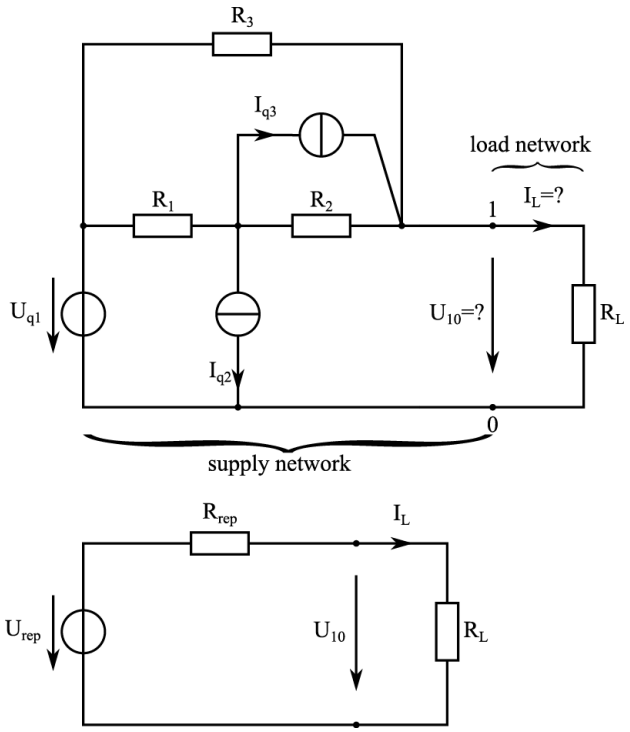

Fig. 5.17: An example for a circuit of a supply network and a simple load network (top); supply network is to be replaced by the Thévenin equivalent (bottom).

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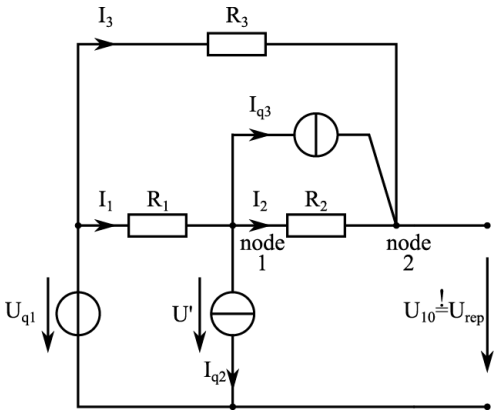

Fig. 5.18: Supply network of the example, currents and voltages are depicted in the figure.

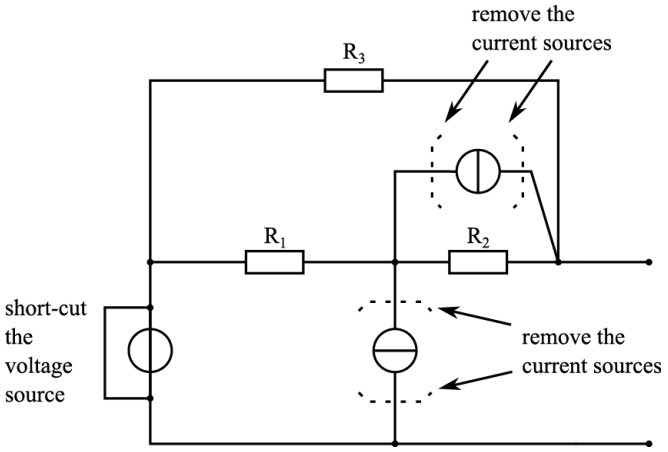

Fig. 5.19: Supply network of the example for determination of R_{rep}: removal of sources.

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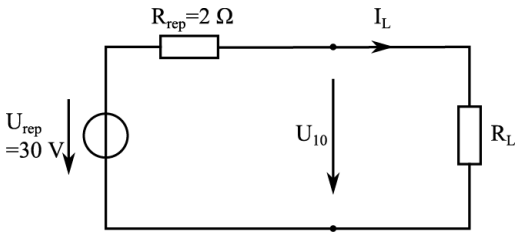

Fig. 5.20: The Thévenin equivalent circuit with values for U_{rep} and R_{rep}.

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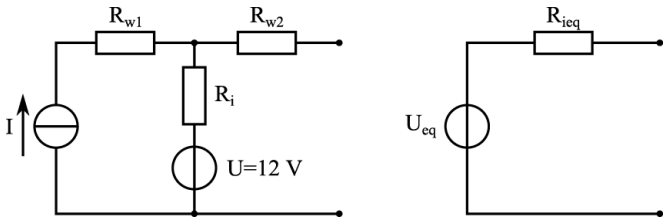

Fig. 5.21: A sub-circuit with alternator, battery and resistances (left) and corresponding Thévenin equivalent (right).

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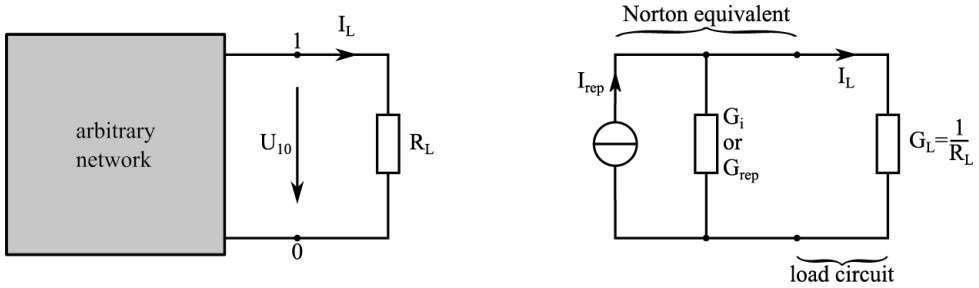

Fig. 5.22: Arbitrary (supply) network (left) and Norton's equivalent (real current source, right).

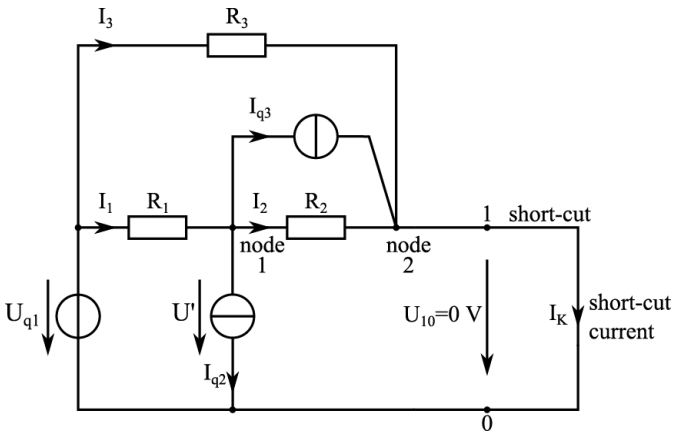

Fig. 5.23: Supply circuit for application of Norton's theorem, load circuit is short-cut for determination of I_{rep}.

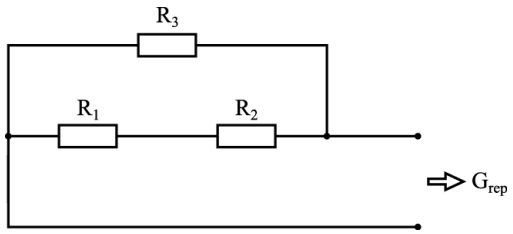

Fig. 5.24: Replacement circuit of supply network for determination of G_{rep}.

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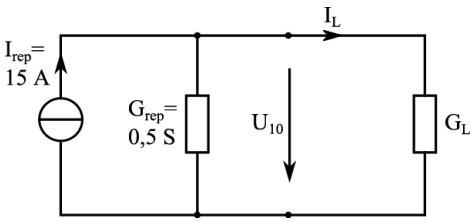

Fig. 5.25: Norton's equivalent with I_{rep} and G_{rep}.

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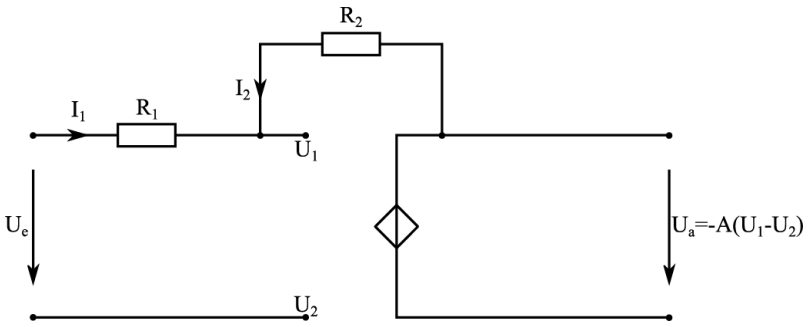

Fig. 6.1: Voltage controlled voltage source with feedback loop via resistor R_2.

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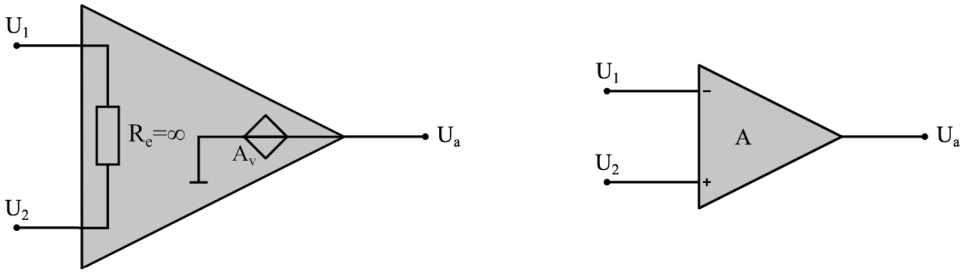

Fig. 6.2: Circuit and model of an ideal voltage amplifier with gain A.

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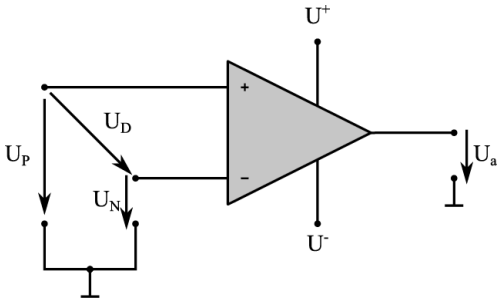

Fig. 6.3: Symbol of an OpAmp; U_N: voltage at inverting input; U_P: voltage at non-inverting input; U_D: differential input voltage; U_a: voltage at output; U^+ and U^-: power supply terminals.

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	Ideal OpAmp	Real OpAmp
Open loop gain	$A = \infty$	$A \approx 10^4$–10^7
Input resistance	$R_e = \infty\ \Omega$	$R_e > 1\ M\Omega$
Output resistance	$R_a = 0\ \Omega$	$R_a \approx 1$–$100\ \Omega$

Tab. 6.1: DC characteristics of ideal and real OpAmps.

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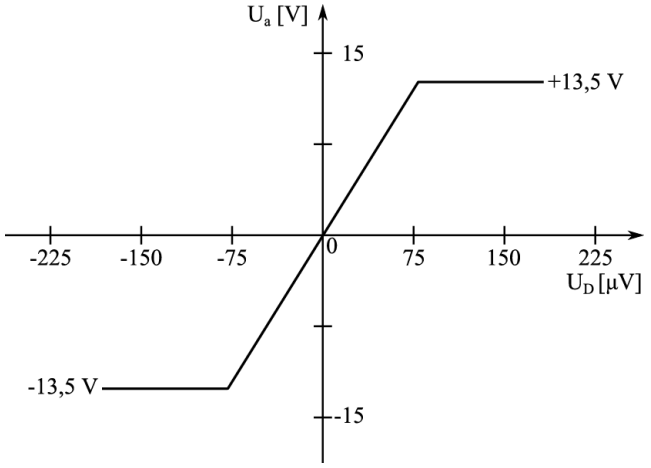

Fig. 6.4: Output voltage of a real OpAmp as a function of the differential input.

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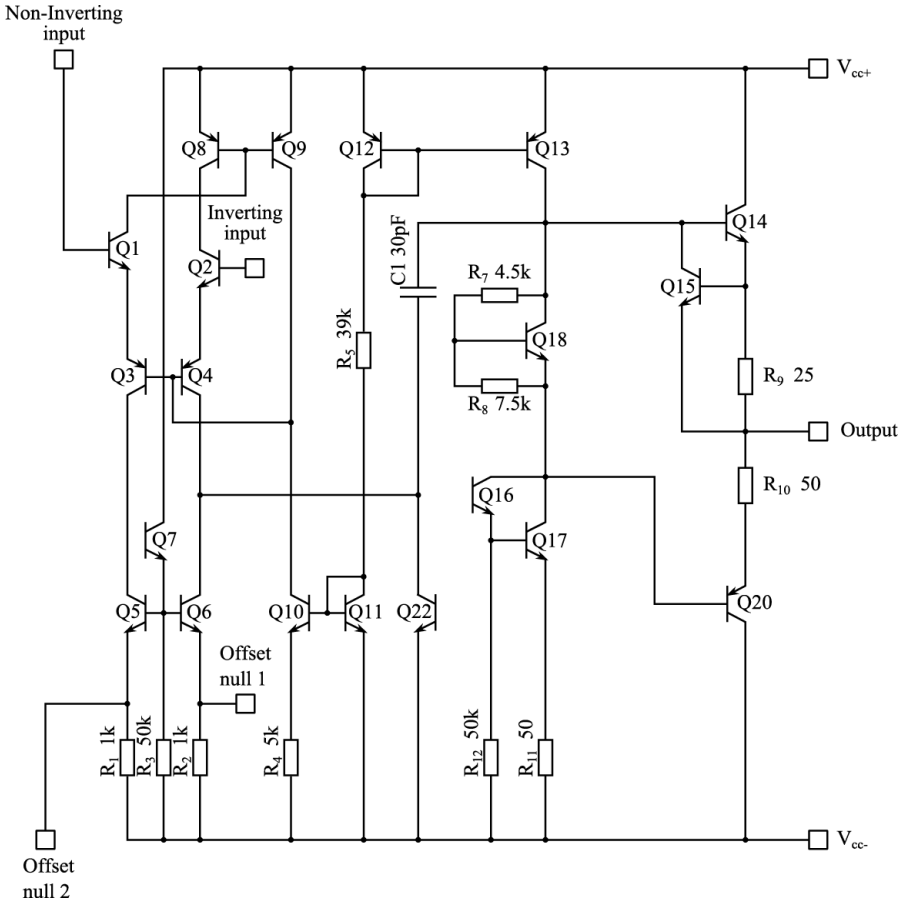

Fig. 6.5: Circuit of the µA741 OpAmp from STMicorelectronics (µA741 datasheet).

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Fig. 6.6: Examples of packages for operational amplifier: DIP-8 (package of µA741 OpAmp, left); SOP-8 (right). Package drawings by Infineon Technologies AG.

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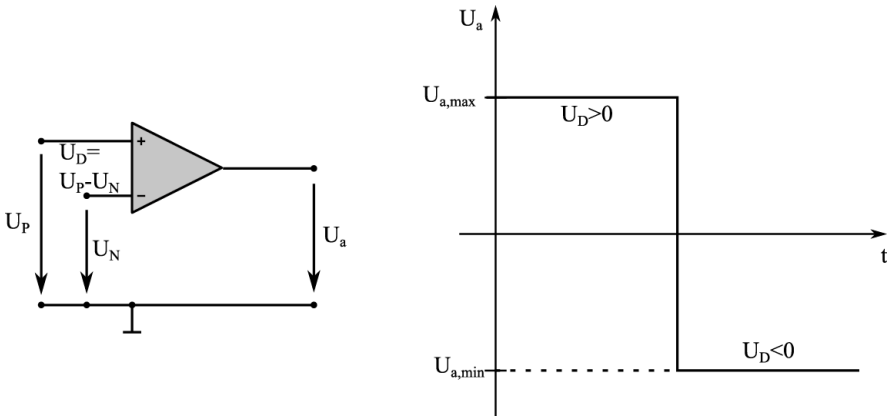

Fig. 6.7: Simple comparator circuit (left) and output voltage as a function of U_D (right).

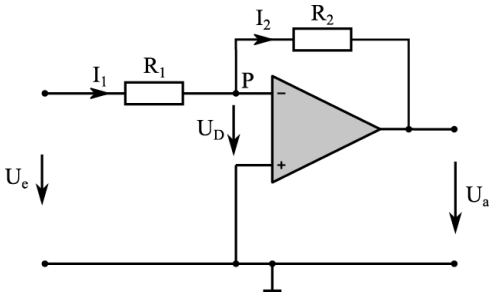

Fig. 6.8: An inverting amplifier.

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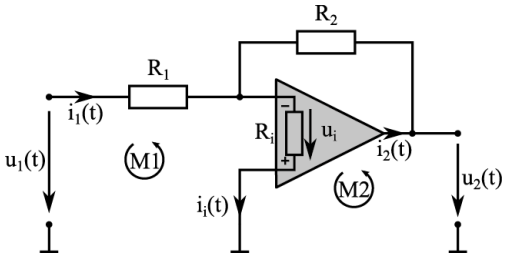

Fig. 6.9: Real OpAmp with input resistance and finite gain V.

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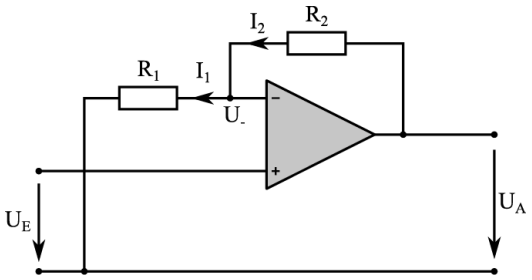

Fig. 6.10: A non-inverting amplifier.

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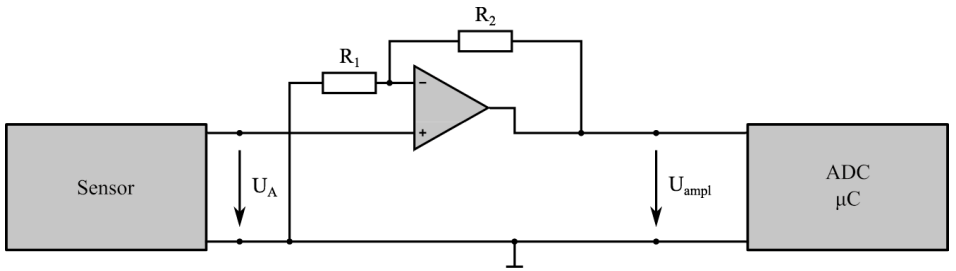

Fig. 6.11: Amplification of an analog sensor signal by a non-inverting amplifier, measurement by ADC of microcontroller (µC).

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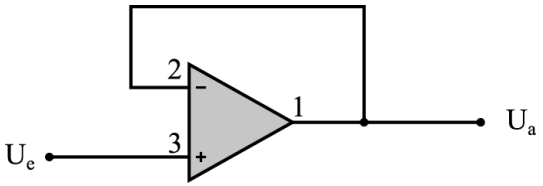

Fig. 6.12: A unity gain buffer.

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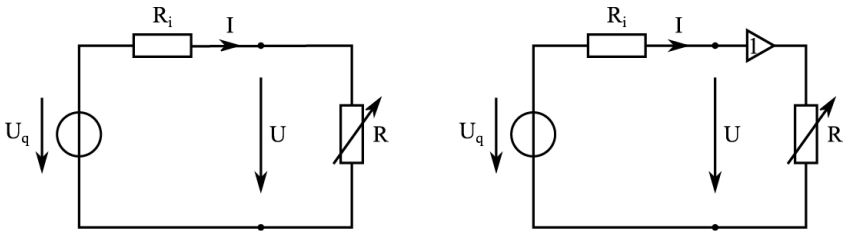

Fig. 6.13: Voltage source with internal resistance and variable load (left); same circuit like on the left side but with a unity gain buffer to separate the load from the source circuit.

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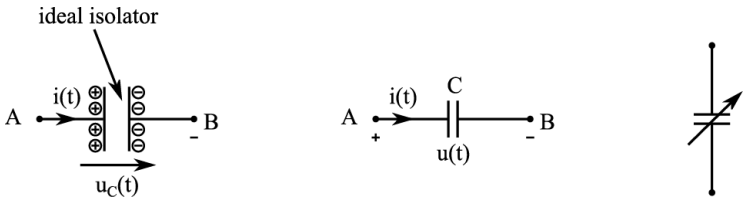

Fig. 7.1: A simple image of a capacitor; current i(t) causes positive charges to accumulate on one electrode and negative on the other; circuit symbol of a capacitor (center) and adjustable capacitor (right).

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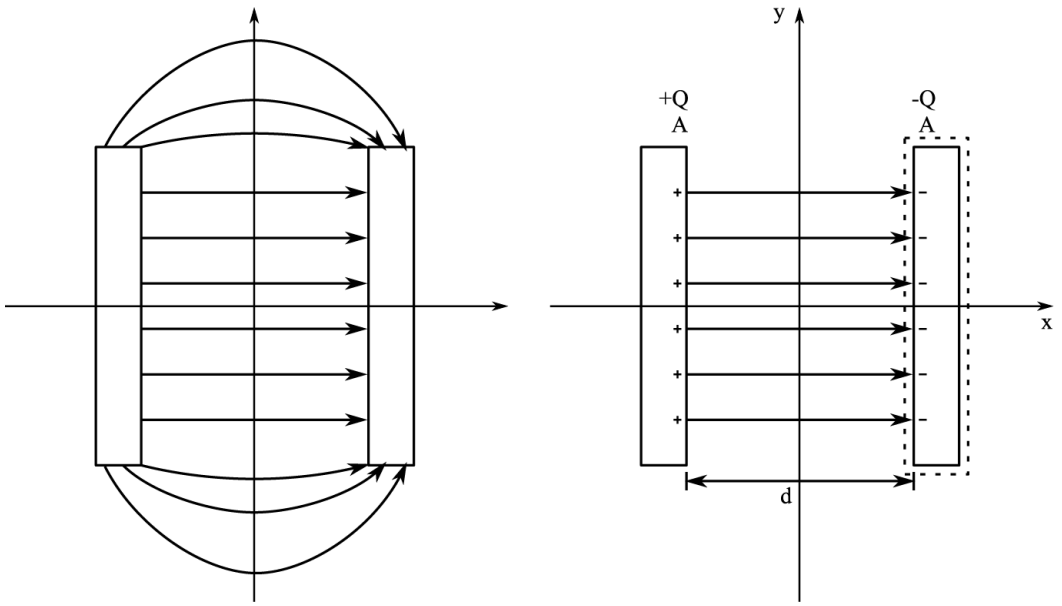

Fig. 7.2: Plate capacitor with charges +Q and –Q on both plates respectively; left: stray field outside the capacitor; right: simplification: displacement field just inside the capacitor.

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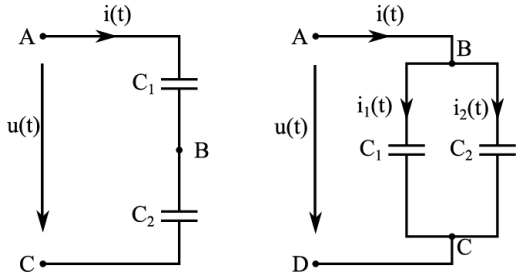

Fig. 7.3: Series (left) and parallel (right) connection of capacitors.

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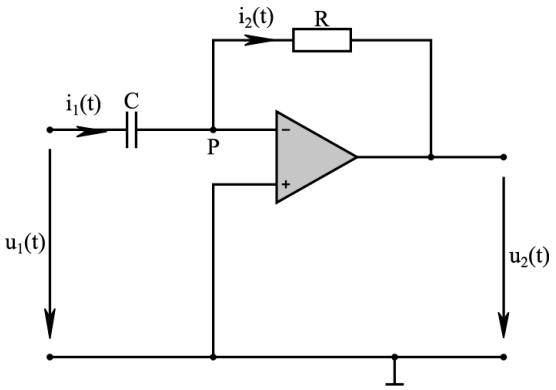

Fig. 7.4: OpAmp circuit with a capacitor in the input line. The circuit acts as a differentiator.

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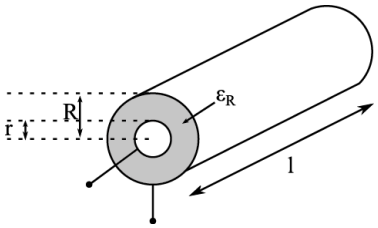

Fig. 7.5: A cylinder-type capacitor.

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Material	Capacitance range	Maximum voltage range [V]
Mica	1 pF–0.1 µF	50–600
Ceramic	10 pF–1 µF	50–1600
Paper	10 pF–50 µF	50–400
Electrolytic	0.1 µF–0.2 F	3–600

Tab. 7.1: Characteristics of capacitors with different dielectric.

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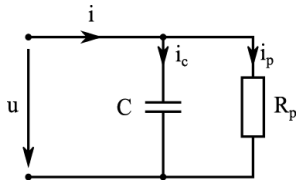

Fig. 7.6: Model of capacitor with parasitic resistor in parallel to the capacitance due to imperfect dielectric.

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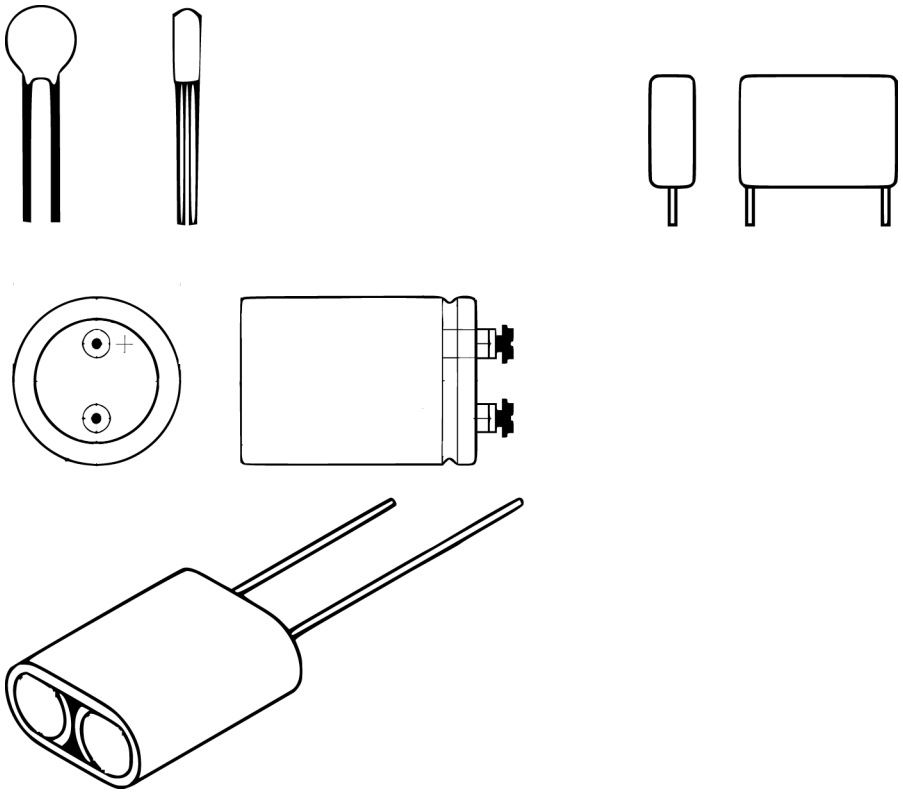

Fig. 7.7: Typical packages for capacitors: ceramic (top left); film (top right); electrolytic, positive terminal marked with + (center); supercap, positive terminal marked by longer pin (bottom).

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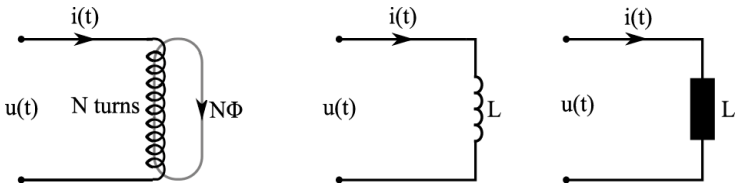

Fig. 7.8: A single inductive coil with N windings (left); American circuit symbol of an inductor (mid) and European symbol (right).

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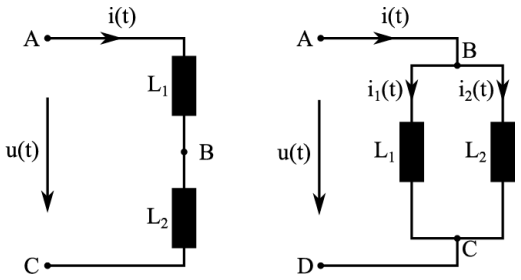

Fig. 7.9: Series (left) and parallel (right) connection of inductors.

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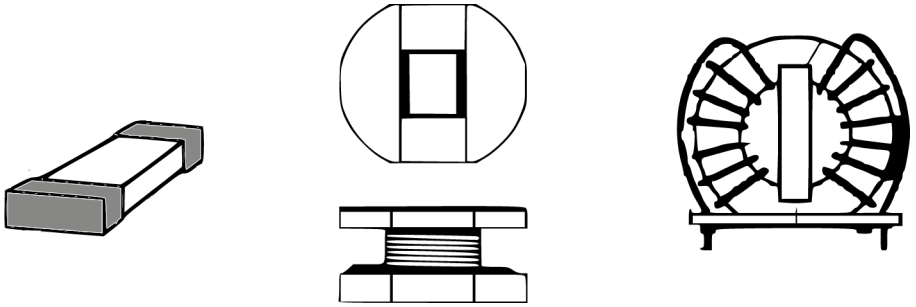

Fig. 7.10: Examples for inductor packages: shielded SMD (surface mount device, left); unshielded SMD (center); unshielded THD (through hole device, right).

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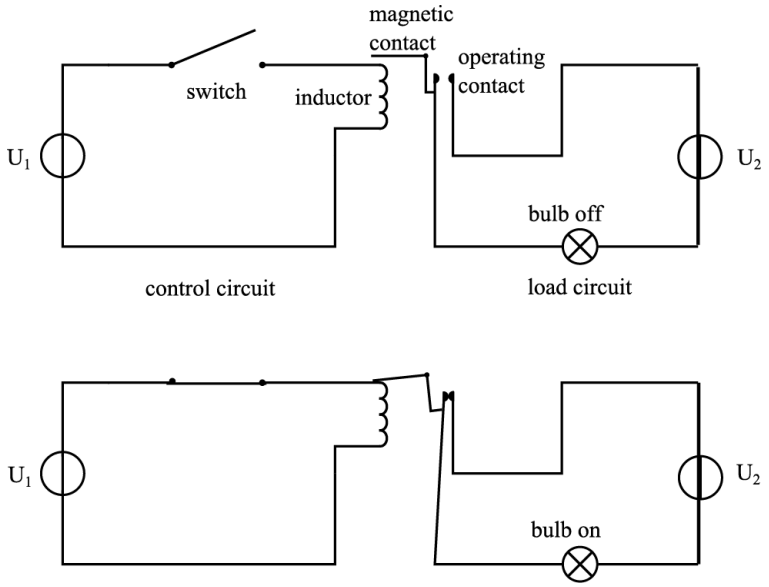

Fig. 7.11: Circuit of an electrical relais to switch a load circuit.

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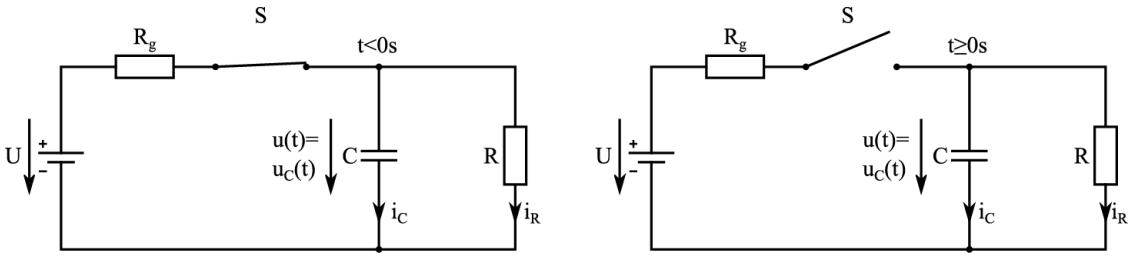

Fig. 7.12: A simple circuit with a switch.

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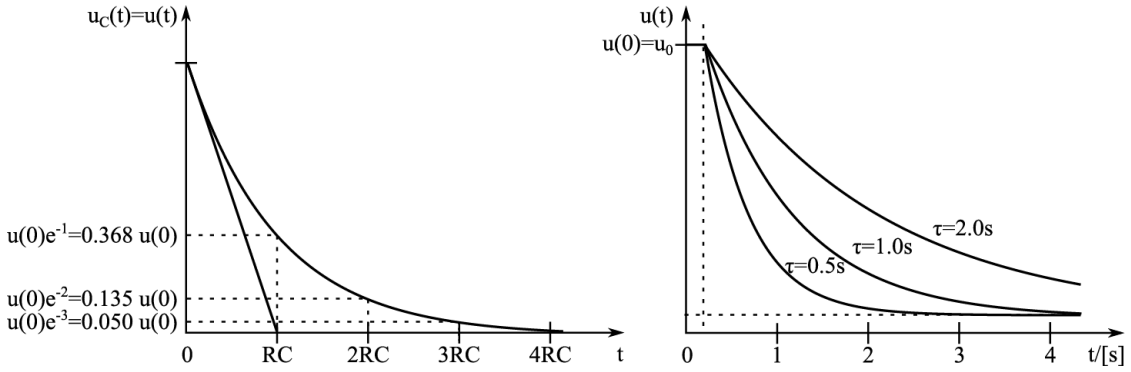

Fig. 7.13: Voltage across the capacitor (and the resistor), time constant τ=R·C determines how quickly the voltages decreases and settles to its final value.

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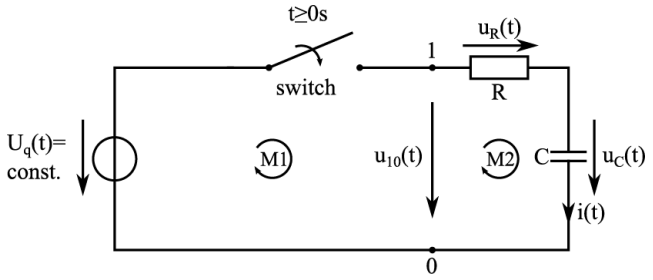

Fig. 7.14: A first order circuit with a RC combination and a voltage source as excitation.

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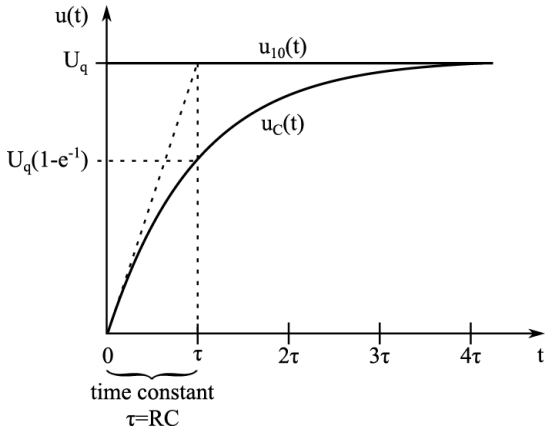

Fig. 7.15: The complete response of inhomogeneous first order ODE for an RC circuit.

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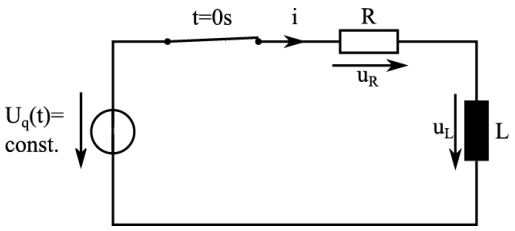

Fig. 7.16: RL circuit with a switch. Switch closes at t = 0 s.

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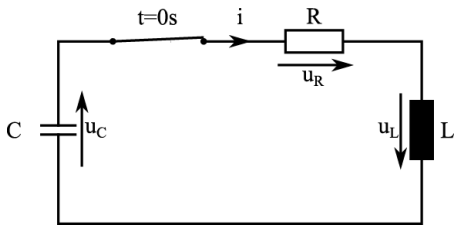

Fig. 7.17: Series connection of resistor, inductor and capacitor as an easy example for a second order circuit.

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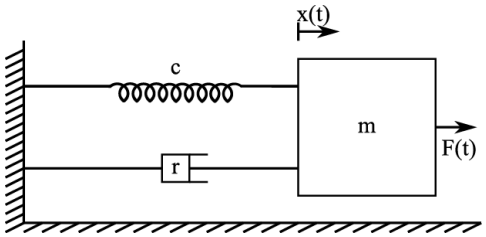

Fig. 7.18: A mechanical analog to the electrical RLC circuit.

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Mechanical	Electrical
Force	Voltage
Velocity	Current
Displacement	Charge
Damper ($f(t) = d \cdot v(t)$)	Resistor ($u(t) = R \cdot i(t)$)
Spring ($f(t) = c \cdot x(t) = c \cdot \int v(t)dt$)	Capacitor ($u(t) = 1/C \cdot \int i(t)dt$
Mass ($f(t) = m \cdot dv(t)/dt$)	Inductor ($u(t) = L \cdot di(t)/dt$

Tab. 7.2: Analog quantities of mechanical and electrical systems.

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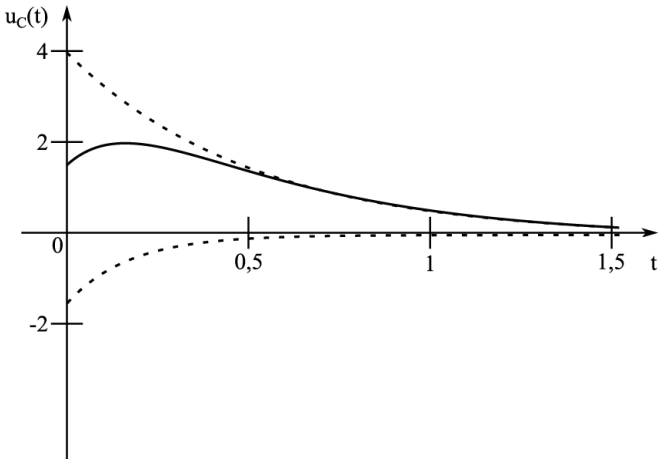

Fig. 7.19: A capacitor’s voltage as a function of time for the overdamped case.

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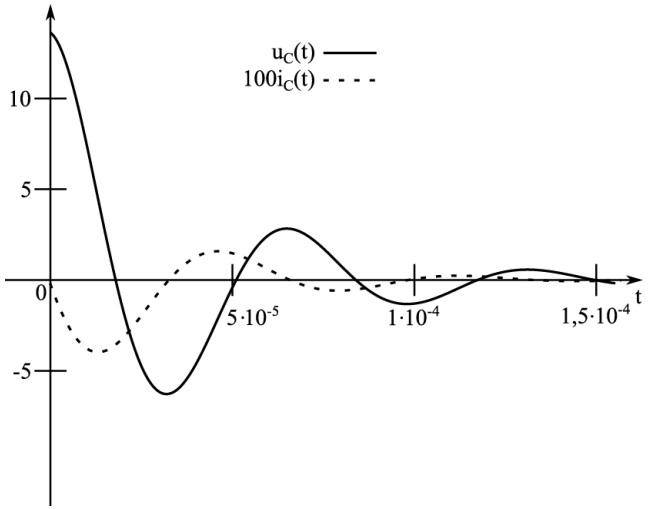

Fig. 7.20: A Capacitor's voltage and current for the underdamped case.

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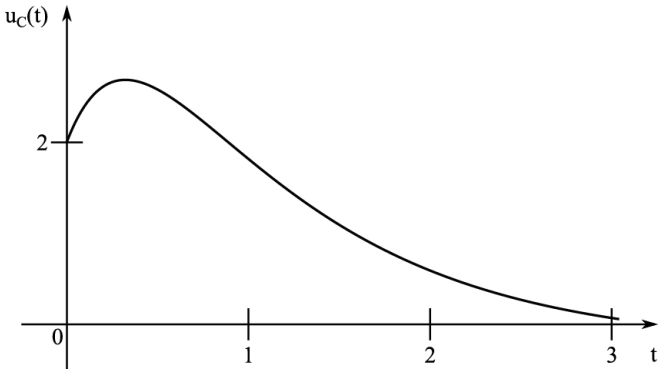

Fig. 7.21: A capacitor’s voltage for the critically damped case.

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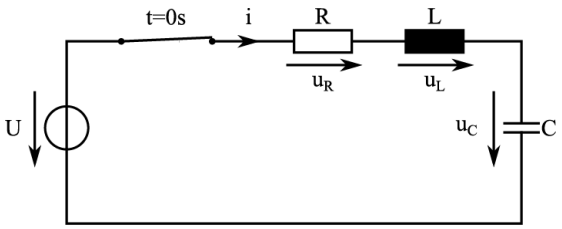

Fig. 7.22: RLC series connection, voltage source connected at t = 0 s.

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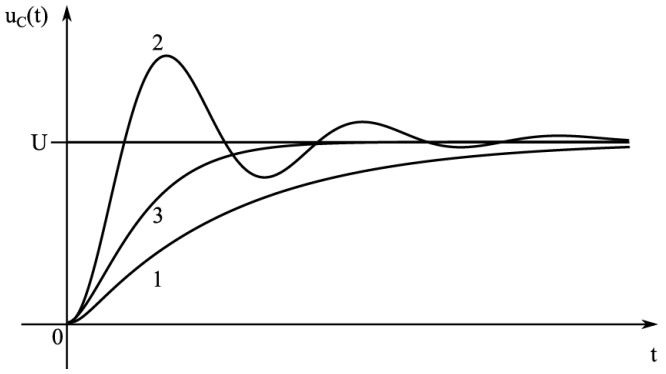

Fig. 7.23: A capacitor's voltage as a function of time for an RLC series connection, voltage source U connected at t = 0 s : 1: overdamped; 2: underdamped; 3: critically damped.

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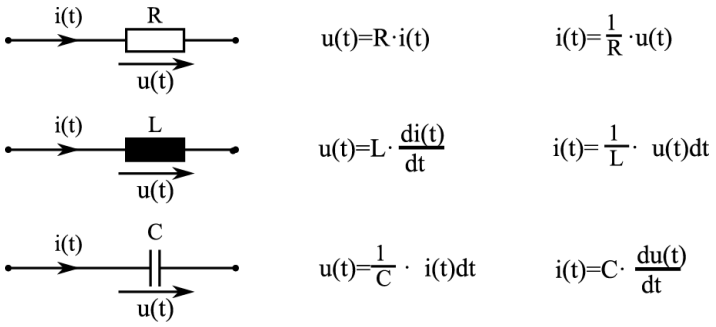

Fig. 7.24: Linear elements and their current-voltage relation.

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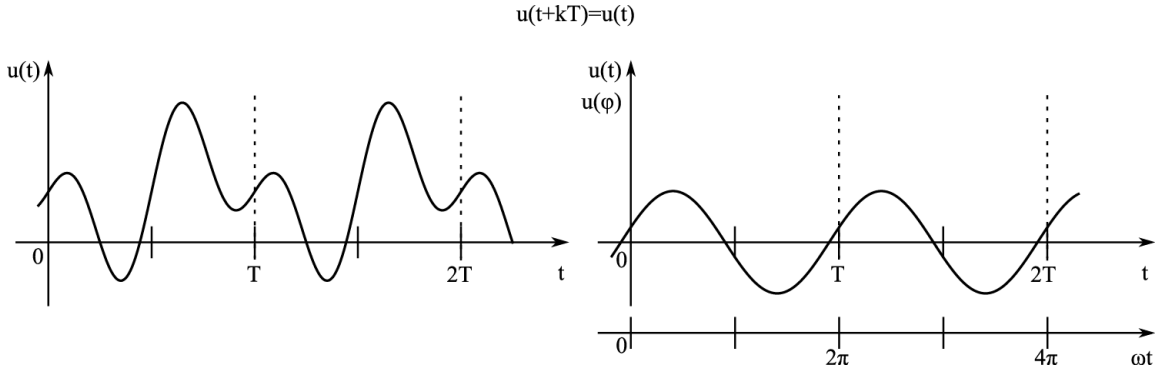

Fig. 7.25: Periodical functions u(t): arbitrary shape (left) and sinusoidal shape (right).

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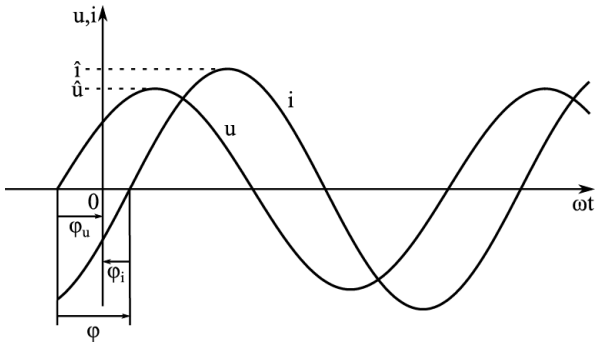

Fig. 7.26: Sinusoidal voltage and current with different phase angle and same frequency.

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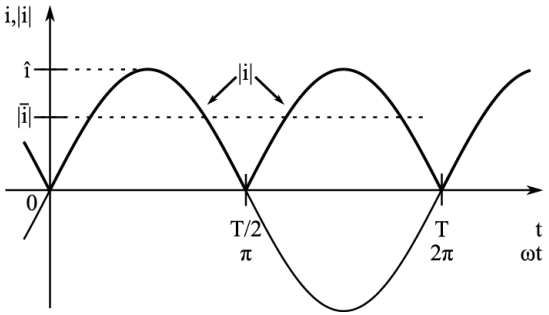

Fig. 7.27: Sinusoidal current, absolute value and rectified value.

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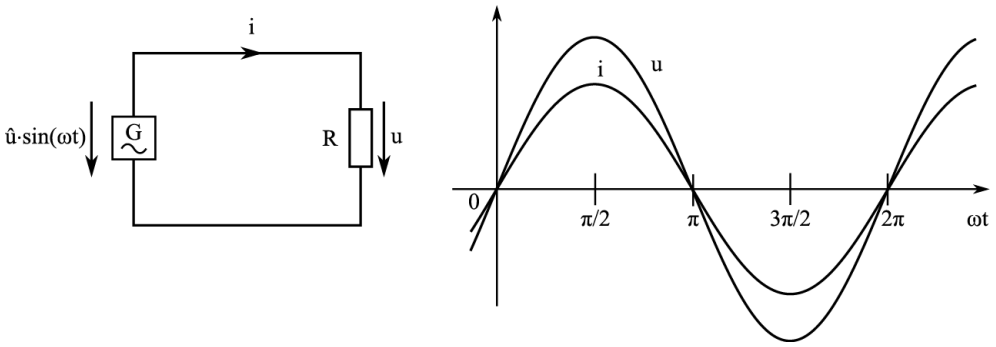

Fig. 7.28: A resistor connected to a sinusoidal voltage source: circuit (left) and line diagram (right) of current and voltage.

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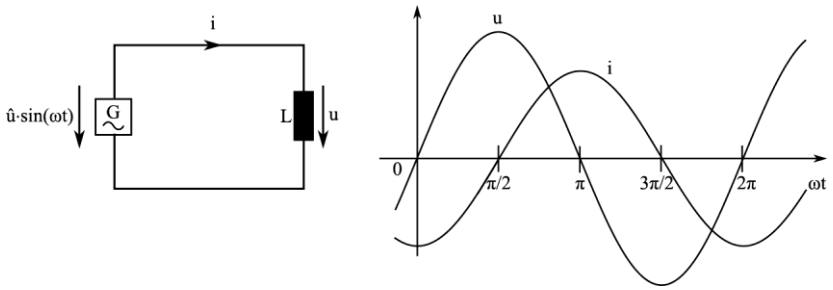

Fig. 7.29: An inductor connected to a sinusoidal voltage source: circuit (left) and line diagram (right) of current and voltage.

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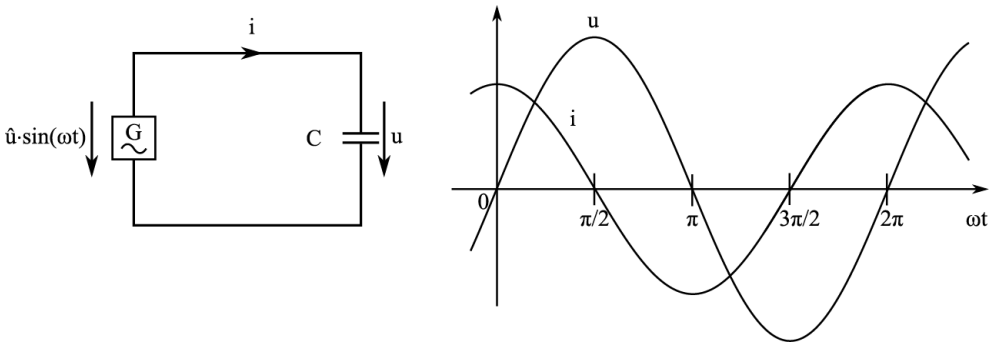

Fig. 7.30: A capacitor connected to a sinusoidal voltage source: circuit (left) and line diagram (right) of current and voltage.

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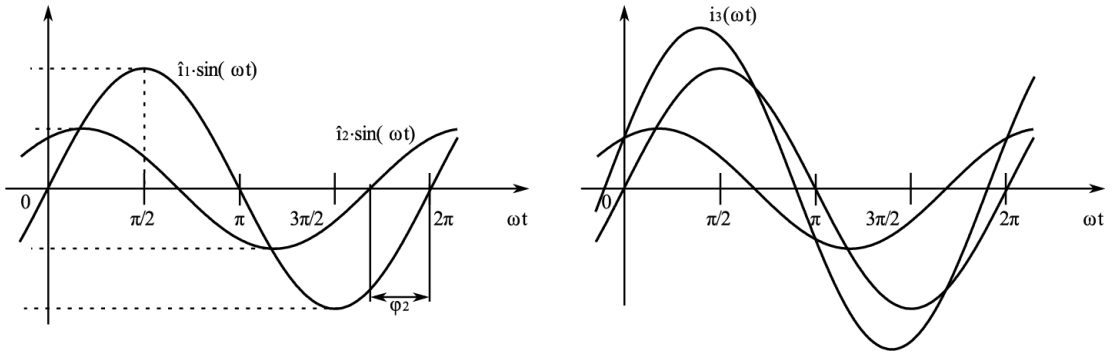

Fig. 7.31: Two sinusoidal currents that should be added (left); result of addition (right).

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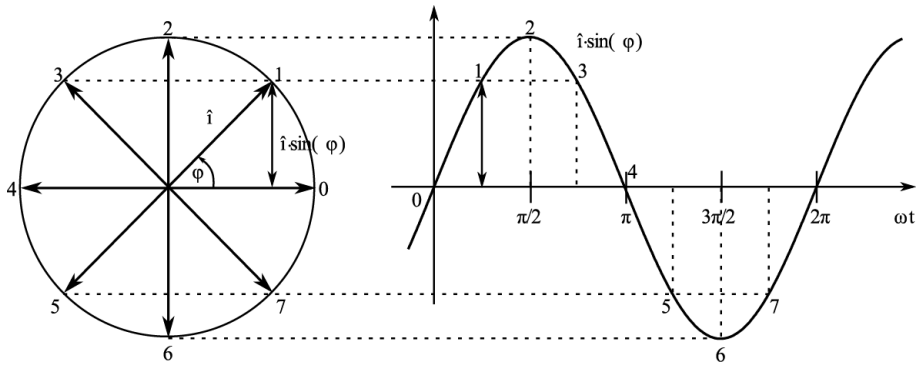

Fig. 7.32: Line (right) and vector representation (left) of a sinusoidal function.

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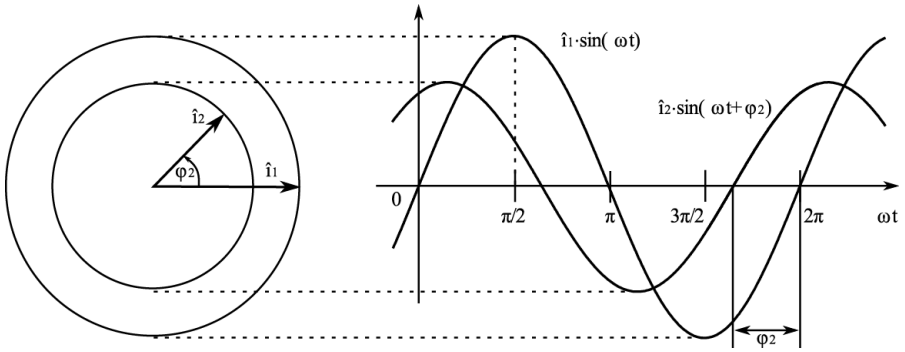

Fig. 7.33: Two currents with the same frequency but phase difference φ: line (right) and vector (left) representation.

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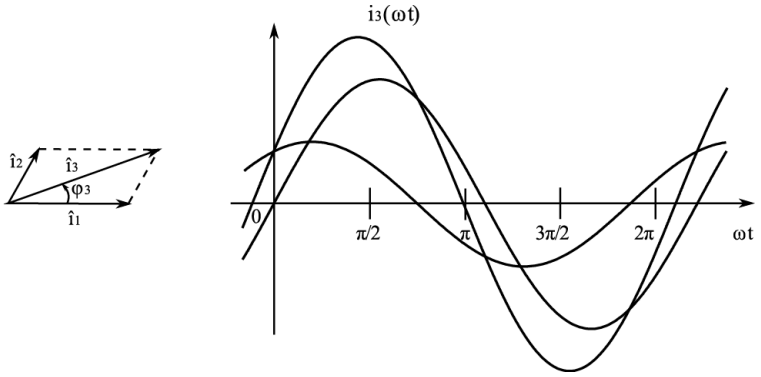

Fig. 7.34: Vector addition of two currents (left) and resulting line diagram (right).

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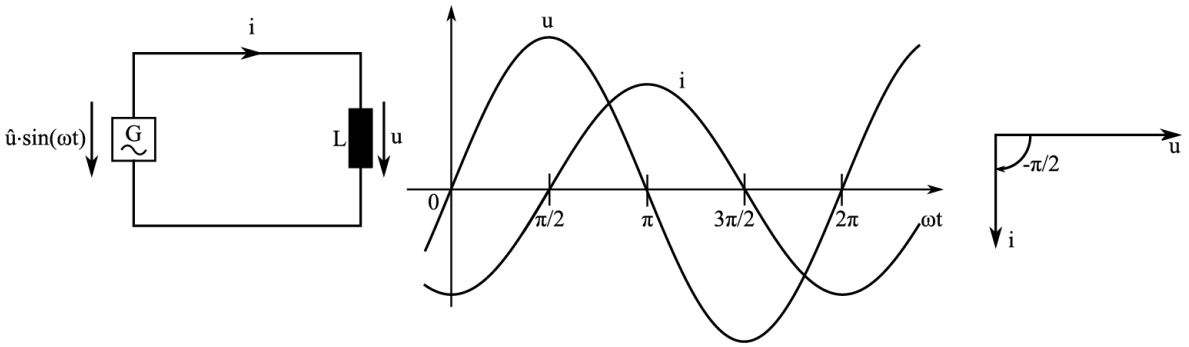

Fig. 7.35: Inductor connected to a sinusoidal voltage source: circuit (left), line diagram (mid) and vector diagram of current and voltage.

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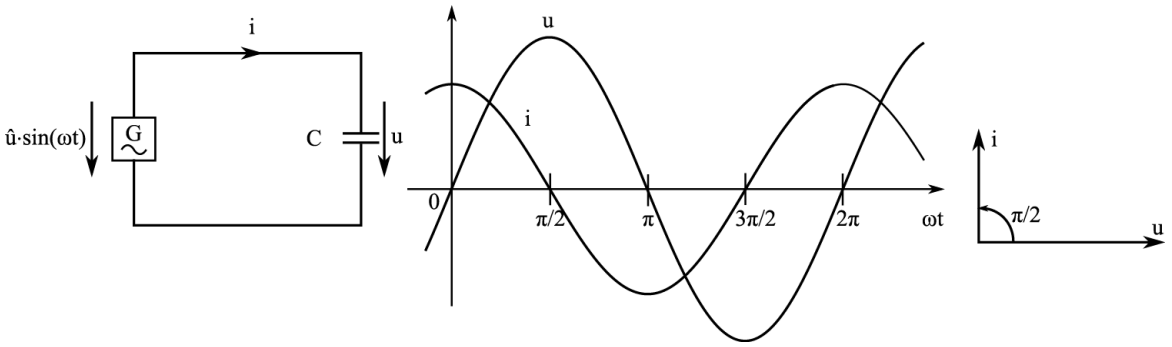

Fig. 7.36: Capacitor connected to a sinusoidal voltage source: circuit (left), line diagram (mid) and vector diagram (right) of current and voltage.

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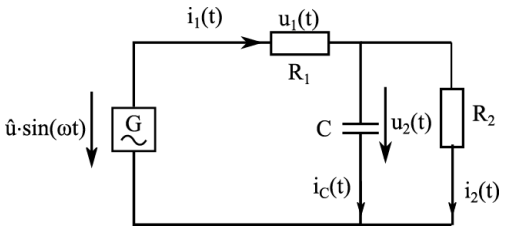

Fig. 7.37: A circuit with resistors, a capacitor and a sinusoidal voltage source.

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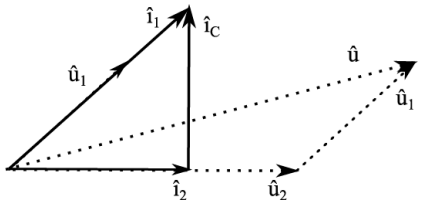

Fig. 7.38: Vector diagram of the RC circuit.

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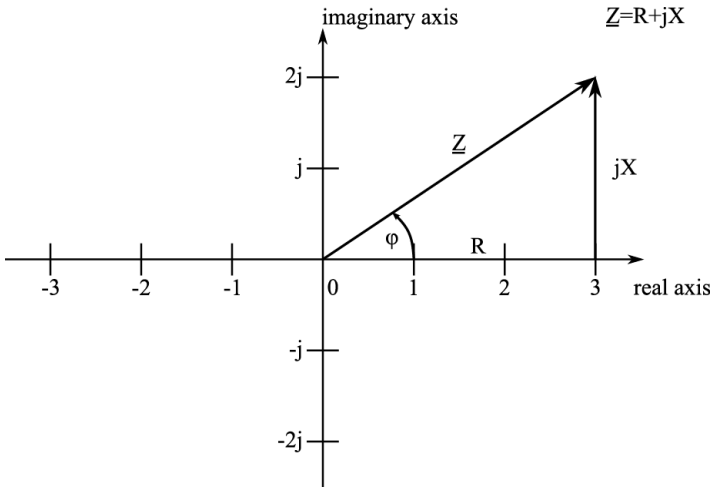

Fig. 7.39: Complex number Z in a Gaussian coordinate system.

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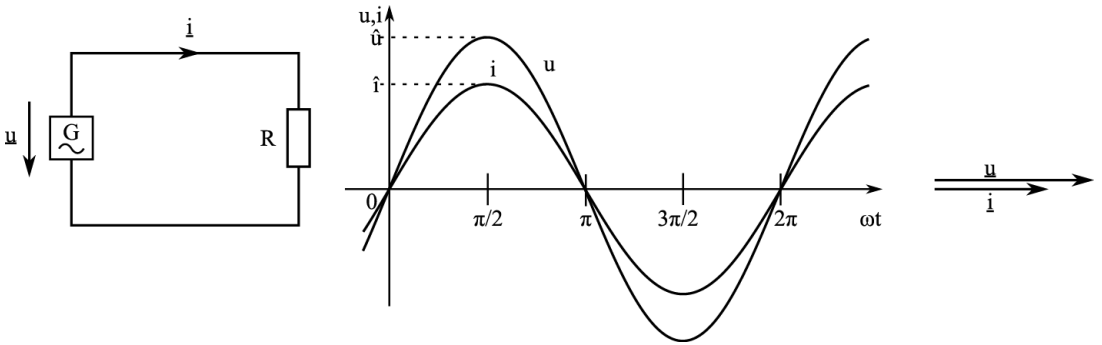

Fig. 7.40: A simple AC circuit with just a resistor (left), line diagram of current and voltage (center) and vector diagram (right).

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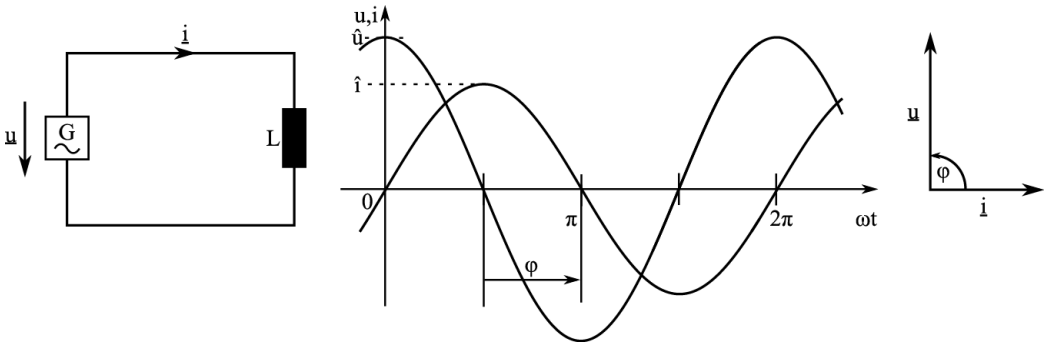

Fig. 7.41: A simple AC circuit with just an inductor (left), line diagram of current and voltage (center) and vector diagram (right).

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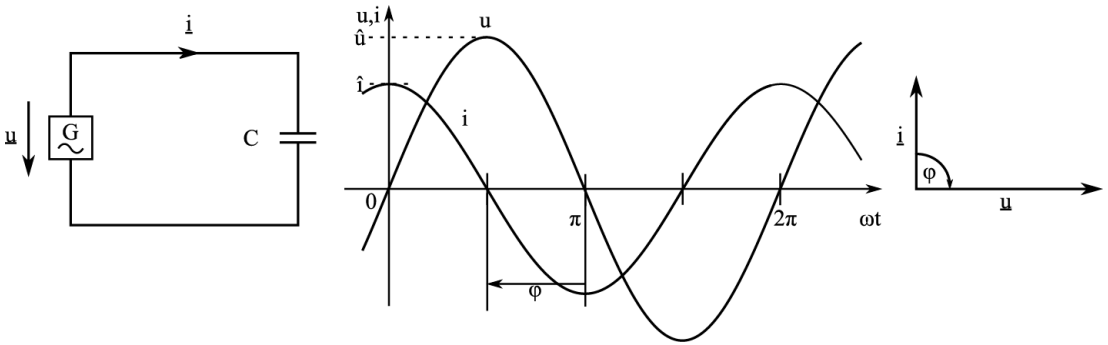

Fig. 7.42: A simple AC circuit with just a capacitor (left), a line diagram of current and voltage (center) and a vector diagram (right).

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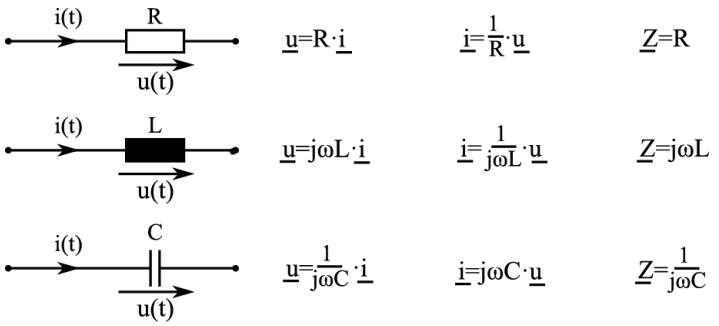

Fig. 7.43: Impedances for the basic elements resistor, inductor and capacitor in complex form.

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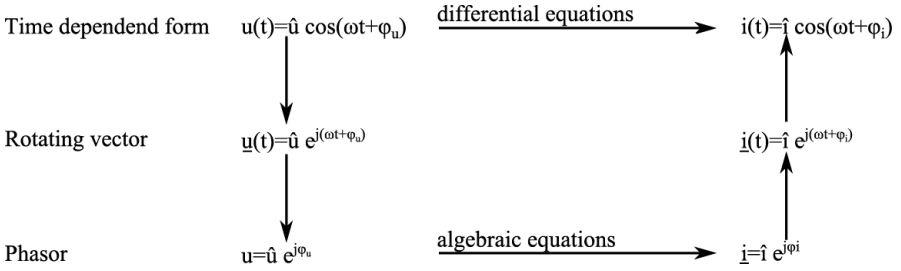

Fig. 7.44: Steps for analysis of an AC circuit using phasors.

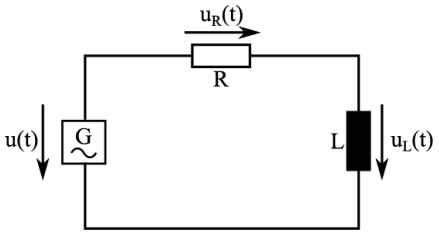

Fig. 7.45: An RL circuit with a sinusoidal voltage source.

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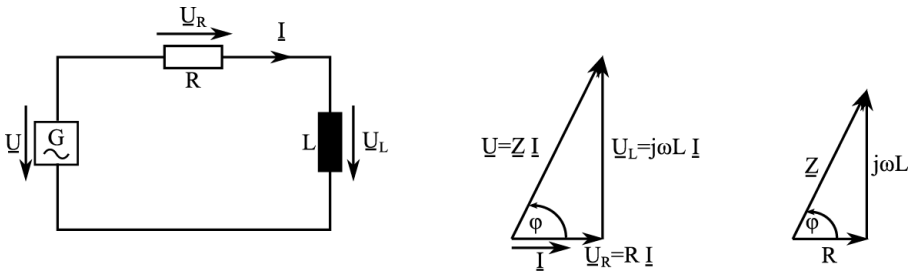

Fig. 7.46: Vector diagrams of the series connection of resistor and inductor.

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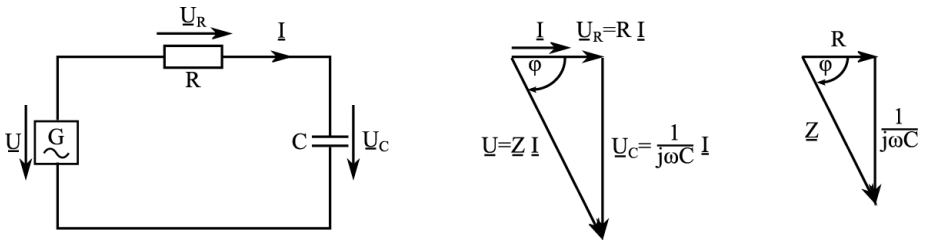

Fig. 7.47: Series connection of resistor and capacitor (left), vector diagram for voltages (center) and impedances (right).

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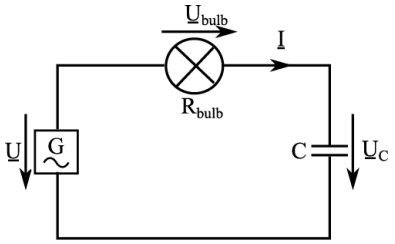

Fig. 7.48: A bulb operated in series with a capacitor.

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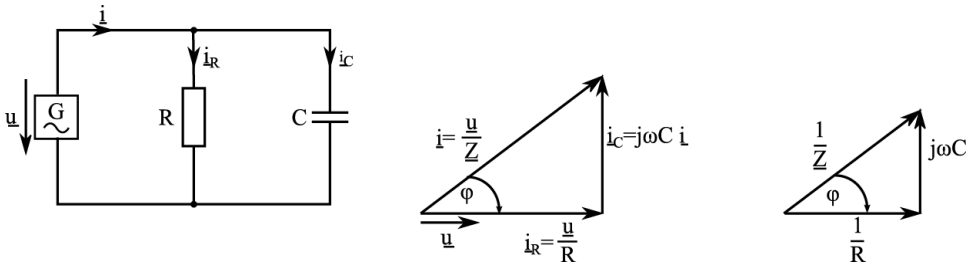

Fig. 7.49: Parallel connection of resistor and capacitor (left), vector diagram for currents (middle) and admittances (right).

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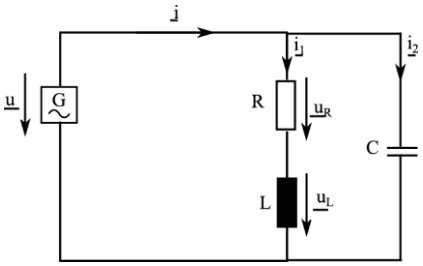

Fig. 7.50: RLC circuit with R and L in series.

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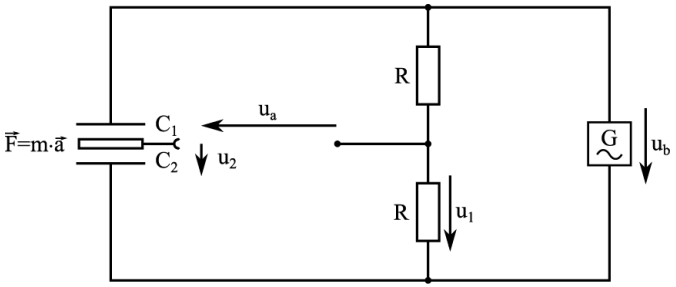

Fig. 7.51: The capacitive Wheatstone bridge of an acceleration sensor with a differential capacitor.

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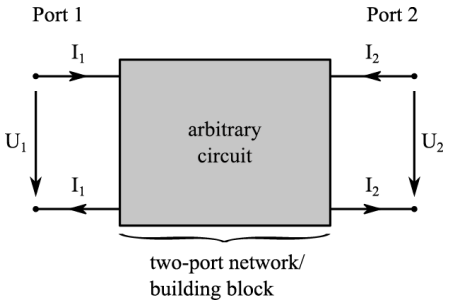

Fig. 8.1: An arbitrary two port network fulfilling the port conditions.

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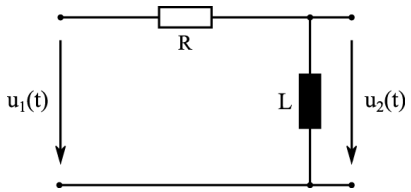

Fig. 8.2: -Two port network consisting of R and L; input voltage is $\underline{u}_1(t)$, voltage across the inductor is the output voltage $\underline{u}_2(t)$.

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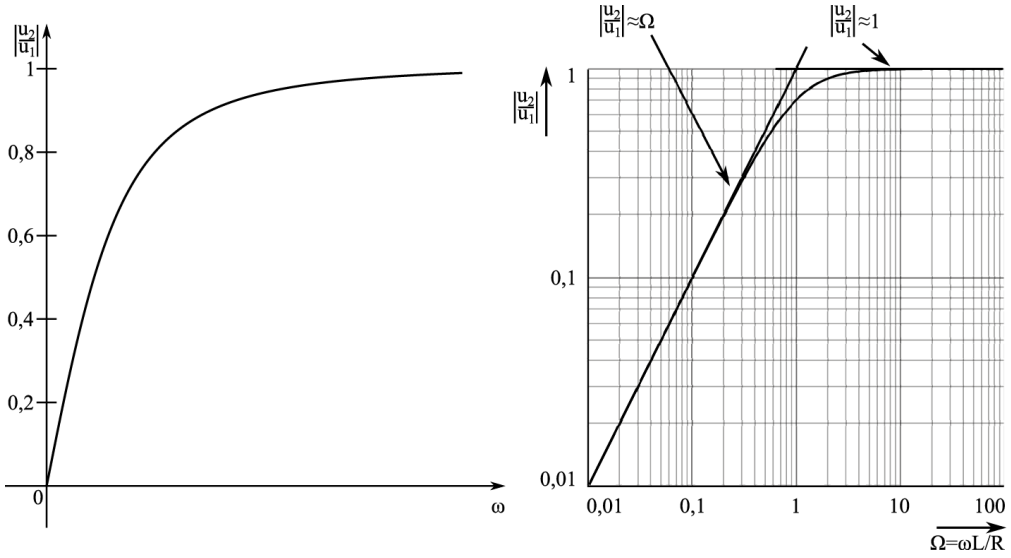

Fig. 8.3: The transfer function of the voltage; left: scaling using angular frequency; right: logarithmical scaling using Ω=ωL/R; straight lines show linear approximations for high and low frequencies.

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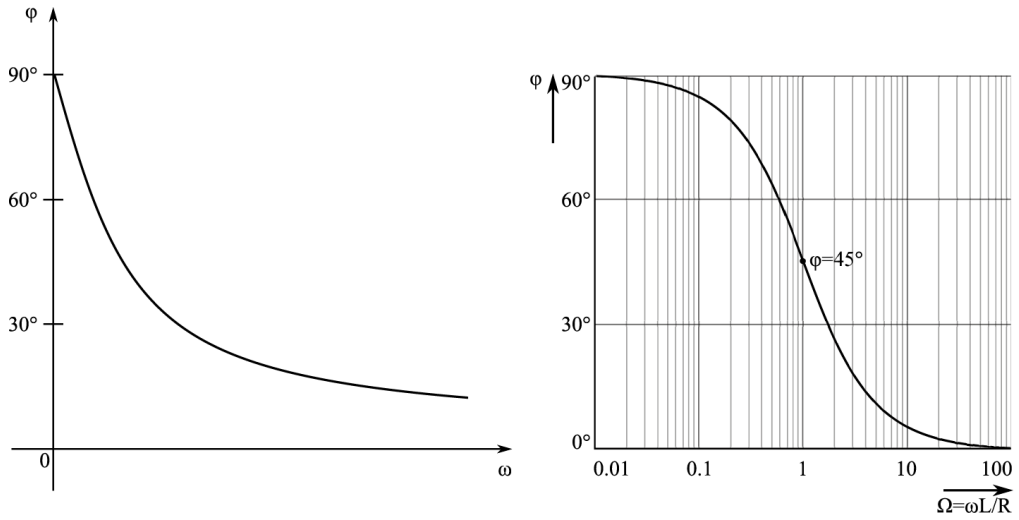

Fig. 8.4: The phase difference between output and input voltage; left: scaling using angular frequency; right: logarithmical scaling using Ω = ωL/R.

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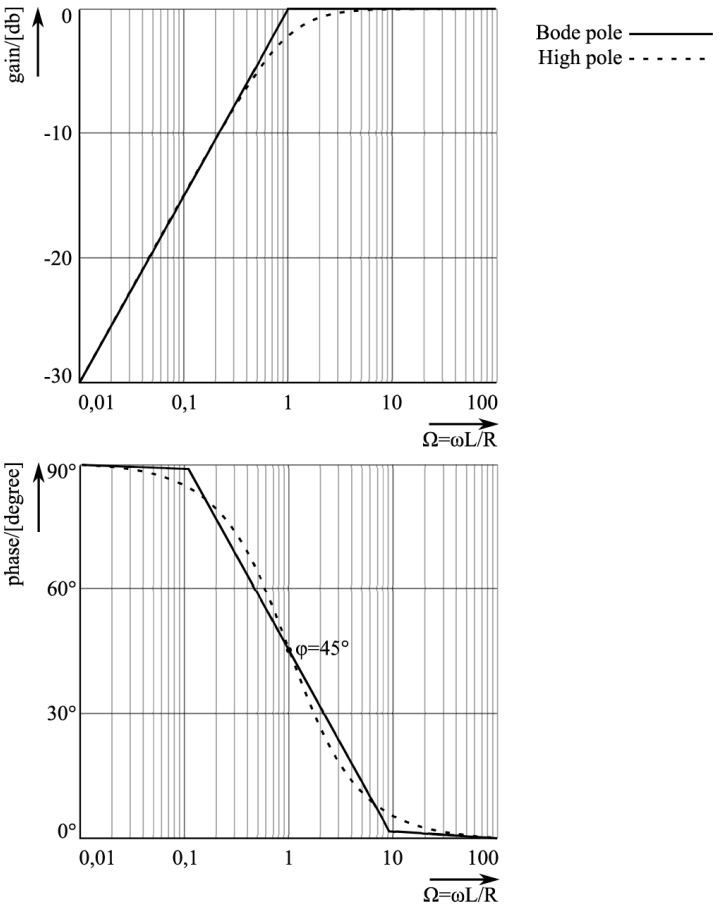

Fig. 8.5: A Bode plot of a high-pass filter.

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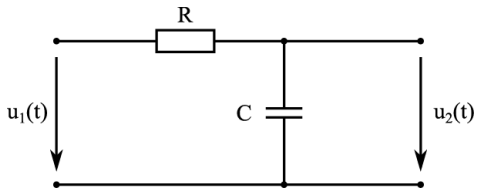

Fig. 8.6: An RC low-pass filter.

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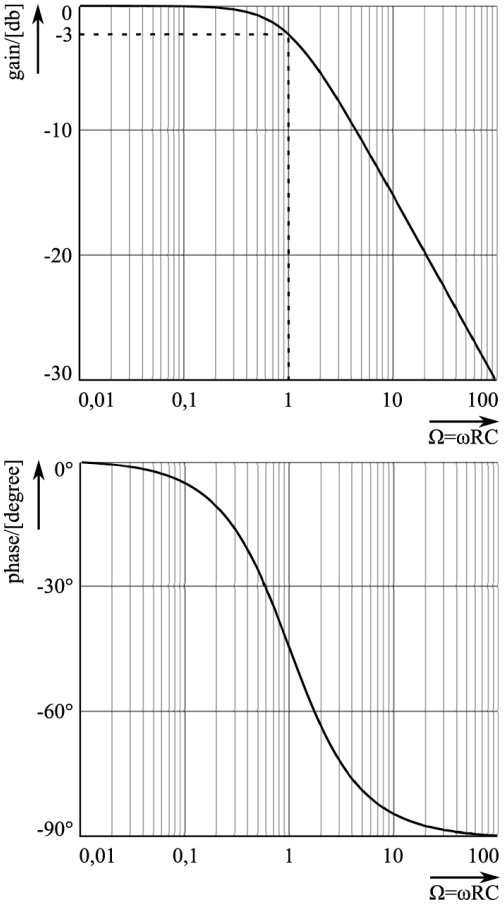

Fig. 8.7: A Bode diagram of a RC low-pass.

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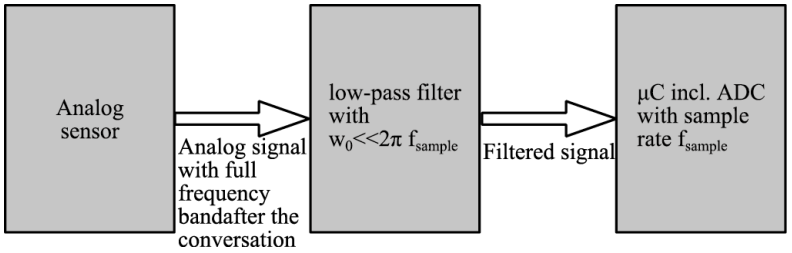

Fig. 8.8: A sensor system with microcontroller and low-pass (anti-aliasing) filter for the analog sensor signal.

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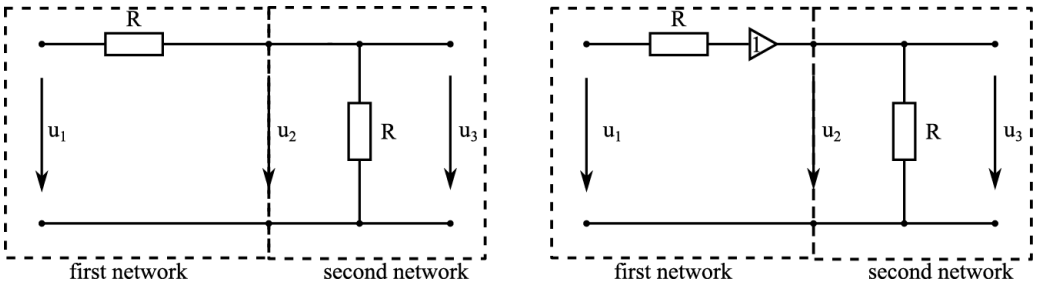

Fig. 8.9: Concatenation of two building blocks: without output termination (left), with an unity gain buffer at the output (right).

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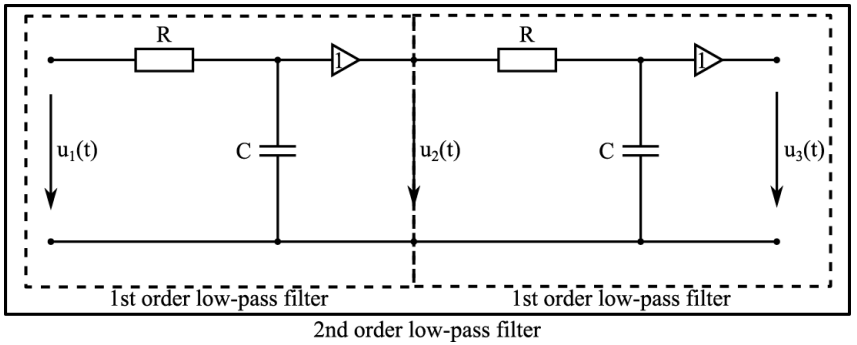

Fig. 8.10: A 2nd order low-pass filter, constructed by concatenation of two 1st order low-pass filters.

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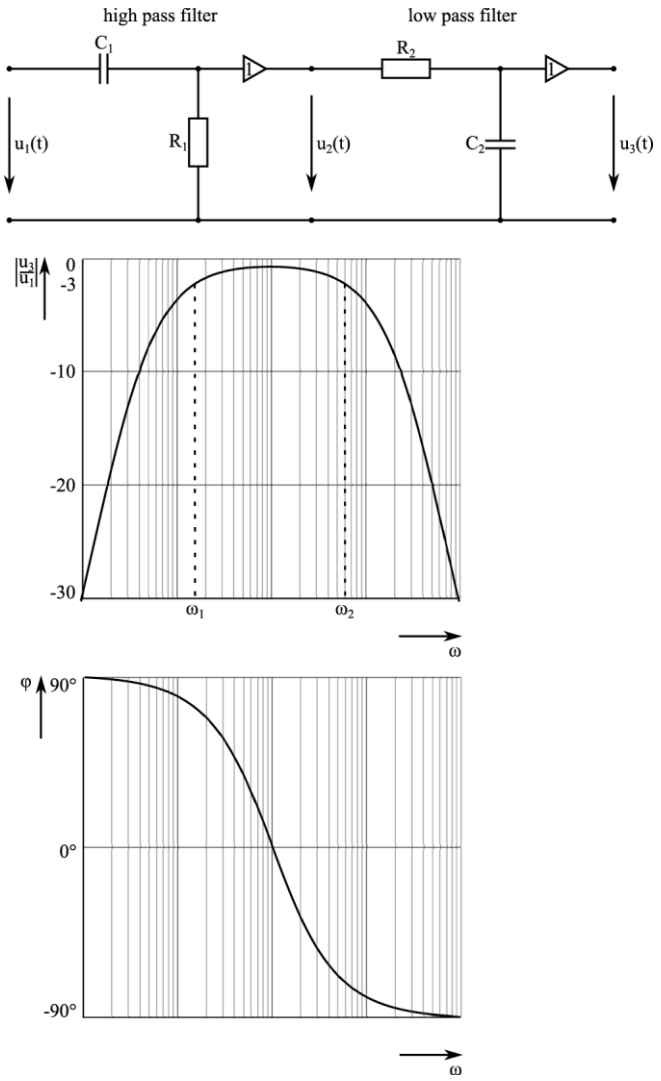

Fig. 8.11: A 2nd order band-pass filter, constructed by concatenation of a 1st order high-pass and low-pass filter (top); Bode plot of the band-pass filter (bottom).

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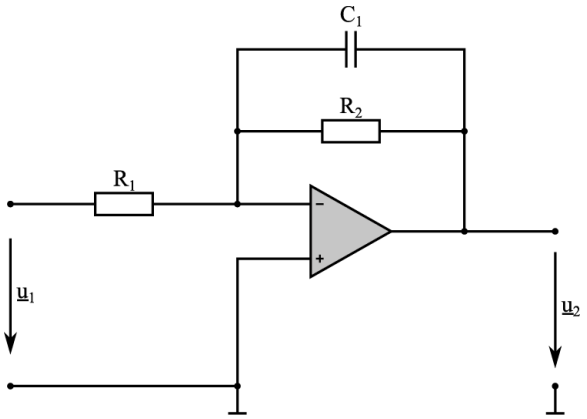

Fig. 8.12: An active high-pass filter.

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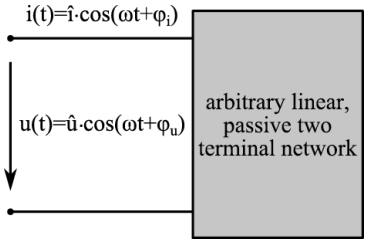

Fig. 9.1: Current and voltage of an arbitrary linear two terminal network.

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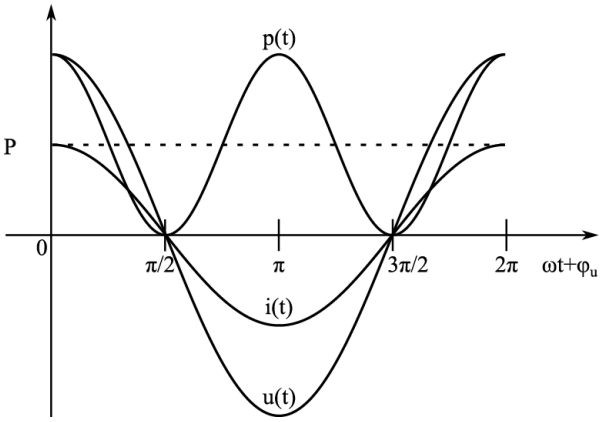

Fig. 9.2: AC power of a resistive network with voltage $\hat{u} \cdot \cos(\omega t + \varphi_u)$ and current $i(t) = \hat{i} \cdot \cos(\omega t + \varphi_i)$.

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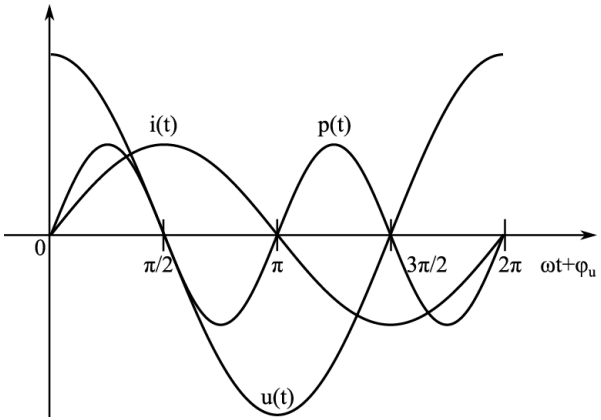

Fig. 9.3: AC power of a pure inductive network.

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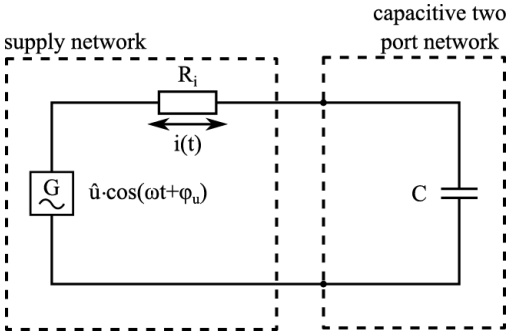

Fig. 9.4: A voltage source with internal resistance connected to a pure capacitive network.

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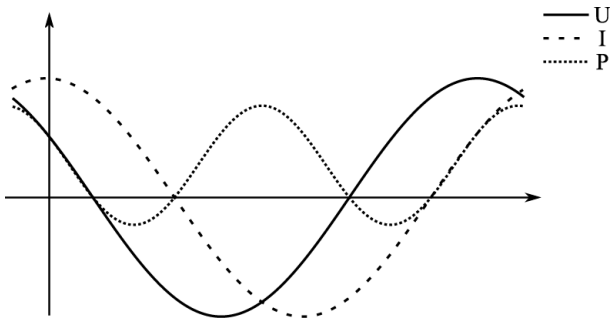

Fig. 9.5: AC power of a mixed resistive-capacitive network.

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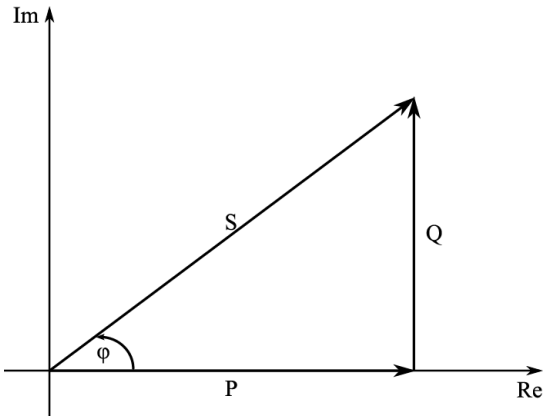

Fig. 9.6: An AC power diagram with active (P), reactive (Q) and apparent power (S).

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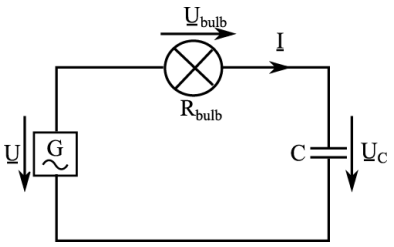

Fig. 9.7: A bulb in series with a capacitor to be operated by a sinusoidal voltage source.

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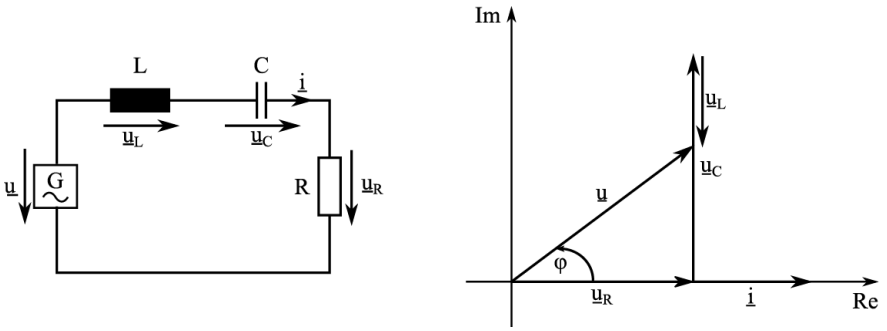

Fig. 10.1: An RLC oscillating circuit in series configuration (left); vector diagram of voltages and current (right).

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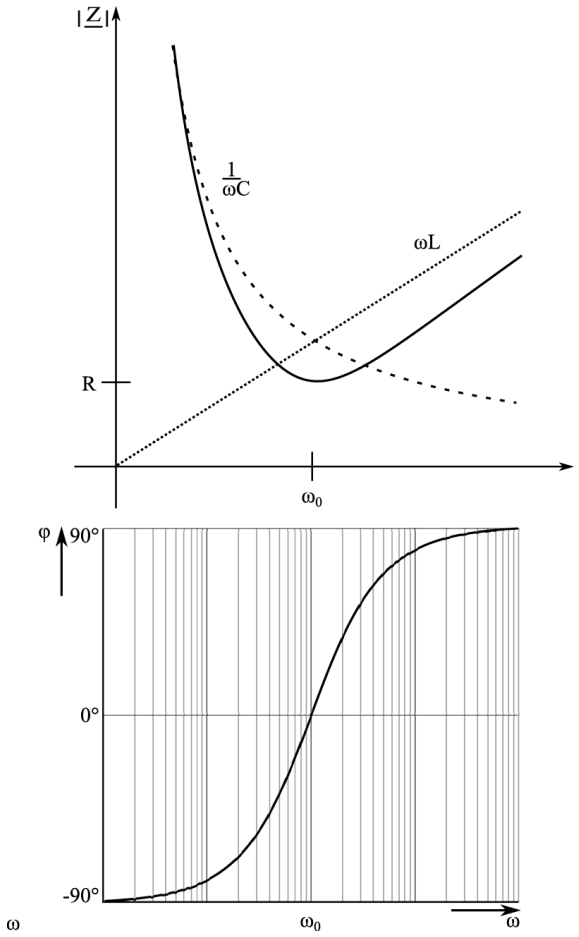

Fig. 10.2: Magnitude of the impedance of the series RLC circuit with the minimum value of R at resonance frequency (top); the corresponding phase angle (bottom).

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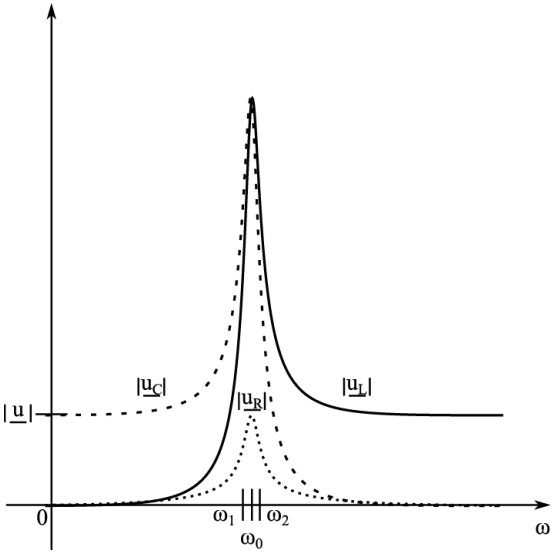

Fig. 10.3: The frequency dependence of the voltages across the inductor, capacitor and resistor, ω_1 and ω_2 are the cut-off frequencies.

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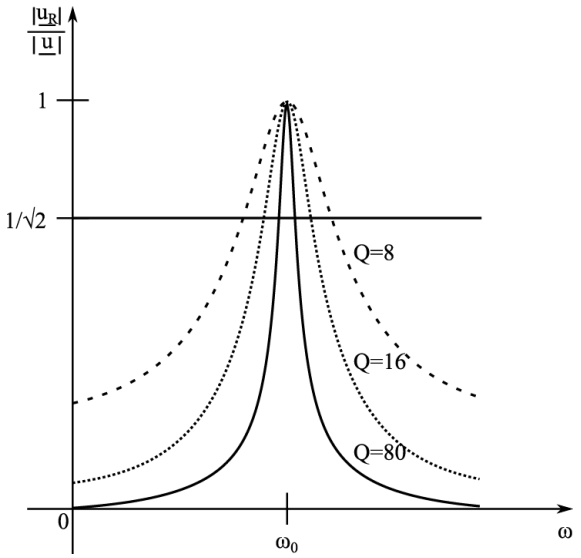

Fig. 10.4: The frequency response of a series RLC circuit with different quality factors but same resonance frequency.

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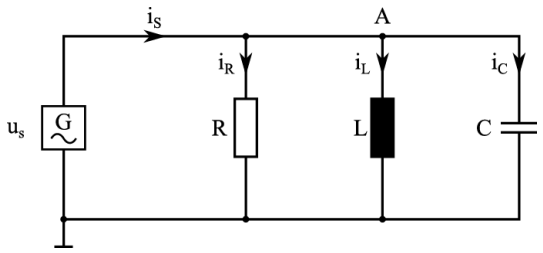

Fig. 10.5: A parallel RLC circuit.

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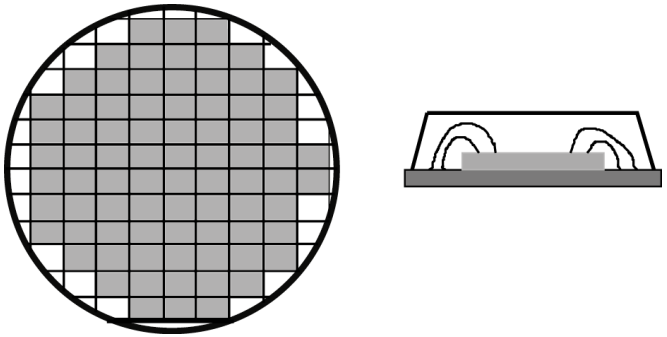

Fig. 11.1: A wafer with dies, complete dies are marked grey (left); packaged die (light grey) on a leadframe (dark grey) with bond wires (lines) in a package (right).

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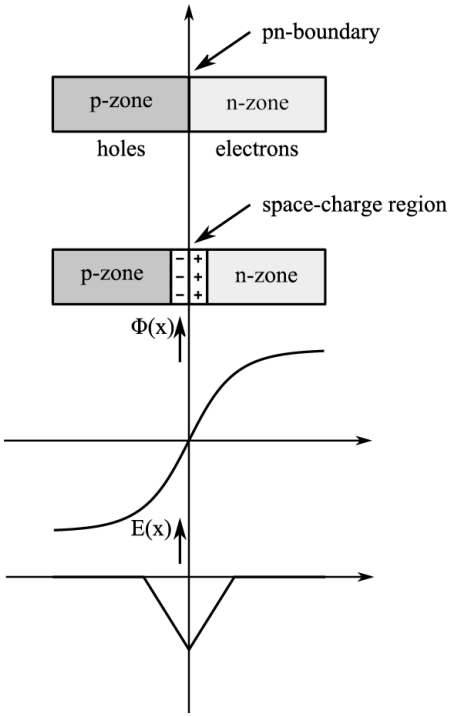

Fig. 11.2: From top to bottom: A theoretical pn-junction without electron transfer; a pn-junction with charge carrier diffusion and space-charge region; an electric field in x-direction and electric potential of the pn-junction.

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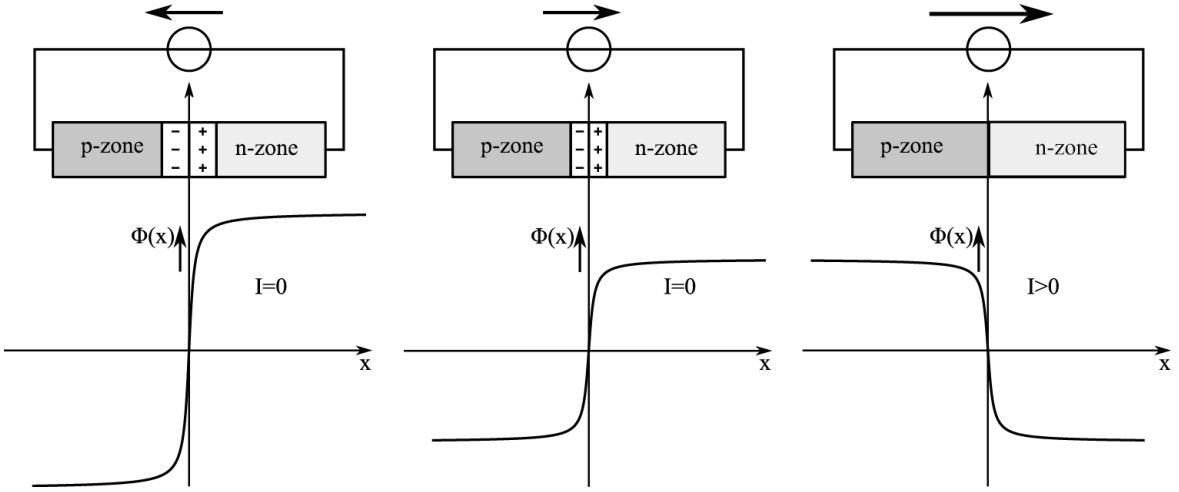

Fig. 11.3: An electric potential of a pn-junction with external voltage source.

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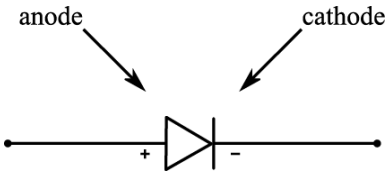

Fig. 11.4: Symbol of a diode with anode and cathode.

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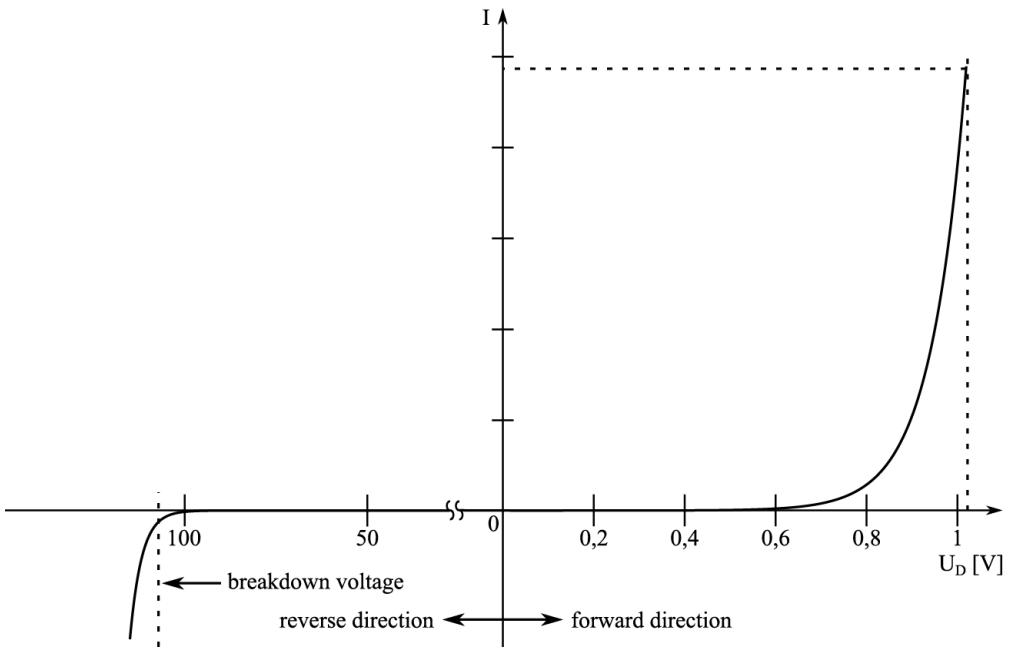

Fig. 11.5: A characteristics of a diode.

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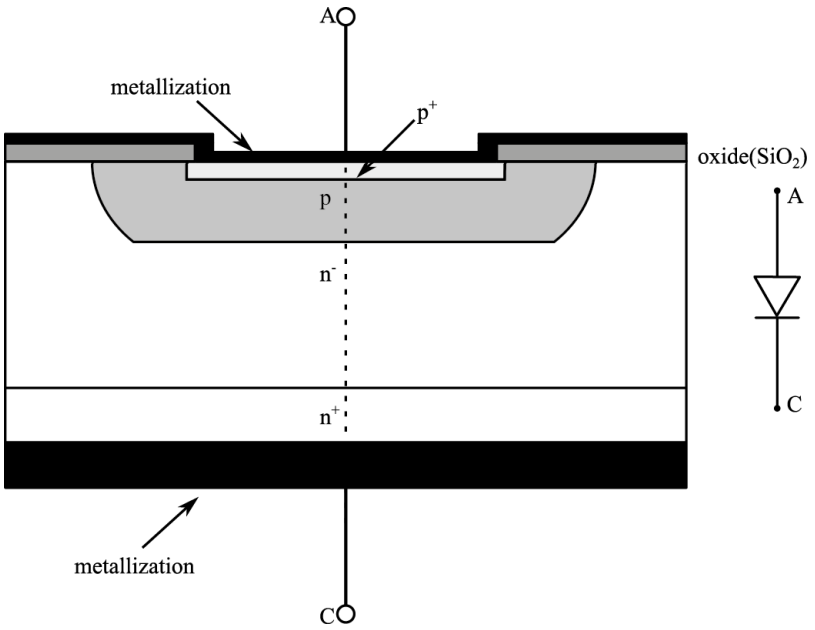

Fig. 11.6: Cross-section of a diode.

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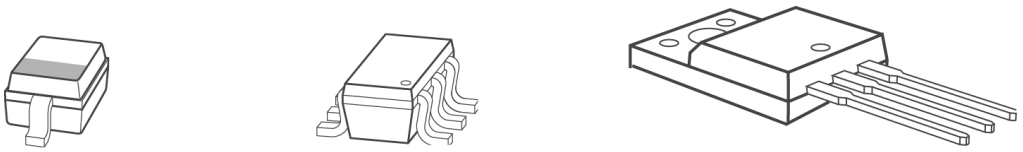

Fig. 11.7: Diode packages: SOD-323 SMD package (left), SC-74 SMD package (mid), TO-220 THD package (right). Package drawings by Infineon Technologies AG.

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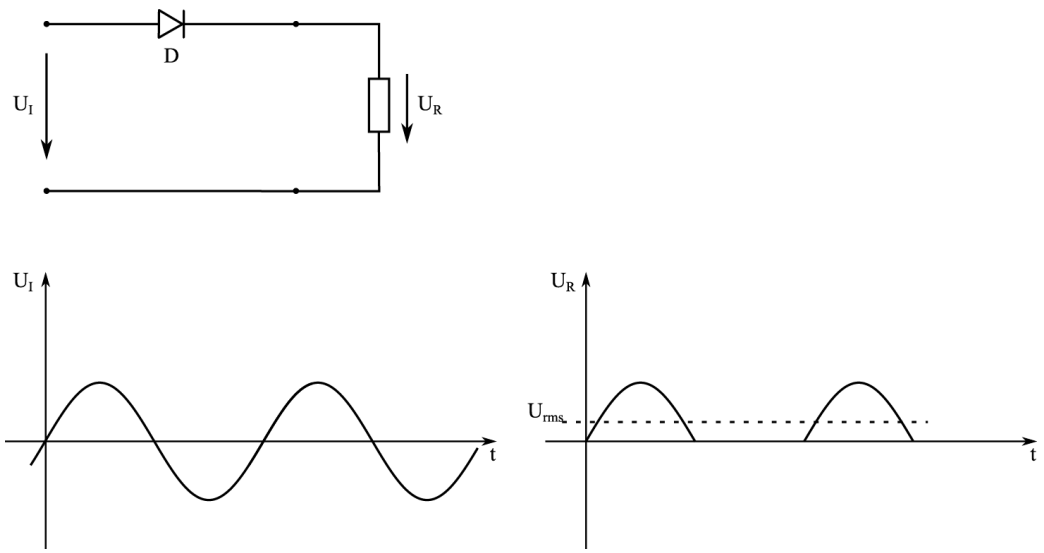

Fig. 11.8: A rectifier circuit with diode and resistor (top); an AC input voltage (bottom left) and a schematic drawing of rectified voltage at resistor (bottom right).

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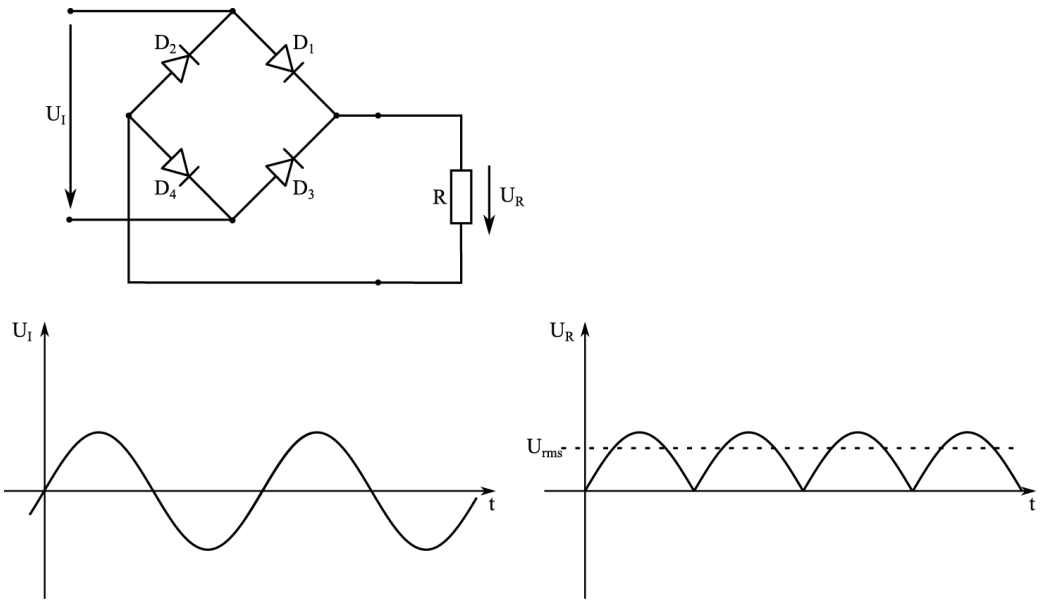

Fig. 11.9: A rectifier circuit with full bridge and resistor (top); an AC input voltage (bottom left) and a schematic drawing of rectified voltage at resistor.

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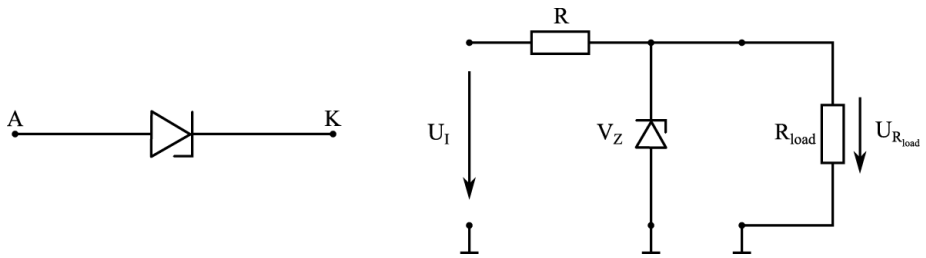

Fig. 11.10: The symbol of a Zener diode (left) and circuit for overvoltage protection (right).

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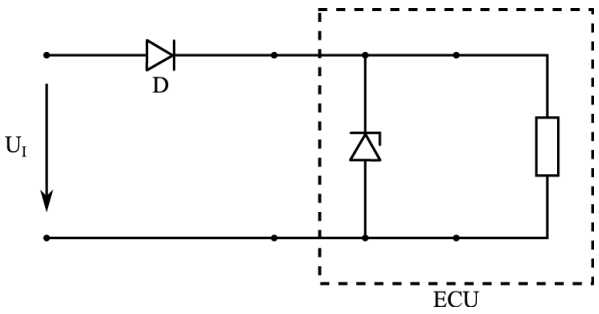

Fig. 11.11: A diode for reverse polarity protection of an ECU.

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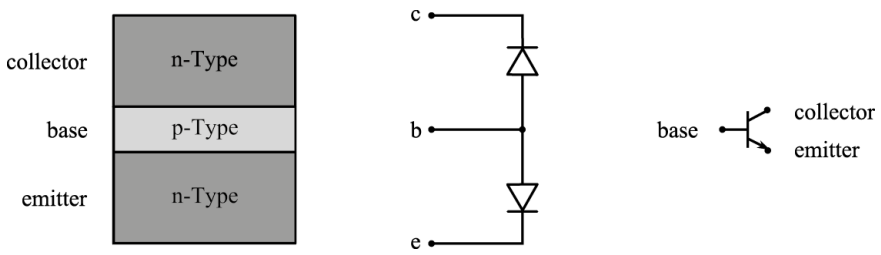

Fig. 11.12: An npn-BJT: layer structure (left); antiparallel diodes (center); circuit symbol (right).

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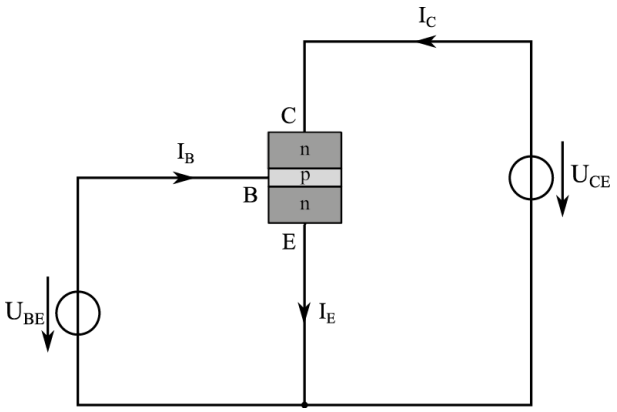

Fig. 11.13: An npn-BJT with external circuit: the base current drives the collector current.

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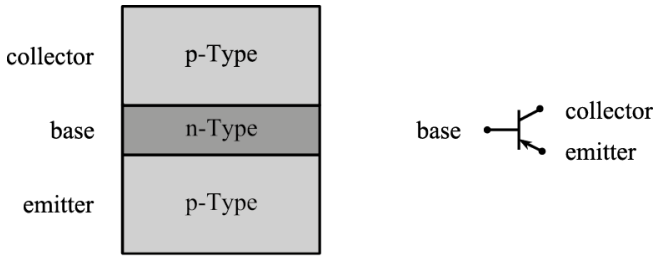

Fig. 11.14: A pnp-BJT: layer structure (left) and circuit symbol (right).

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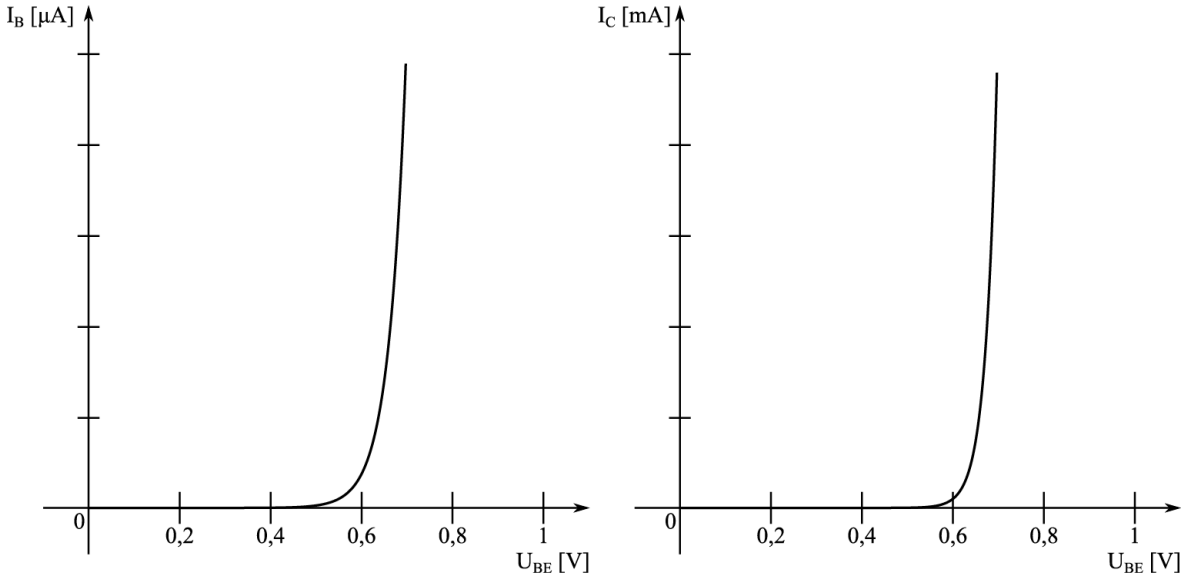

Fig. 11.15: Input characteristics of a npn-BJT: base current (control current, left); collector current (output current, right).

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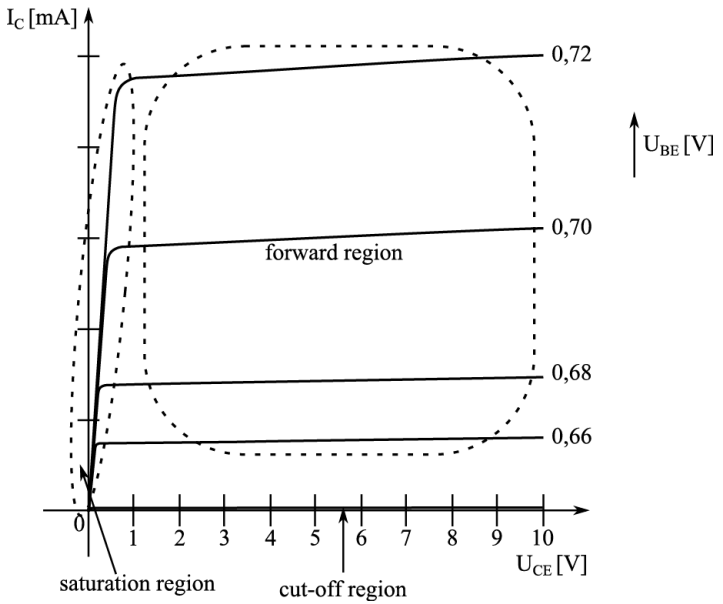

Fig. 11.16: Output characteristics of an npn-BJT: the parameter for the collector current is the base-emitter voltage.

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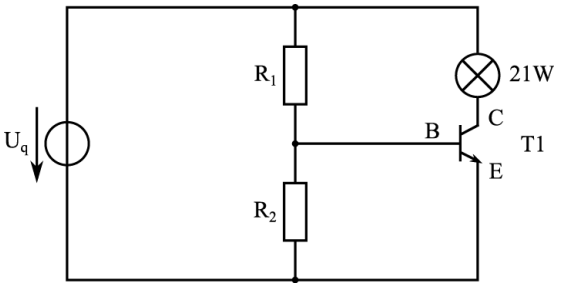

Fig. 11.17: A circuit with a bipolar transistor, the bulb acts as a resistive element with a resistance of 6.9 Ω.

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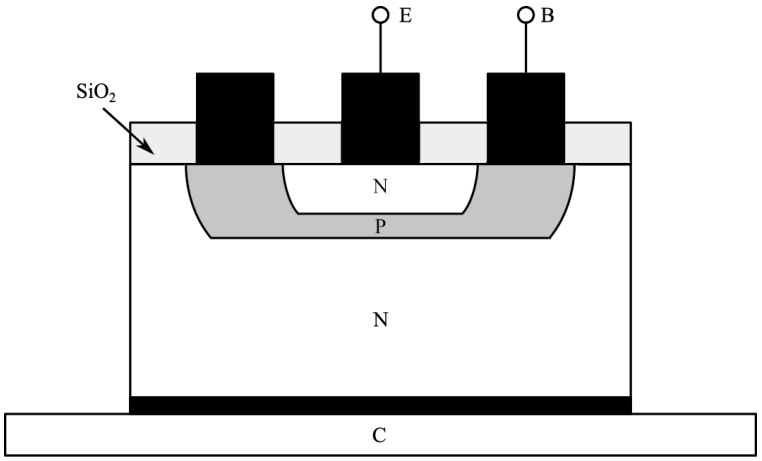

Fig. 11.18: The layer structure of an npn-BJT.

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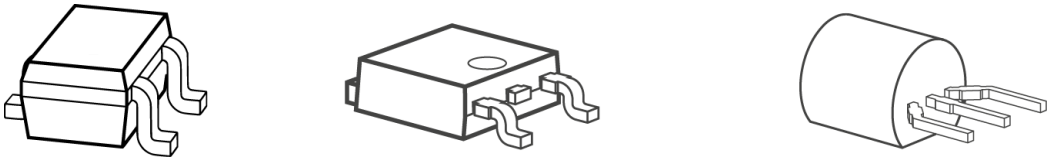

Fig. 11.19: Typical packages for BJT: two surface mount devices (SMD), small SOT-23 (left) and DPAK (TO-252, mid); TO-92 through hole device (THD, right). Package drawings by Infineon Technologies AG.

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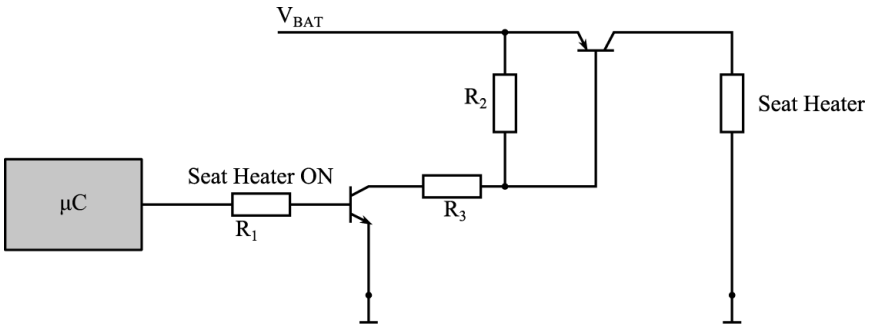

Fig. 11.20: BJT in a switching application, e.g. for seat heating.

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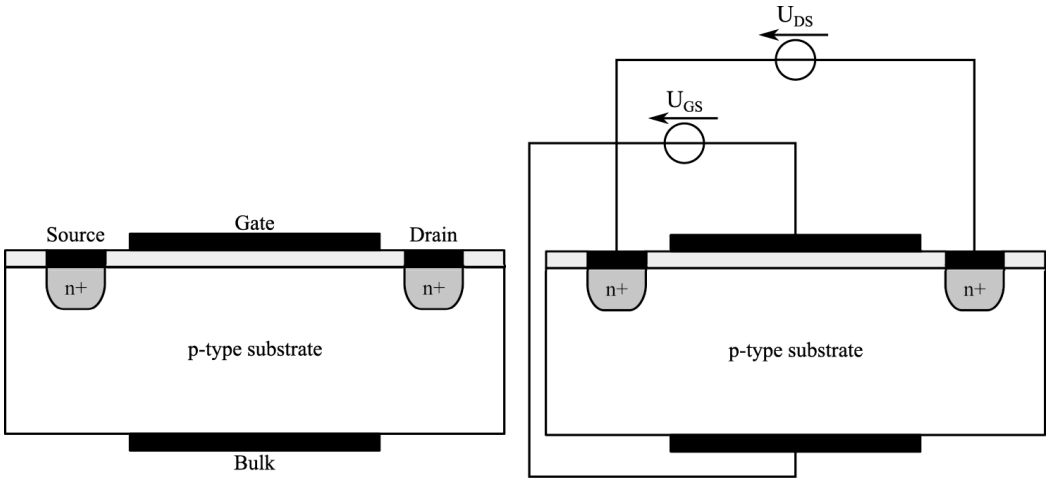

Fig. 11.21: Structure of a lateral n-type MOSFET with the four connections source, drain, gate and bulk (left); external connections for operation of the MOSFET.

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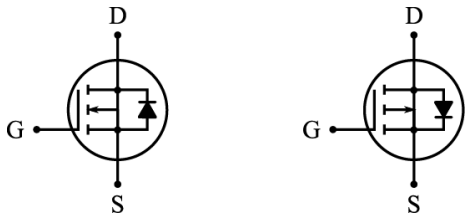

Fig. 11.22: Circuit symbols of an n-type MOSFET (left) and a p-type MOSFET (right).

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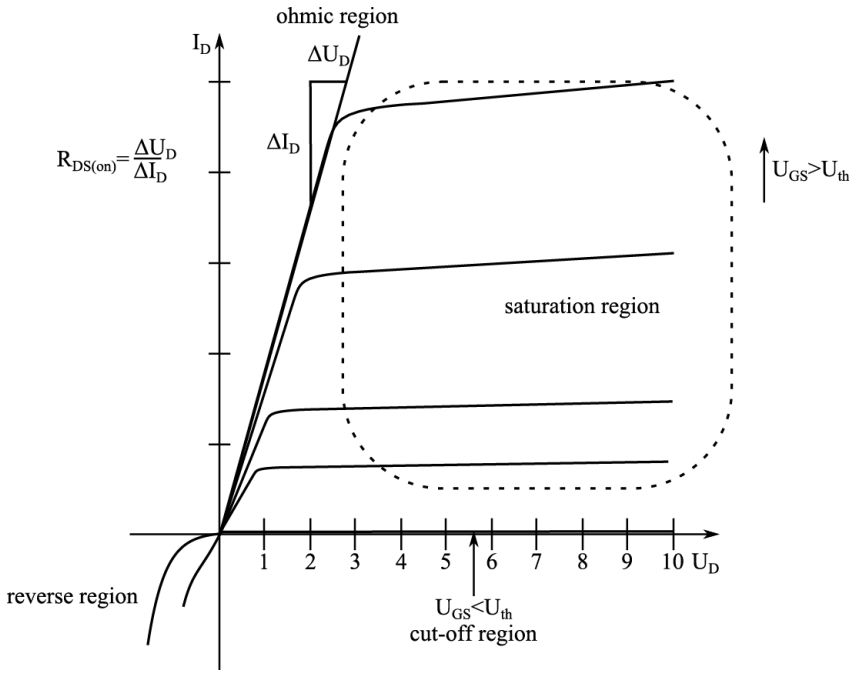

Fig. 11.23: Output characteristics of a n-type MOSFET.

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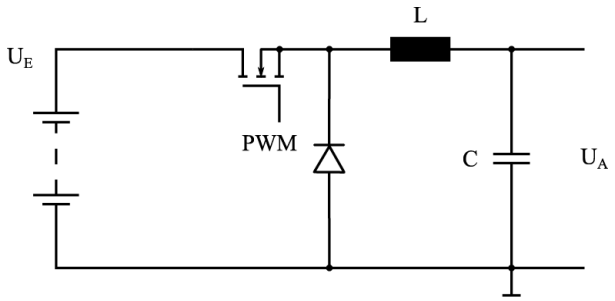

Fig. 11.24: Schematic of a buck converter.

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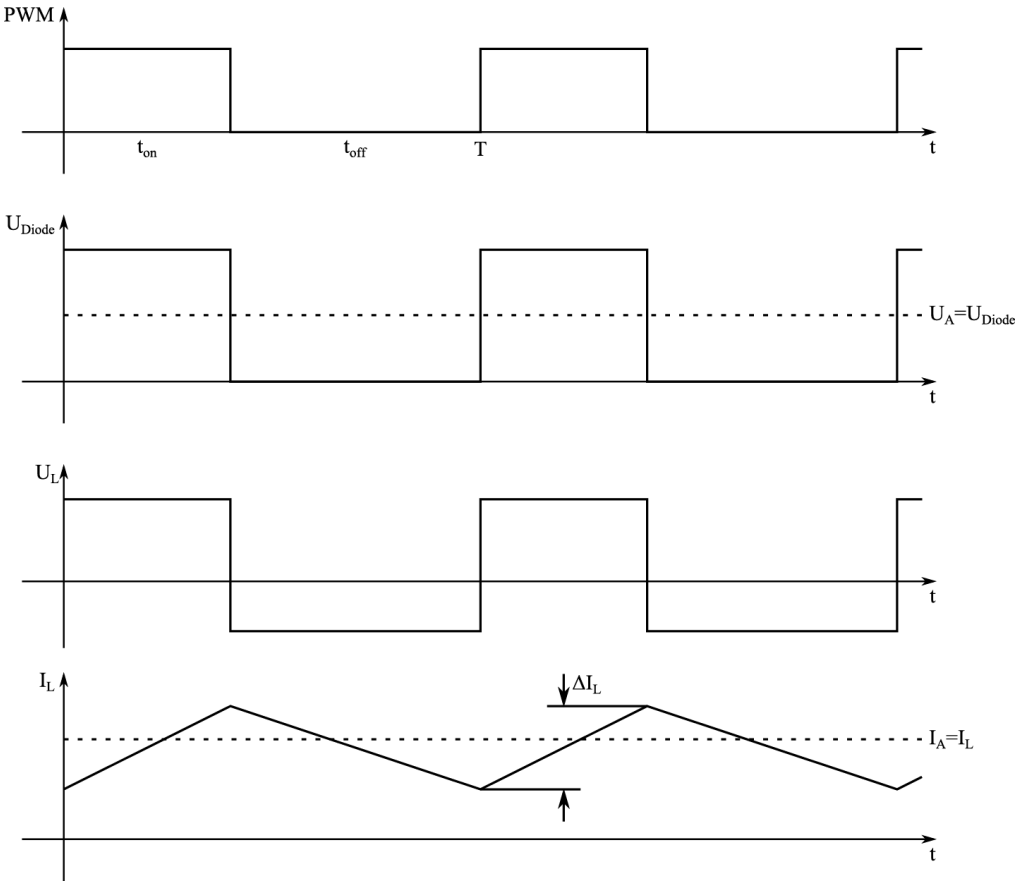

Fig. 11.25: Signals of a buck converter in continuous mode.

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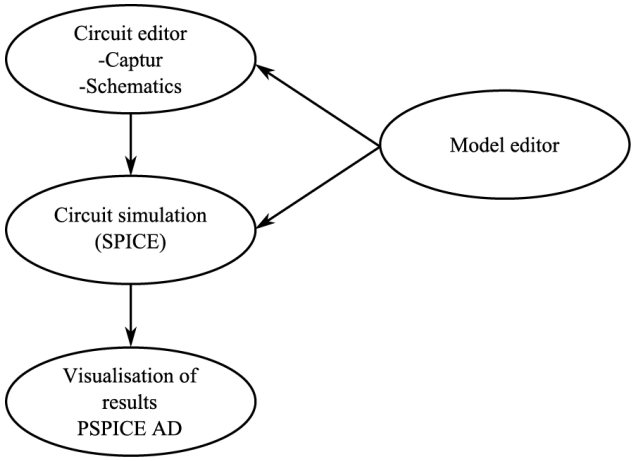

Fig. 12.1: Workflow of PSPICE simulation.

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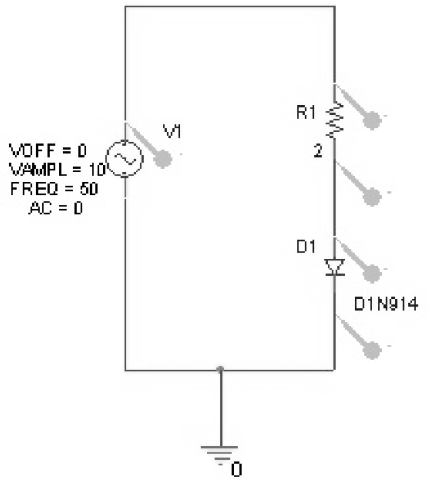

Fig. 12.2: A schematic of a simple AC circuit with probe marks in PSPICS capture.

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```
1:   * source  TEST  START
2:   V_V1  N00603  0
3:   +SIN  0  10  50  0  0  0
4:   D_D1  N00759  0  D1N914
5:   R_R1  N00603  N00759  2
```

Fig. 12.3: The netlist of the circuit depicted in Fig. 12.2.

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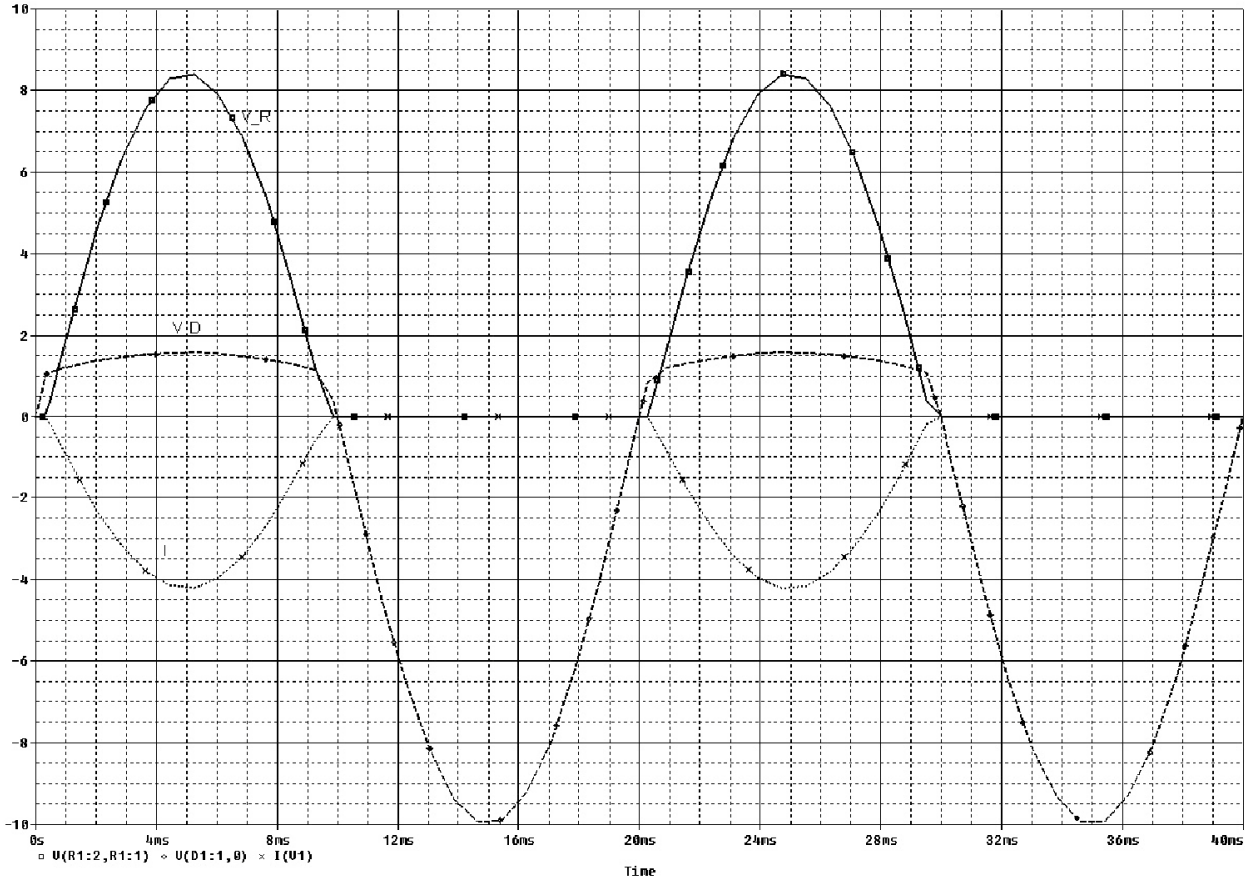

Fig. 12.4: Time domain simulation with PSPICE.

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Fig. 12.5: PSPICE model of a Power MOSFET NP50N04YUK by Renesas Electronics.

```
.SUBCKT NP50N04YUK 1 2 3
**************************************
*      Model Generated by Renesas    *
*         All Rights Reserved        *
*Commercial Use or Resale Restricted *
**************************************
* Model generated on December 1, 2012
* MODEL FORMAT: SPICE2G.6
* POWER MOSFET Model (Version 3.1)
* External Node Designations
* Node 1 -> Drain
* Node 2 -> Gate
* Node 3 -> Source
**************************************
M1  4 5 3 3 NMOS W=5198515.2u L=0.4u
DDS   3  1    DDS
CGS   5  3    5.880E-10
RG    2  5    3.57
RD    1  4    RTEMP 0.805264E-3
FGD   1  5    VFGD 1
EVGD  7  0 1 5 1
DDG1  8  7    DD1
DDG2  8  0    DD1
EGD1  9  0 7 8 1
EGD2 10  0 8 0 1
COX  10 11    9.07886E-10
DCRR 11  9    DDG
VFGD 11  0    0
**********************************************************************
.MODEL  NMOS       NMOS  (LEVEL  = 3           TOX    = 500E-10
+ XJ     = 0.14E-06       LD     = 0           WD     = 0
+ TPG    = 1              RS     = 0.9E-3      RD     = 0.8235604E-3
+ RG     = 0              NSUB   = 2.811E17    IS     = 0
+ UO     = 600            KAPPA  = 0.006
+ NFS    = 0.146E12       THETA  = 0.241
+ KP     = 2.4061E-5      PHI    = 0.87296     VMAX   = 1.51E5
+ CGSO   = 0              CGDO   = 0           CGBO   = 0
+ XQC    = 1.0            AF     = 1           CBD    = 0
+ CBS    = 0              CJ     = 0           CJSW   = 0
+ FC     = 0.5            JS     = 0           KF     = 0
+ MJ     = 0.5            MJSW   = 0.33        PB     = 0.8
+ RSH    = 0)
**********************************************************************
.MODEL DDS D (CJO=3.06687E-9 VJ=1.542717618 M=1.027746599
+RS=0.001593006 IS=2.543E-12 TT=0.9876E-8 N=1.012594482 BV=40)
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FC=1E-08)
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.MODEL DD1 D (CJO=0 N=1)
**********************************************************************
.MODEL RTEMP RES (TC1=15.825349E-03  TC2=4.84641E-05)
**********************************************************************
.ENDS NP50N04YUK
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Fig. 12.5: (Fortsetzung)

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