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1. Introduction

During the course, the basic information about electronic circuits will be presented. For better understanding of the subject, it is advised to use some helpful information available in books or magazines.

One of the most valuable help sources is the internet, with web pages of manufacturers of electronic components or measurement equipment.

A very useful software package is also available for download for free – the LTspice IV. This software allows to simulate the behavior of the circuits, measure voltages and currents. Although one should always bear in mind that simulation results can differ significantly from a real-life circuit behavior, due to the effects that were not included in the simulation, using this simulator for simple circuits provide invaluable help in process of understanding the principles of operation of the circuits.

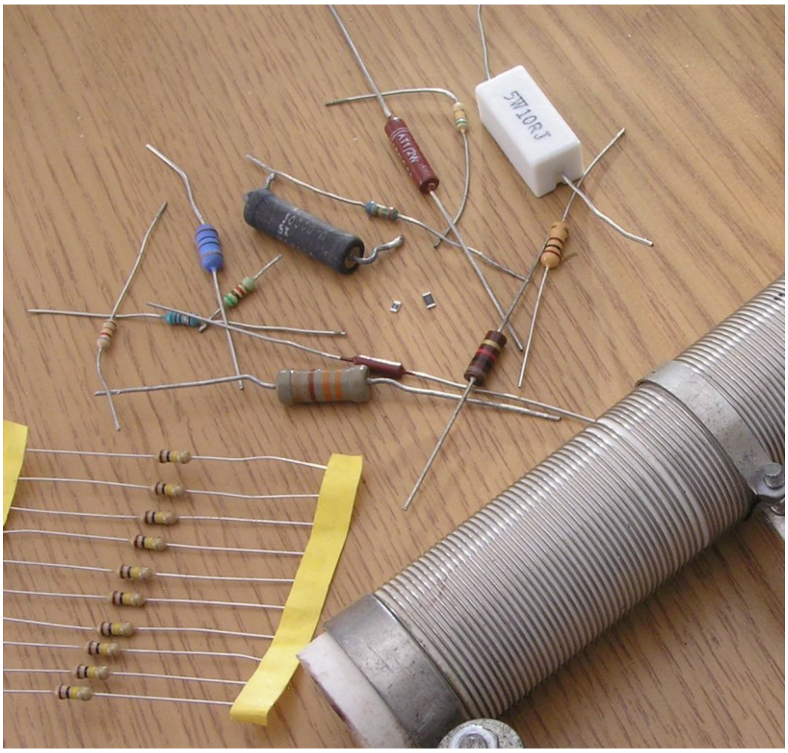
2. Passive components

Passive components are those components, that do not supply any power to the circuit they are used in. They either only consume power or repetitively store and release energy. The passive components are commonly used in electronic circuits and therefore it is very important to understand and memorize their properties.

The basic passive components are:

- resistors,
- capacitors,
- inductors.

Those three types of passive components will be discussed in the following sections.



2.1 Resistors

The simplest passive component is a resistor. It is probably the most common discrete electronic component. On schematics, it is usually depicted as one of the symbols shown on Figure 2.1.

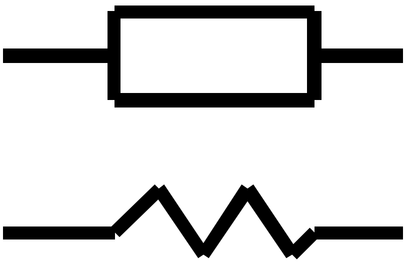


Figure 2.1 Schematic symbols for the resistor

The resistor opposes the current flow by developing a voltage that is proportional to the amount of current flowing through it, according to a known formula:

$$U = I \cdot R \tag{2.1}$$

The meaning of the symbols is the following:
U – voltage developed across the component,
I – current flowing through the component,
R – a specific value of resistance of a component, specified in Ohms (Ω).

The orientation of the voltage and current is shown on Figure 2.2. It is important to follow the same way of orienting the currents and voltages for all the components. Current flowing in the opposite direction than the one shown with an arrow will have a negative value.

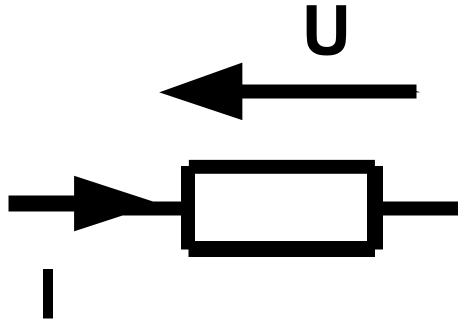


Figure 2.2. Current and voltage across the resistor

The most important parameters of a resistor are the following:

- **resistance** – the degree to which the given resistor opposes the current flow
- **tolerance** – the initial accuracy of the resistance value,
- **power** – the maximal value of power that can be safely dissipated by the given resistor,
- **voltage** – the maximum value of voltage that can be applied to the given resistor,
- **stability** - the ratio at which the given resistor changes its resistance with temperature, with time or with voltage applied to it.

Example values, valid for the resistor from Figure 2.6, are the following:

- resistance 200kΩ,
- tolerance ±1%,
- power 0.6W providing its temperature is held below 70°C,
- working voltage 250V, overload 500V,
- temperature stability ±50 ppm/°C (parts per million per one degree Celsius).

It is very important to use the resistors according to the limiting values of maximal power and voltage. Resistor that dissipates too much power will burn, and the resistor experiencing too high voltage may be damaged and shorted.

Apart from the desirable element of resistance, all the resistors exhibit parasitic capacitance and inductance, that is they behave not like a simple resistor, but more like a complex connection of resistance, capacitance and inductances, as shown below.

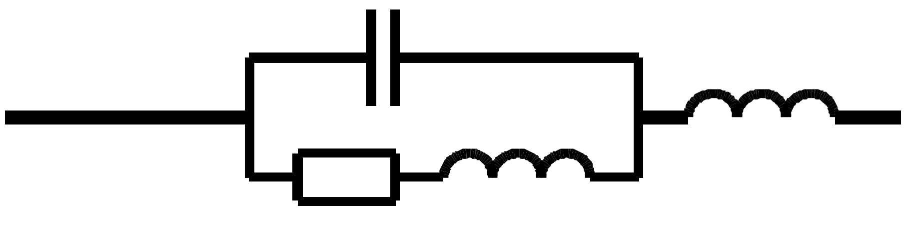


Figure 2.3 Parasitic elements of a real life resistor

The values of capacitance and inductances are very low, but they need to be taken into consideration in high frequency circuits.

The parasitic elements values, as well as other properties of the resistors depend on the technology that was used to manufacture the resistor. The different technologies are listed below.

Carbon volume resistors – very old technology, the resistor is a small pipe filled with carbon resistance compound. Those resistors typically have inaccurate resistance values, produce much electrical noise, but can dissipate bigger powers when compared to other resistors of similar size. Rare type nowadays.

Figure 2.4 Carbon volume resistors

Carbon film resistors –old technology, the resistor is a small ceramic pipe with carbon resistance compound deposited on its surface. Those resistors typically have mediocre accuracy and produce much electrical noise. They are very cheap and are still popular in less demanding applications.

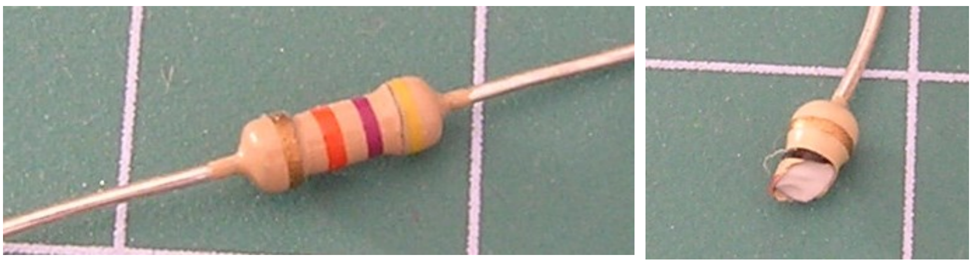


Figure 2.5 Carbon film resistor

Metal film resistors – the resistor is a small ceramic pipe with metalized resistance alloy deposited on its surface. Those resistors typically have acceptable accuracy and produce less electrical noise than carbon types. They look very similar to carbon film resistors.

Figure 2.6 Metal film resistor

Thick film resistors – the resistor is a small ceramic slab with thick (~0.1mm) resistive layer on its surface, deposited in a form of paste and baked. Those resistors typically have acceptable accuracy. They are very popular due to the fact that most modern (so called surface mount – SMD – resistors) are manufactured in this technology, and therefore are the cheapest resistors on the market.

Thin film resistors – the resistor is a small ceramic slab with thin (~0.1μm) resistive alloy vacuum deposited on the surface. Those resistors have better accuracy and stability than thick film. They are, however, more expensive. On the outside they are similar to thick film ones, with similar SMD packages.

Wire wound resistors – the resistor is formed by a wire made of a resistive alloy wound around a non-conductive (usually ceramic) cylinder. They can dissipate large powers and are very durable. They can be made to a high accuracy and stability. Although special ways of winding the wire are devised, they usually have considerable inductive parasitic element, therefore are not suited well for high frequency applications.

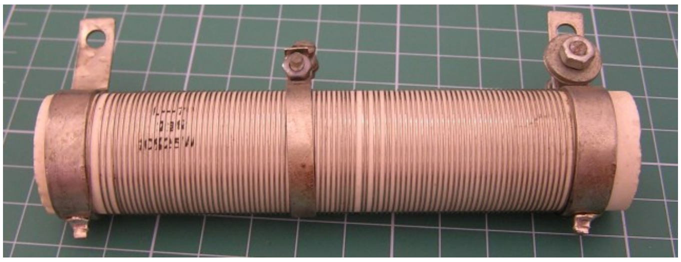


Figure 2.7 Wire wound resistor

Metal foil resistors – the resistor is made from a thin foil made of a stable resistive alloy. They are more delicate than thick or thin film resistors, but provide much better accuracy and stability.

Table 2.1. SMD resistor sizes

type	typical		width [mm]	length [mm]
	max. power [W]	max. voltage [V]		
0201	0.05	25	0.3	0.6
0402	0.1	50	0.5	1.0
0603	0.1	75	0.8	1.6
0805	0.125	150	1.2	2

Resistance values

Any given resistance value (up to a given precision) can be ordered from manufactures, but such an order is expensive and usually one is expected to buy large quantities of such resistors. It is, however, much cheaper to use readily available resistors. Those resistors have specific resistance values, according to a series of values. For every decade (decade = value changes ten-fold), resistors of certain values are available. For example in a value series called E6, the following values are available:

For 1Ω decade: 1Ω, 1.5 Ω, 2.2 Ω, 3.3 Ω, 4.7 Ω, 6.8 Ω,
For 10Ω decade: 10Ω, 15 Ω, 22 Ω, 33 Ω, 47 Ω, 68 Ω,
For 100Ω decade: 100Ω, 150 Ω, 220 Ω, 330 Ω, 470 Ω, 680 Ω,
and so on…

The more accurate resistors are manufactured with values of more precise series, like E24 or E96.

The resistance value is marked using one of the following methods:

1. Color stripes
   The value is encoded by 4, 5, or 6 color stripes, according to the table below.

Table 2.2 Color code for resistors

color	**value**	**multiplier**	**tolerance**	**temperature coefficient**
Silver		$\cdot 10^{-2}$	±10%	
Gold		$\cdot 10^{-1}$	±5%	
Black	0	$\cdot 10^{0}$		
Brown	1	$\cdot 10^{1}$	±1%	100ppm
Red	2	$\cdot 10^{2}$	±2%	50ppm
Orange	3	$\cdot 10^{3}$		15ppm
Yellow	4	$\cdot 10^{4}$		25ppm
Green	5	$\cdot 10^{5}$	±0.5%	
Blue	6	$\cdot 10^{6}$	±0.25%	
Purple	7	$\cdot 10^{7}$	±0.10%	
Gray	8		±0.05%	
White	9			

Usually a resistor will have 4 stripes, like the one in Figure 2.5. The first two are the digits of resistance value, the third stripe is a multiplier and the fourth - tolerance. Therefore, the resistor from Figure 2.5, has the resistance:

4 (yellow)
7 (purple)
10^3 (orange)
±5% (gold)
= 47000 Ω ±5%

Another example is a resistor with 5 stripes, as shown below:

Figure 2.8 An example of a resistor with 5 stripes

The resistance in such a case is encoded the following way: the first 3 stripes encode digits, the fourth encodes the multiplier, the fifth – encodes the tolerance. Thus, the resistor from Figure 2.8 has the resistance:
5 (green)
1 (brown)
0 (black)
10^{-1} (gold)
±1% (brown)
= 51 Ω ±1%

If a resistor has six stripes, the last one shows the temperature coefficient of a resistor.

Example:

The resistor has the following, fictious marking:

Red, Blue, Orange, Red, Brown, Red.

This means that its nominal resistance is:
$2\ 6\ 3 \cdot 10^2 \pm 1\%$ 50ppm/°C
Its nominal value at nominal temperature (usually 25°C) is 26300 Ω. However, its 1% tolerance means that the actual value can be anything within the range 26300 · 0.99 to 26300 · 1.01:

from 26037 Ω to 26563 Ω

In addition to that, with every degree of temperature change, the resistance value can change as much as 50 parts per million, so by nominal 26300 · 50 / 1 000 000 = 1.315 Ω. This is the maximal change and usually the resistance rises with temperature.

The resistor with the marking specified can have the resistance of 26037 Ω at 25°C, while at the temperature 50°C its resistance can be 26069 Ω.

It is said that the stripes should be painted in a way that makes it possible to tell which side the code starts, like the distance between stripes (larger between digits and multiplier) or stripe width (larger for tolerance).
In practice, however, it is really difficult to note any differences. Therefore I suggest the following approach:
For 4 striped resistors you look for the golden/silver stripe and you know the stripe that tolerance is marked with (the 4 striped resistors are usually made to tolerance of ±5% or worse).
For 5 or 6 stripes there is no easy and practical rule.

2. Number code
   The resistance value can be marked using digits, an approach used for different kinds of resistors. The resistance is encoded the same way as with the color stripes – the first 2 or 3 digits encode resistance digits, while the third or fourth digit encodes multiplier exponent.
   The resistor with the following digits: 123 will have the resistance of 12000 Ω.
   Compared to the color stripe code, in this case it is not possible to mistakenly read the resistance “backwards”. The tolerance is not marked in case of this method.

3. Resistance value

For physically larger resistors it is common to find the resistance written explicitly on them. The comma can then be replaced by a letter R (from *radix*). The tolerance is marked with a letter code. The letters correspond to the following tolerances (Table 2.3).

Table 2.3 Tolerance letter code

Letter	**Corresponding tolerance**
E	±0.5%
F	±1%
G	±2%
H	±3%
J	±5%
K	±10%
M	±20%
N	±30%

Potentiometers

A very important type of a special purpose resistor is a potentiometer. A potentiometer is a resistor with at least 3 pins. Resistance between two pins is constant, while the resistance between the third pin (so called wiper) and the remaining 2 pins can be altered by turning the axle of the potentiometer. The symbols used for potentiometers are shown on Figure 2.9.

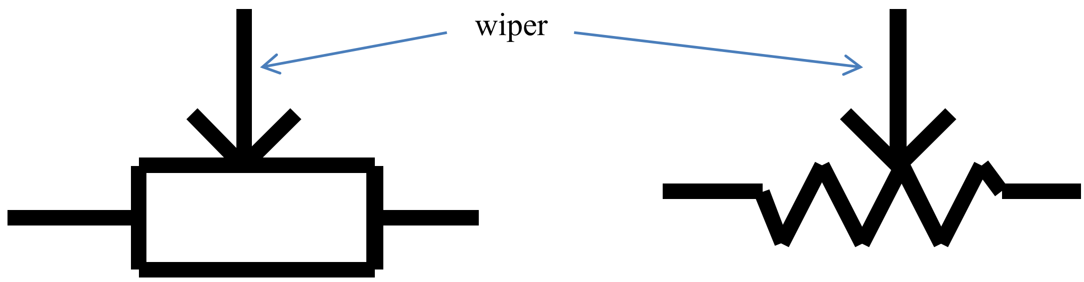


Figure 2.9 Potentiometers

The main use of potentiometer is to adjust the voltage in a manner similar to a resistor divider, as shown on Figure 2.10.

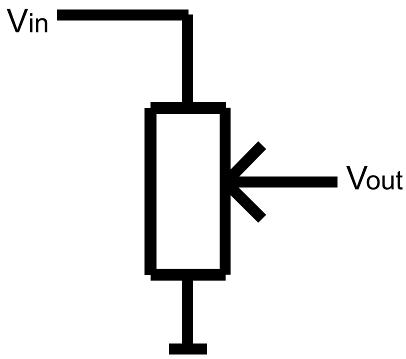


Figure 2.10 Potentiometer as a voltage divider

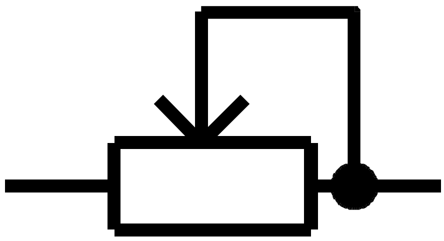


Figure 2.11 Potentiometer as a variable resistor

A less popular application is to use it as a variable resistor, with two legs (wiper and one of the remaining pins) connected together, as on Figure 2.11.

The potentiometers can be either a one turn (Figure 2.12) or multi-turn one (Figure 2.13). The latter allow for more precise setting, but are much more expensive. There are also different kinds of mechanical solutions for potentiometer, like, for example, slide potentiometers (Figure 2.14).

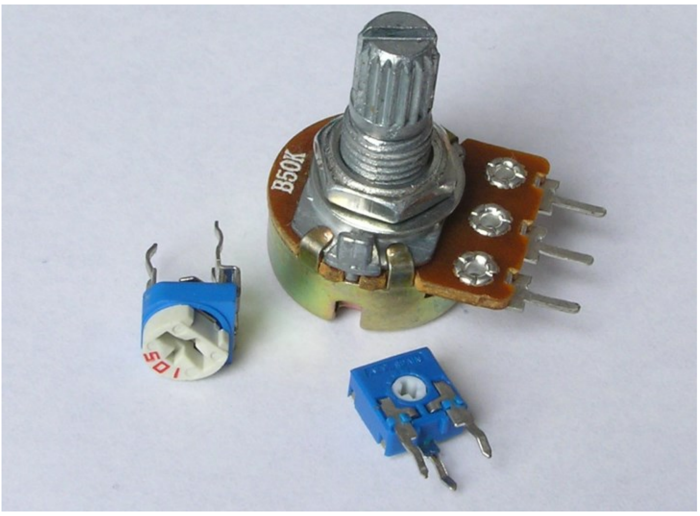


Figure 2.12 Single turn potentiometers

Figure 2.13 Multi-turn potentiometers

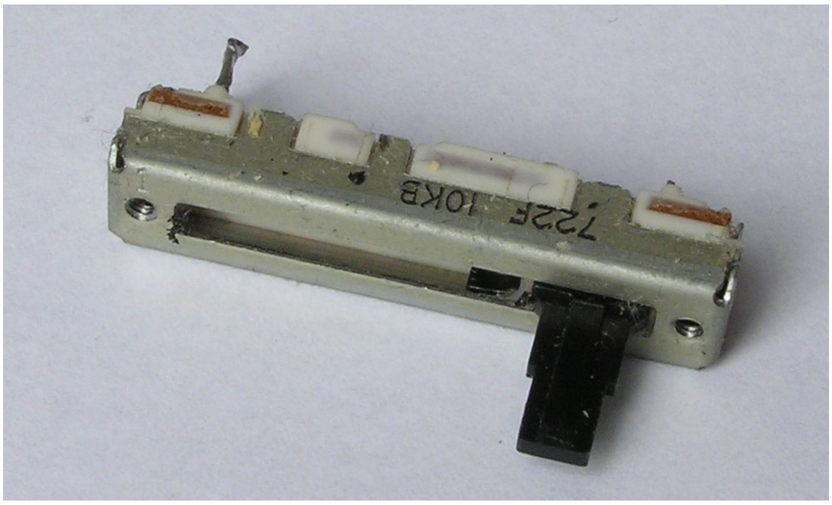


Figure 2.14 Slide potentiometer

2.2 Capacitors

The second important electronic component is a capacitor. There are different types of capacitors, with very different properties. Not every type of capacitor can be used in specific applications and some capacitors need to be connected in the circuit in a certain way, observing their internal polarity. On schematics, a capacitor is usually depicted as one of the symbols shown on Figure 2.15.

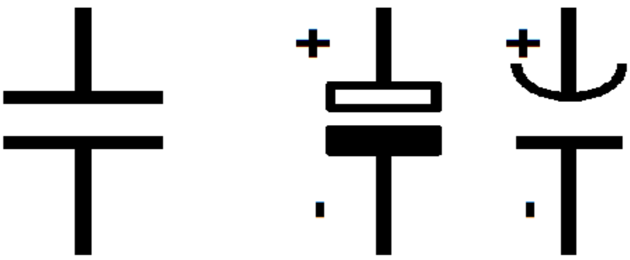


Figure 2.15 Schematic symbols for capacitor. Left – non-polarized capacitor, right – polarized capacitor.

The operation of the capacitor is best described using the following formula:

$$I = C\,\frac{dU}{dt} \tag{2.2}$$

The meaning of the symbols is the following:
U – voltage developed across the component,
I – current flowing through the component,
C – a specific value of capacitance of a component, specified in Farads (F).

From the formula, it should be understood that the current flowing through the capacitor depends on the capacitance of the capacitor and the rate of change of the voltage across the capacitor.

The voltage and current used in the above equation are shown on Figure 2.16.

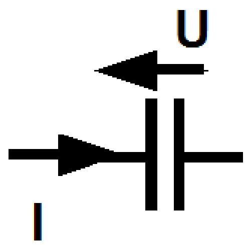


Figure 2.16 Current and voltage across a capacitor

A Farad is relatively large value of capacitance, and in most cases, the capacitors used in electronic circuits have capacitance of a fraction of Farad, usually ranging from picofarads (10^{-12}) to milifarads (10^{-3}). There are, however, capacitors of capacitance in order of tens or hundreds Farads.

Apart from capacitance, there are other values characterizing a capacitor. The most important parameters of a capacitor are listed below:

- **capacitance** – the capability of storing the energy in the form of electric field,
- **voltage** – the maximum value of voltage that can be applied to the given capacitor,
- **polarity** – some types of capacitors are constructed in such a way, that the voltage across them can have only a certain polarity, applying reverse polarity can destroy capacitor and even cause an explosion,
- **tolerance** – the initial accuracy of capacitance value,
- **stability** – the ratio at which the given capacitor changes its capacitance with temperature, with time or with voltage applied to it,
- **dissipation, ESR (Equivalent Series Resistance)**– an ideal capacitor does not dissipate any power. In reality, however, the internal resistances do dissipate power – this is usually a very undesirable effect. Large dissipation limits the use of capacitors in applications where large spikes of current are expected to flow in or out of capacitor and increases the impedance of the capacitor.

Depending on the application, the typical values and form factors of a capacitor can vary significantly. For the capacitor visible on Figure 2.17, the basic properties are the following:

- capacitance 100nF (0.0000001 F),
- tolerance ±5%, in temperatures -55°C to 105°C
- working voltage 63V,
- dissipation factor (tgδ) $<250\cdot10^{-4}$ for frequencies below 100 kHz.

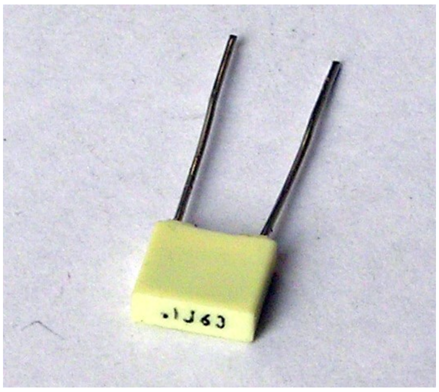


Figure 2.17 Example capacitor

Apart from the desirable element of capacitance, all the capacitors exhibit parasitic resistance and inductance, that is they behave not like a simple capacitor, but more like a complex connection of resistances, capacitance and inductance, as shown below.

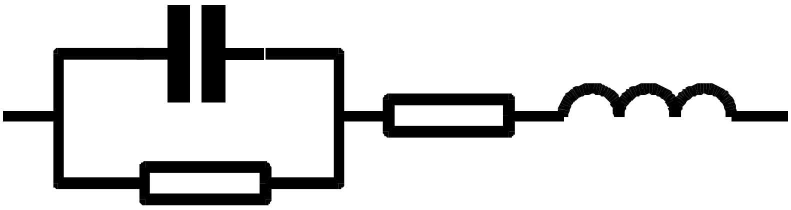


Figure 2.18 Model of parasitic elements of a real life capacitor

In many circumstances, the parasitic resistances and inductances have to be taken into account, even in low frequency or DC applications, due to leakage (modeled as the resistor parallel to the capacitor). For the capacitor from the previous photograph, the manufacturer specifies inductance of 7nH plus 1nH for each 1mm of leads and capacitor length.

Capacitor types

There are many types of capacitors, but they can be grouped in a few categories. All categories have different properties and for most applications, only a certain categories can be successfully used. Three main categories of capacitors are listed below.

Foil. The foil capacitors are made with the use of two conducting stripes of metal insulated with a plastic foil. The plastic used influences the properties of capacitors significantly. They have a limited range of capacitance, usually up to several tens of microfarads. They are successfully used in DC, low and medium frequency applications.

Different foil capacitors are shown below on Figure 2.19.

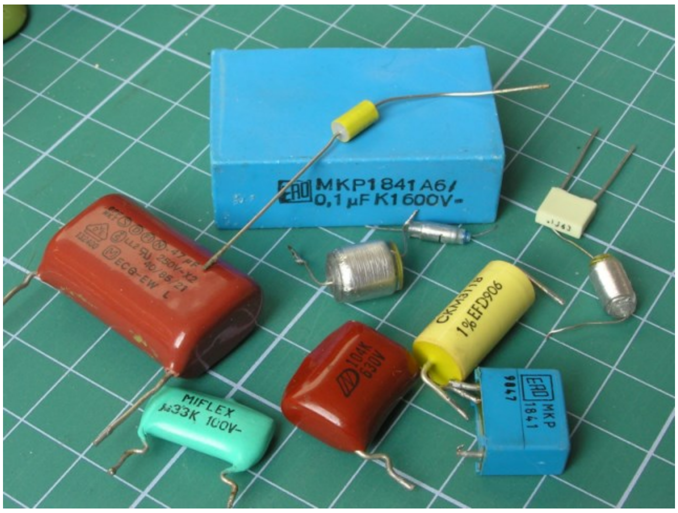


Figure 2.19 Foil capacitors

Ceramic. Ceramic capacitors are currently the most popular type, due to the ease of manufacture in surface-mount form. The capacitance range is almost the same as for foil capacitors, with very low values below 1pF possible, as well as ever-extending highest capacity limit, for contemporary parts – several tens of microfarads. This type of capacitors is usable in all types of circuits, even for high frequencies and high voltages. There are ceramic capacitors with specific temperature coefficients, positive (capacitance grows as the temperature increases) or negative (capacitance falls as the temperature rises) – it is usable for compensation of temperature variations of different precise circuits.

Different ceramic capacitors are shown below on Figure 2.20.

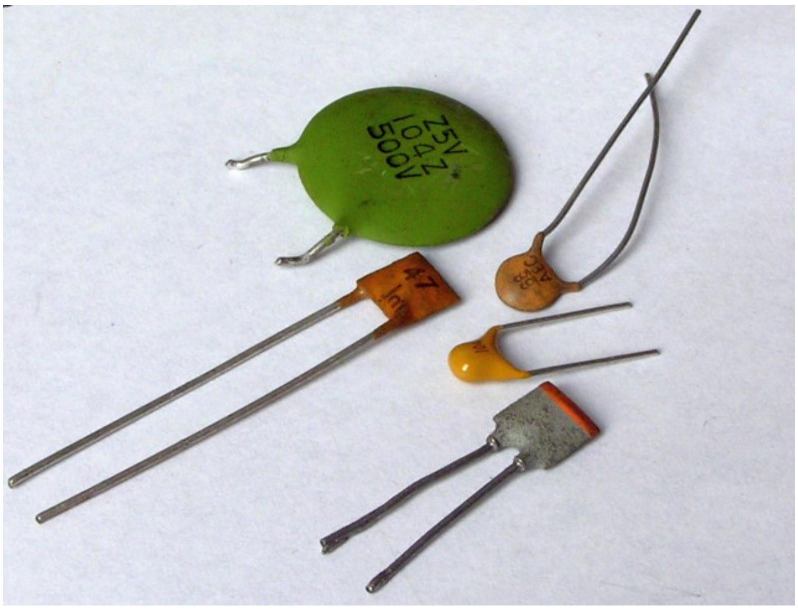


Figure 2.20 Ceramic capacitors

Electrolytic. The electrolytic capacitors have a very distinctive feature – they are polarized. This means that they can be inserted in circuit only in a specific way that ensures proper voltage polarity. For special purposes, there are, however, non-polarized electrolytic capacitors, but they are rare and expensive. One more important property of electrolytic capacitors is that they can lose capacitance with time, and the process is sped up with the temperature. The popular brands of capacitors are guaranteed to work and maintain their specified parameters only for a few thousands hours.

Different electrolytic capacitors are shown below on Figure 2.21.

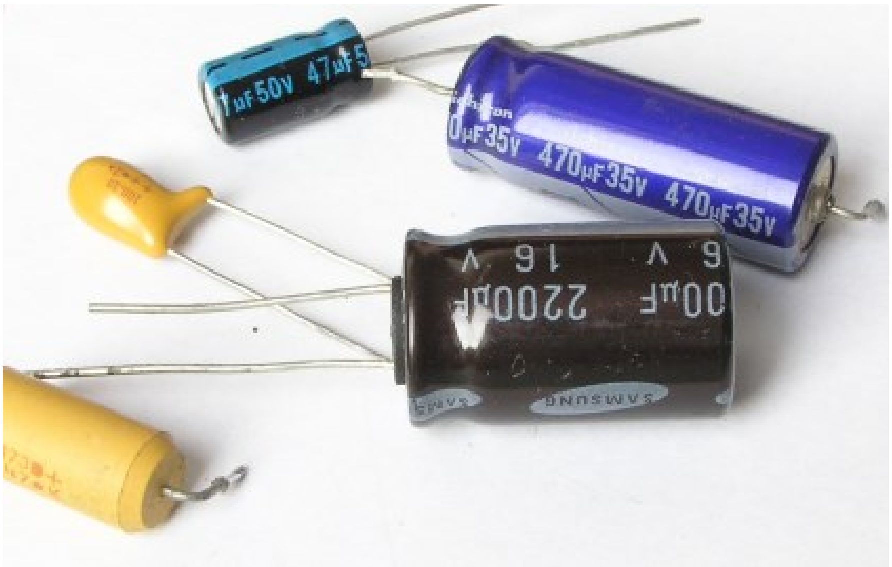


Figure 2.21 Electrolytic capacitors

Capacitance values

Similarly to resistors, capacitors are manufactured with capacitances of a given series of values, but the popular values are from coarser series – it is very uncommon for capacitors to be manufactured with values from E24 (or finer) series.

The capacitors are marked similarly to resistors – a three digit code is very popular (the capacitance is then expressed in picofarads), although for some capacitors the explicit capacitance is printed on them, as in Figure 2.21. The accuracy, if specified at all, is using the letter code, similar as for resistors. It is also possible that the capacitance is marked with colored dots or stripes, the color code is the same as for resistors – see Table 2.2. The capacitance is then also specified in picofarads.

Example:

A ceramic capacitor with code 223 has the capacitance of

22 000 pF = 22nF

For ceramic capacitors, it is common to use a two letter and one digit code to specify their working temperature range. Those properties depend mostly on the ceramic material properties that is used for manufacturing a certain capacitor. The meaning of the codes is explained in the Table 2.4.

Table 2.4 Codes for ceramic capacitors

Letter (low temp)	Digit (high temp)	Letter (change)
X= −55 °C (−67 °F)	2= +45 °C (+113 °F)	D= ±3.3%
Y= −30 °C (−22 °F)	4= +65 °C (+149 °F)	E= ±4.7%
Z= +10 °C (+50 °F)	5= +85 °C (+185 °F)	F= ±7.5%
	6=+105 °C (+221 °F)	P= ±10%
	7=+125 °C (+257 °F)	R= ±15%
	8=+150 °C (+302 °F)	S= ±22%
		T= +22 to −33%
		U= +22 to −56%
		V= +22 to −82%

Example:

A ceramic capacitor has capacitance of 100nF. It is marked as a X5R capacitor.

The code means that for temperature range from -55°C (X) to +85°C (5) the capacitance can change by no more than ±15% (R). The capacitance in this temperature range can therefore be in range from 100 – 100*15% to 100 + 100*15% = 85nF to 115nF.

Another important code to know is C0G or NP0 – this marking means that the capacitance varies with temperature only in a very limited range (±30 ppm/K – Parts Per Million per Kelvin), or, ideally, 0 ppm/K. These are very temperature – stable capacitors.

Example:

A ceramic capacitor has capacitance of 100pF. It is marked as a C0G capacitor.

The capacitance of this capacitor will change by no more than 30 ppm for each Kelvin degree temperature change.

The nominal capacitance is usually specified for temperature 25°C.

A change of 1°K is the same as change of 1°C. Therefore by rising the temperature by 1°C, to 26°C, the capacitance will change by no more than:

100pF ·30 / 1 000 000 = 0.003pF

The capacitance in temperature 26°C is between 99.997pF and 100.003 pF.
In temperature 35°C, the capacitance will be in the range from 99.97pF to 100.03pF.

Variable capacitors

Apart from regular capacitors, there are also variable capacitors, sometimes called as trimmers. Their main use is in high frequency circuits and radios. In some applications (such as radio receivers) they are being replaced by other, cheaper to manufacture and easier to adjust components. Variable capacitors of different kinds are presented on Figure 2.23. The symbol used to depict them on a schematic is shown on Figure 2.22.

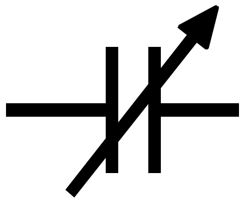


Figure 2.22 Variable capacitor symbol

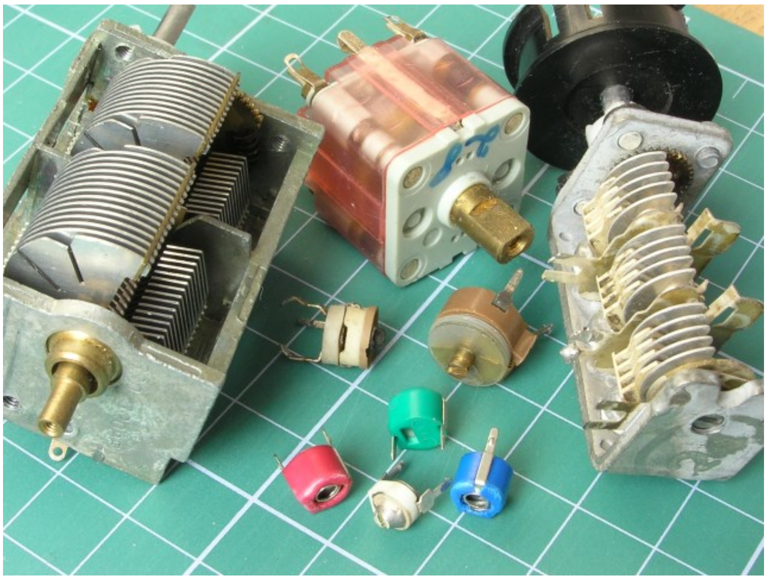


Figure 2.23 Variable capacitors

2.3 Inductors

The third basic component of electronic circuits is an inductor. While not so frequently used as resistors and capacitors, they are essential components in some applications, like power conversion and in radio frequency circuits. The inductors, compared to capacitors and resistors, are more often made to order, due to their specific properties that must be adjusted for certain application. The very distinctive and important group of inductive components are transformers, that are constituted by at least two separate inductors that are magnetically coupled to each other. The area of their uses is power supplies and, less frequently, radio frequency circuits. On a schematic, the inductor can be marked as shown on Figure 2.24.

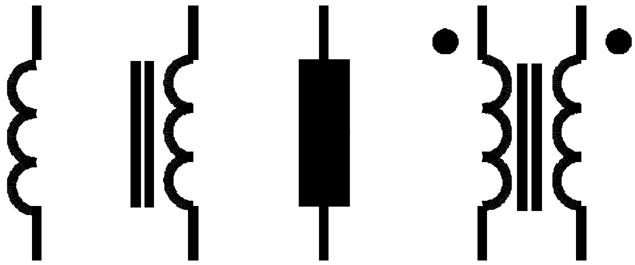


Figure 2.24 Schematic symbols for inductors. From left to right: air inductor, core inductor, alternative form of inductor marking, transformer with direction winding marks.

The operation of inductor is described by the following formula:

$$U = L\,\frac{dI}{dt} \tag{2.3}$$

The meaning of the symbols is the following:
U – voltage developed across the component,
I – current flowing through the component,
L – a specific value of inductance of a component, specified in Henrys (H).

From the formula, it should be understood that the voltage developed across the inductor depends on the inductance of the inductor and the rate of change of the current flowing through the inductor.

The voltage and current used in the equation (2.3) are shown on Figure 2.25.

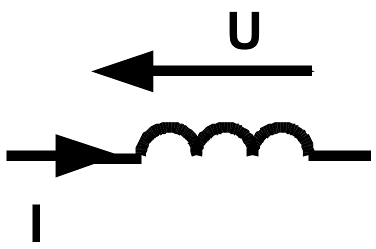


Figure 2.25 Current and voltage across an inductor

A Henry is relatively large value of inductance, and in most cases, the inductors used in electronic circuits have inductance of a fraction of Henry, usually from nanohenrys (10^{-9}) for RF circuits or microhenrys (10^{-6}) for all other circuits. There are, however, larger inductors, whose inductances are much higher, easily larger than tens of Henrys.

Basic parameters of inductors are the following:

- **inductance** – the capability of storing energy in the form of magnetic field,
- winding resistance – total resistance of the conductor (usually a wire) constituting the inductor,
- **saturation current** – the maximum currant that can flow through the inductor without the rapid decrease of inductance (nonlinear effect),
- **core material** – the properties of the inductor, like saturation current, are determined by core material (the substance that the windings are wound around),
- **stability** – the amount of change of inductance with the temperature (also Curie temperature for inductors with core) and time.
- **SRF - Self-Resonant Frequency** – important for inductors, due to large inter-winding capacitances, forming a resonant circuit with the inductance. The part should operate at the frequency lower than this value.

An example of a very small inductor that can be sometimes found in electronic circuits is shown on the Figure 2.26. Its properties are the following:

- inductance 100uH (0.0001 H),
- tolerance ±10%, in temperatures -55°C to 105°C
- resistance (maximally) 3.8Ω
- SRF 5.5 MHz
- Maximum current 165mA

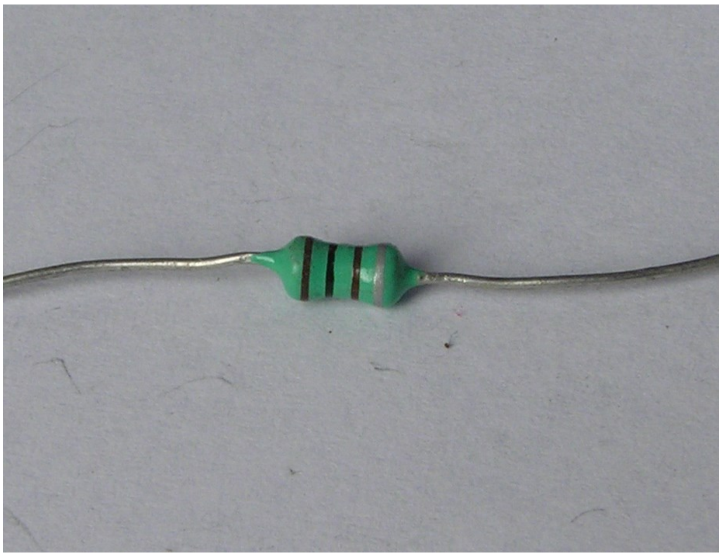


Figure 2.26 Small inductor example

For inductors it is very important to know about the parasitic components – resistance and capacitance. The model of an inductor, including the basic parasitic components, is shown in Figure 2.27.

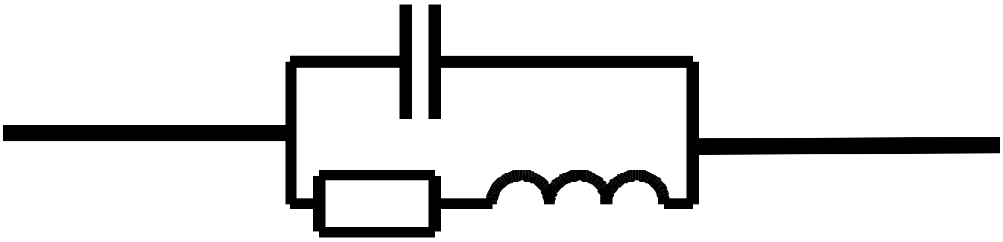


Figure 2.27 Model of parasitic elements of a real inductor

Some examples of small inductors for low current applications can be seen on Figure 2.28.

Figure 2.28 Low current inductors. The EPCOS one on the left is for higher current – a few amperes.

A special kind of inductive component is a popular transformer. Transformer is, simply put, a device consisting of at least two coils that are positioned so that they are closely coupled (they share the same magnetic flux). The most common symbol of a transformer is shown on Figure 2.30. Some small transformers are shown on Figure 2.29.

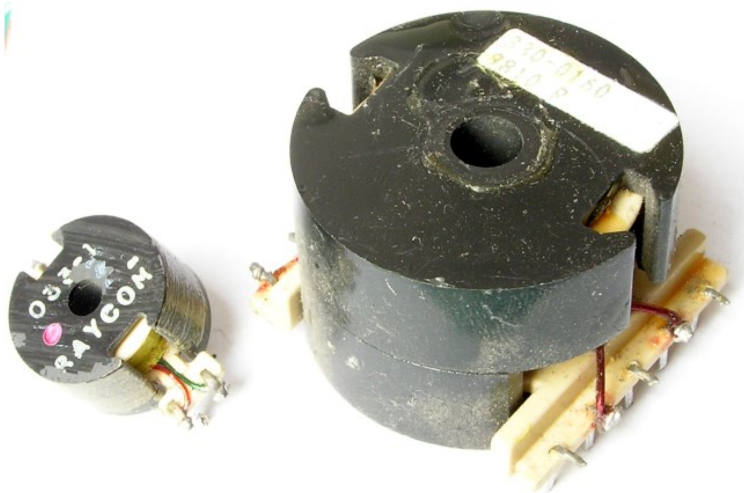


Figure 2.29 Small transformers example

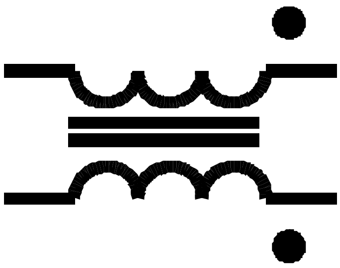


Figure 2.30 Transformer symbol

Variable inductors

Also inductors are available as variable ones. They make use of either taps on the windings (this way only a certain set of specific values of inductance can be obtained) or are working using the principles of transformer operation. This kind of component, however, is very rarely used. Another version of variable inductor uses a core that can be moved in or out of the coil of wire, therefore increasing or decreasing inductance. An example of such a device is on Figure 2.32. They can be found in some radio frequency circuits.

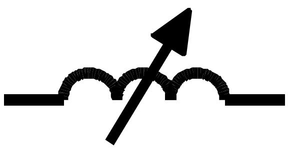


Figure 2.31 Variable inductor

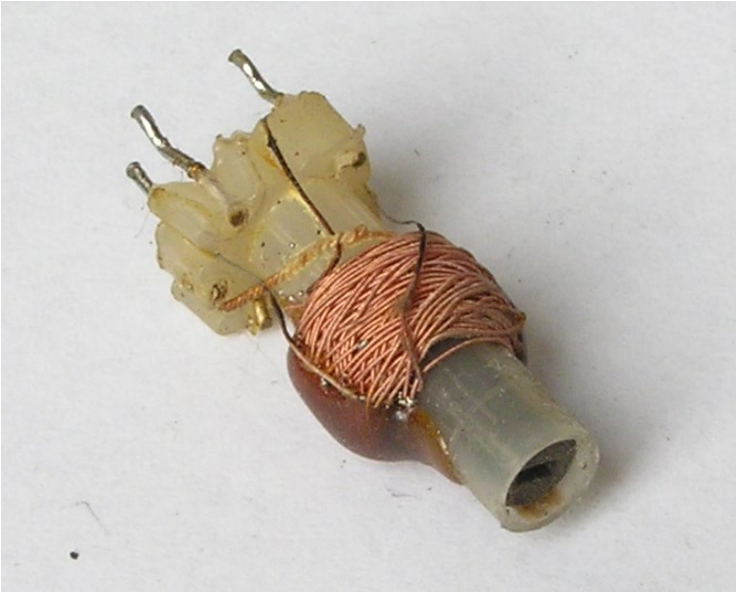


Figure 2.32 Variable inductor with screwed-in core

3. Diodes

The next very important electronic component is a diode. Nowadays the semiconductor diodes are almost exclusively used, but it is possible to use older diodes, as vacuum tubes, as well.

One important fact about diodes needs to be stressed – they are nonlinear components, that means – there are no linear relationships between voltage and current for this component. So, for a diode, the following is true in general:

$$f(a(t)+b(t)) \neq f(a(t))+f(b(t))$$
$$f(k \cdot a(t)) \neq k \cdot f(a(t))$$

For some specific applications and under certain assumptions, it is, however, possible to approximate the relationships with linear equations where it is desirable.

The symbol used to denote a diode is shown on Figure 3.1. A diode has two electrodes – anode and cathode, as denoted on the figure.

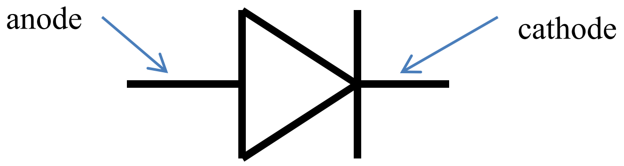


Figure 3.1 Diode symbol

In the most basic way, the operation of a diode (so called ideal diode) can be summarized as the following.

For an ideal diode, the current can flow in only one direction – from anode to cathode. In the opposite direction, no current can flow.

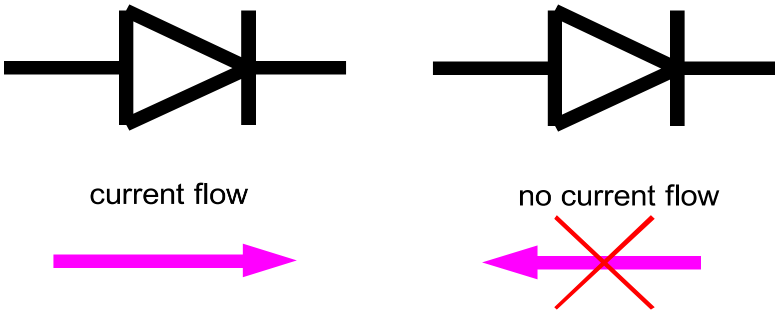


Figure 3.2 Diode current flow

As a rule, the diode current and voltage are oriented in a way shown on Figure 3.3. This way, a positive voltage causes a positive current to flow, while negative voltage causes no current flow for an ideal diode. In practice – there are no ideal diodes, but some get close to that.

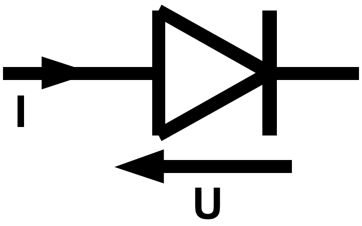


Figure 3.3 Diode voltage and current directions

The semiconductor diode is built using semiconductors (for example silicon or germanium) with different type of doping (additions – like boron or phosphorus). Due to the amount of dopants, different properties of semiconductors can be obtained. In general, there are two main types of semiconductors – P and N type. A semiconductor diode is constructed using P and N type semiconductor, as shown on Figure 3.4. Therefore, a diode is constituted by a single so called PN junction.

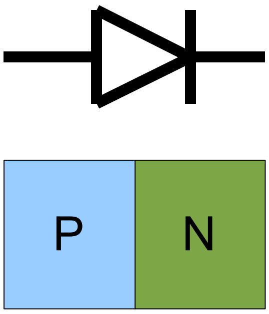


Figure 3.4 Semiconductor types in a diode

There are different models of diode operation, below four basic models will be described. Although simple, they are useful in describing the operation of circuits with diodes. Each model is more complex than the previous one, but it also models a real diode more accurately. The choice of model depends on the actual circuit, as by choosing an incorrect (too simple) model of a diode, some aspects of circuit operation can be omitted. On the other hand, choosing too complex model makes it impossible to perform a quick analysis of circuit operation. For most applications considered in this course, model II or III is sufficient.

3.1 Diode models

Model I

The very simplistic model, modeling an ideal diode, with no internal resistance and no forward voltage drop. A current-voltage dependency of this model is shown on Figure 3.5.

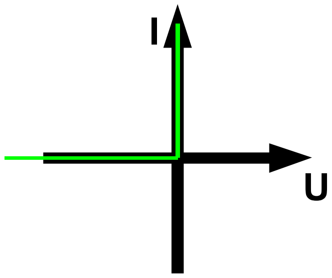


Figure 3.5 Diode model I

The operation of such a diode depends on the voltage applied to it, and the diode can be replaced by the following circuits:

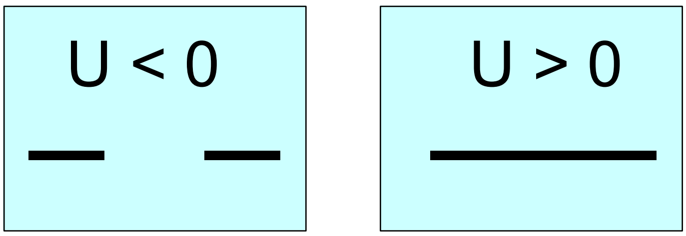


Figure 3.6 Diode equivalent circuits - model I

Model II

This model is more accurate, as it models also a non-zero forward voltage drop on a conducting diode ($U_{forward}$, usually abbreviated as U_f). A current-voltage dependency of this model is shown on Figure 3.7.

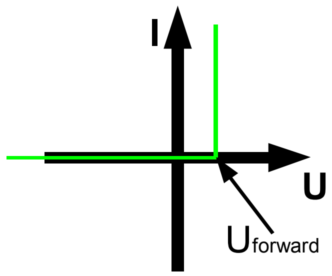


Figure 3.7 Diode model II

$U_{forward}$ depends on a diode – its size and the materials used for its manufacture. The voltage is typically around 0.7V for silicon diodes and around 0.3V for germanium diodes. The operation of such a diode depends on the voltage applied to it, and the diode can be replaced by the following circuits:

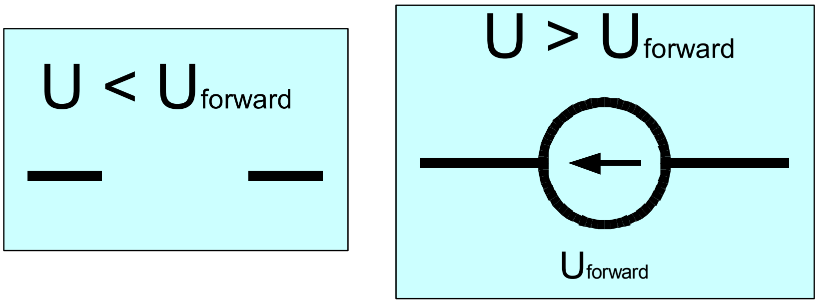


Figure 3.8 Diode equivalent circuits - model II

Model III

The third model described here is an extension of the model II. It models the non-zero dynamic resistance of a diode r_{dyn}. A current-voltage dependency of this model is shown on Figure 3.9.

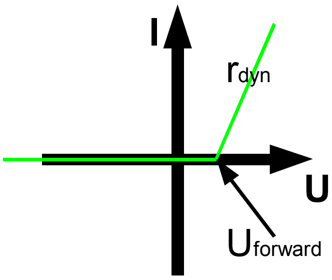


Figure 3.9 Diode model III

According to model III, the diode can be replaced by the following circuits:

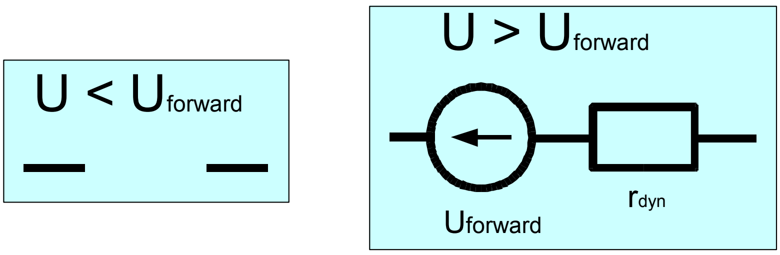


Figure 3.10 Diode equivalent circuits - model III

Model IV

The fourth model is based on a so called Schockley equation, describing the voltage and current relations in a diode:

$$I_D = I_S \left(e^{\frac{U_D}{n \cdot U_T}} - 1 \right)$$

$U_T = \frac{k \cdot T}{q_e}$, for 300°K the value of U_T is approximately 26mV
n – emission coefficient (1 .. 2)
I_s – saturation current in reverse polarity
I_D – diode current
U_D – diode voltage

A current-voltage dependency of this model is shown on Figure 3.11.

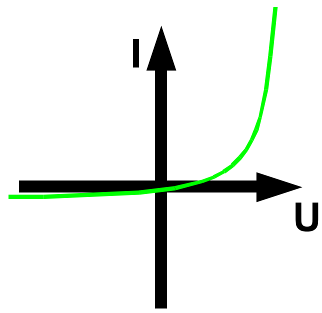


Figure 3.11 Diode model IV

To make things simpler, the Schockley equation is usually approximated by a much simpler one:

$$I_D = I_S e^{\frac{U_D}{U_T}}$$

The dynamic resistance of a diode approximated using this simplified model can be calculated as following:

$$I_D = I_S e^{\frac{U_D}{U_T}}$$
$$U_D = U_T \cdot \ln \frac{I_D}{I_S}$$
$$r_{dyn} = \frac{\partial u}{\partial i}$$
$$r_{dyn} = \frac{U_T}{I_D}$$

As it can be clearly seen, the dynamic resistance is current dependent. This feature of a PN junction is used in some circuits.

The most important properties of a real diode are the following:

Maximal dissipated power
Maximal forward current
Forward voltage
Maximal reverse voltage

For high frequency, the diode can be modeled as shown on Figure 3.12. The diode in this circuit is considered to be ideal.

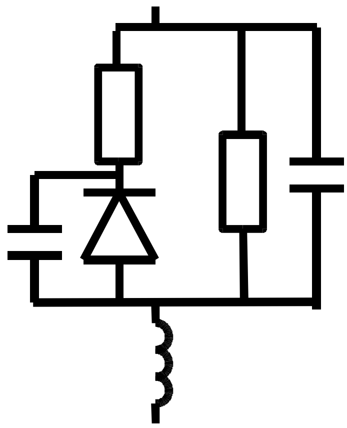


Figure 3.12 HF model of a real diode

3.2 Diode types

There is a number of different diode types, optimized for different applications. Below is a short description of some of the most important types.

Rectifying diode

This is the most popular diode type, usually by saying “diode” one means this type. This is the “generic” diode type, that was discussed above. The rectifying diodes are used in many applications, power supplies being the most obvious one. Below is an image showing the symbol for such a diode.

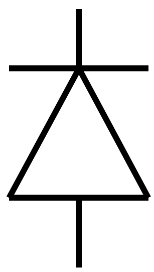


Figure 3.13 Rectifying diode

The U-I characteristics of this kind of diode is shown on Figure 3.14. The U_f for silicon diodes is approximately 0.6V – 0.7V, for germanium diodes it is approximately 0.3V. The U_f voltage changes with temperature, for silicon diode it rises by about 2mV per each Celsius degree temperature decrease.

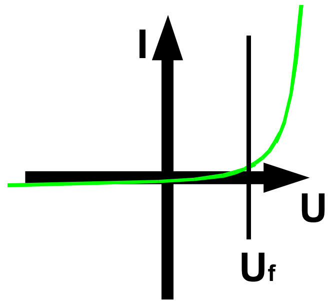


Figure 3.14 Characteristics of rectifying diode

The reverse current (I_s) depends on voltage and on the type of diode. It rises approximately twicefold for temperature increase of 10°C.

There is a limit to a reverse voltage that can be applied to a diode. At certain voltage value the diode starts to conduct current in reverse direction. The voltage for which it happens can range from several tens to several thousands of volts. This phenomenon is discussed in Zener diode section, as it is used to our advantage in this type of diodes.

Zener diode

This type of diode is used mainly for voltage stabilization, voltage limiting and as a source of constant voltage in some applications. It uses the effect of reverse breakdown in diodes. Below is an image showing the symbols for such a diode.

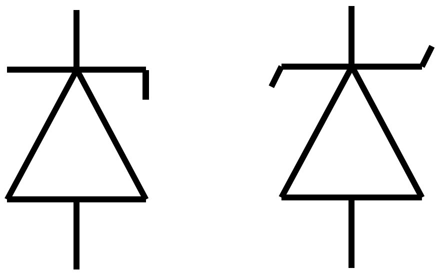


Figure 3.15 Different Zener diode symbols

The U-I characteristics of this kind of diode is shown on Figure 3.16.

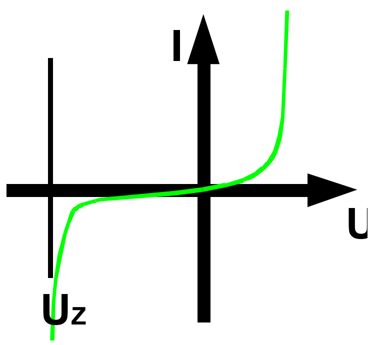


Figure 3.16 Characteristics of a Zener diode

The value of UZ can be easily changed during production, so diodes for different voltage values are available.

There are two basic models used for modeling the Zener diode:

Model I

A very simple model, similar to model II of a regular diode.

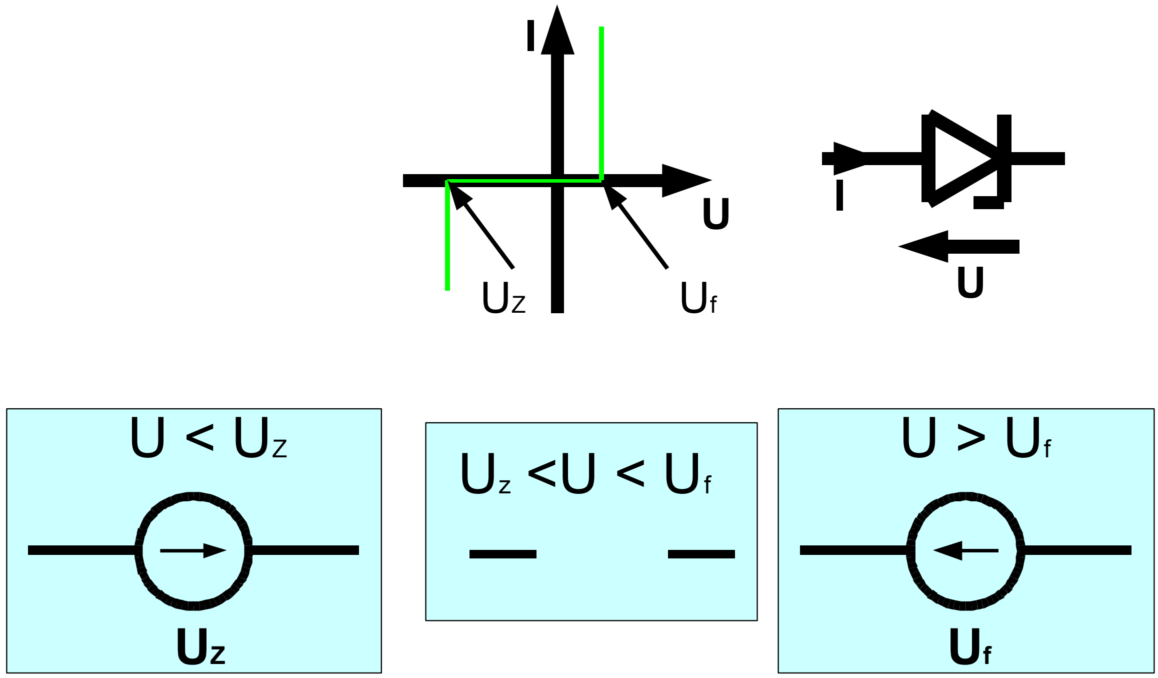


Figure 3.17 Zener diode - model I

Model II

This model also considers non-zero dynamic resistance of Zener diode, similarly to model III of a regular diode.

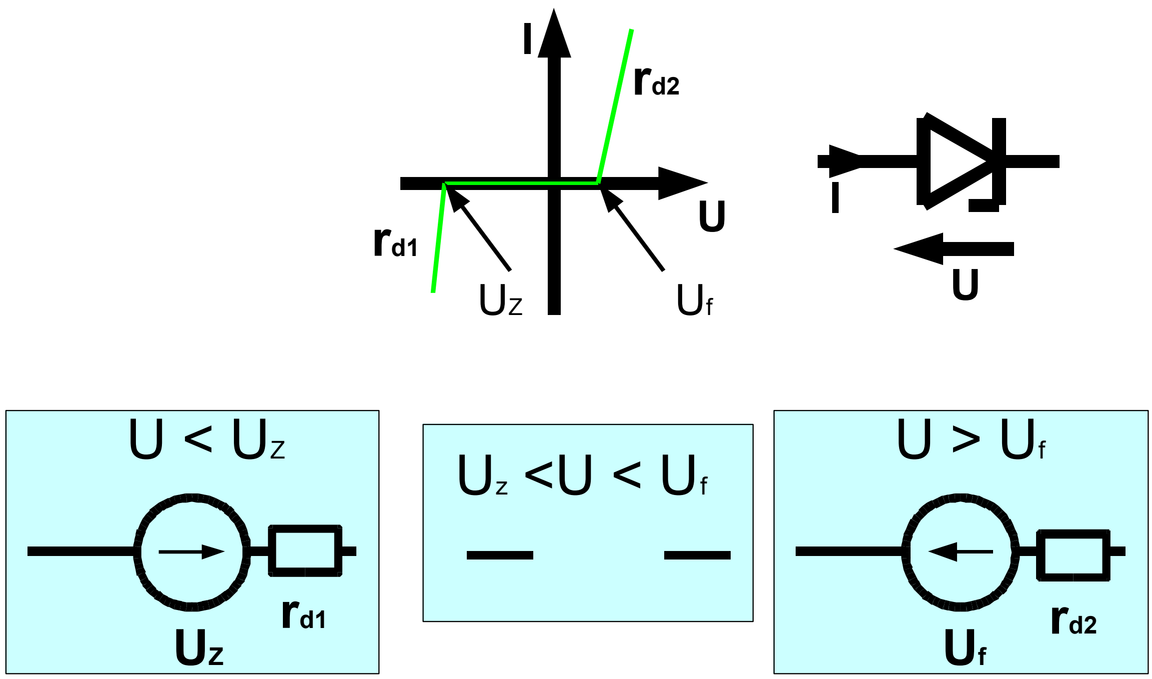


Figure 3.18 Zener diode - model II

The typical circuit that the Zener diode is usually used for voltage stabilization in is shown on Figure 3.19.

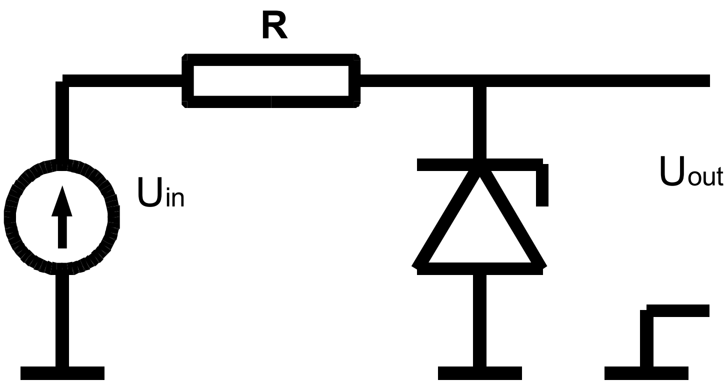


Figure 3.19 Typical application circuit of a Zener diode

In such a circuit, a great influence of dynamic resistance of the diode can be observed – the output voltage changes with the input voltage change. Therefore, a stabilization coefficient, defined as S:

$$S=\frac{\Delta U_{in}}{\Delta U_{out}}=\frac{R+r_d}{r_d}$$

where r_d is a dynamic resistance of the Zener diode.

Transil

A diode similar in concept as a Zener diode is a transil. It is used for circuit protection from voltage spikes. It operates very fast and switches from no conduction to conduction in picoseconds. There are 2 variants – unidirectional or bidirectional transils. Below is an image showing the symbols for such a diode.

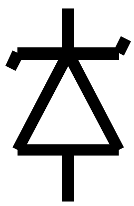


Figure 3.20 Unidirectional transil symbol

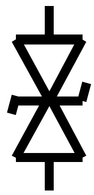


Figure 3.21 Bidirectional transil symbol

Schottky diode

This type of diode is also very popular. Instead of semiconductor, it uses metal anode. It is used for applications where fast switching is required and a low forward voltage is an advantage. The typical forward voltage of such a diode is about 0.3V. Below is an image showing the symbols for such a diode.

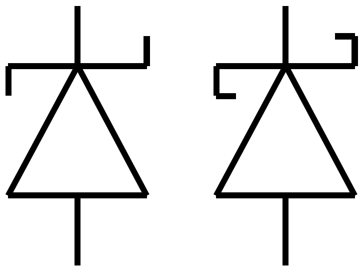


Figure 3.22 Schottky diode symbols

Capacitance diode

This diode is also known as varicap. It is specifically used in applications where there is a need for adjusting capacitance with voltage – for example in radio frequency equipment. The capacitance in reverse polarity varies more linearly and to higher extent with the reverse voltage, compared to other kinds of diodes. Below is an image showing the symbol for such a diode.

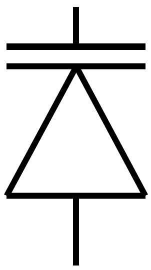


Figure 3.23 Varicap symbol

Tunnel diode

This diode has a very special property – at some point of its I-U curve the dynamic resistance becomes negative. It can be used for amplification purposes. Nowadays it is very uncommon, although some of them are found in high frequency circuits.

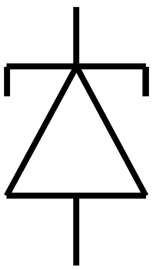


Figure 3.24 Tunnel diode symbol

Photodiode

A photodiode is a diode that is sensitive to lighting conditions. It can be used to sense light or to produce tiny amounts of electrical power from light. It is widely used in telecommunications equipment for light detectors in fiber optic devices.

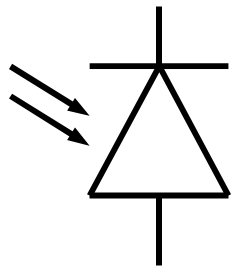


Figure 3.25 Photodiode symbol

Light emitting diode

This kind of diode is also called LED for short. It produces light (visible, infrared or ultraviolet) when a current is forced to flow in the diode. It has much higher forward voltage, in the range of 2V and above, depending on the light color and the substances used to produce the semiconductor.

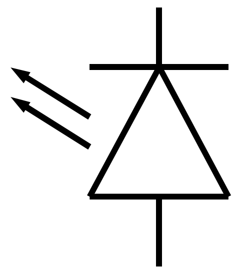


Figure 3.26 LED symbol

3.3 Diode applications

Below are listed a few simple applications of diodes.

Voltage rectifier

This simple circuit can be used to rectify AC (alternating current) and convert it into pulsing current of a single direction, as shown on Figure 3.27.

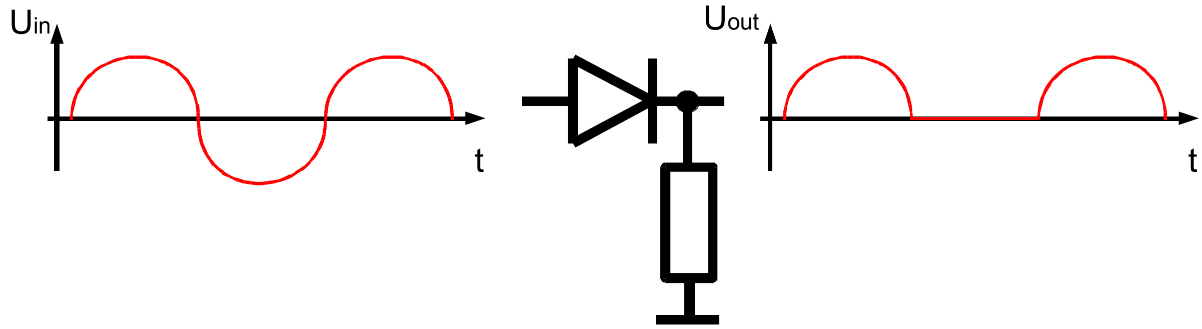


Figure 3.27 Half-wave rectifier

Diode bridge

This circuit is very common in power supplies. It converts AC (alternating current) to pulsing current of a single direction. It provides a so called full-wave rectification, contrary to the previous solution, that provides only a half-wave rectification. This kind of a rectifier is shown on Figure 3.28.

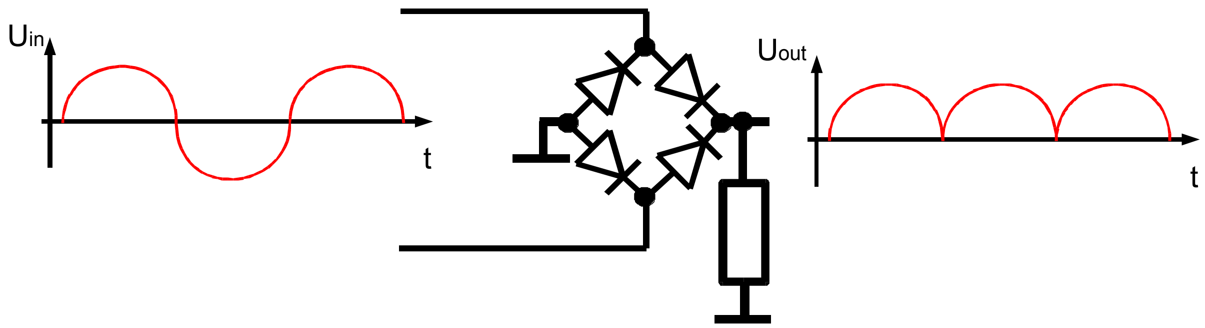


Figure 3.28 Full-wave bridge rectifier

Power supply selector

This simple arrangement is used to provide backup power for simple circuits.

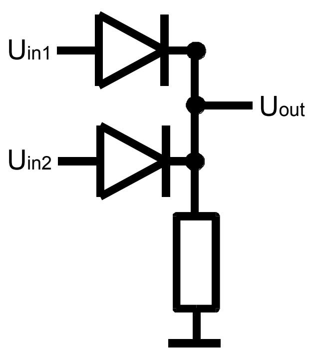


Figure 3.29 Power selector

Voltage limiters

Voltage limiting is another typical application for diodes.

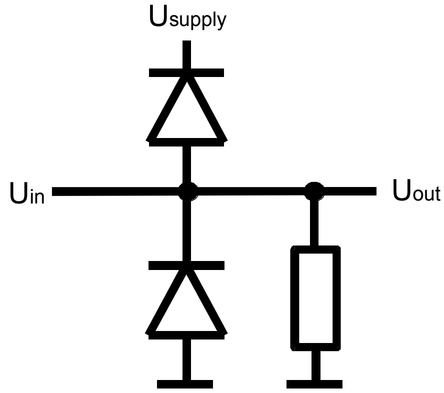
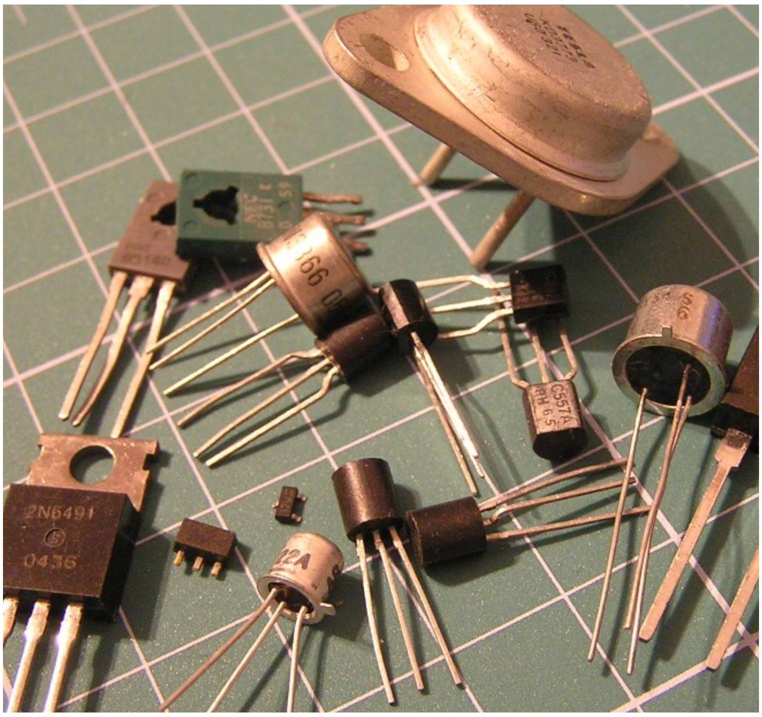


Figure 3.30 Voltage limiter

Sensing elements

Diodes are also widely used as sensing elements for temperaturę, light and similar.



4. Bipolar transistors

4.1.Bipolar transistor basics

Bipolar transistors are devices that have 3 electrodes, connected to 3 different semiconductor layers. There are two general types of bipolar transistors, depending on the internal layer structure – NPN and PNP. The electrode names of a bipolar transistor are the following:

- Emitter (**E**)
- Collector (**C**)
- Base (**B**)

The symbols used for bipolar transistors are shown on Figure 4.1 and Figure 4.2.

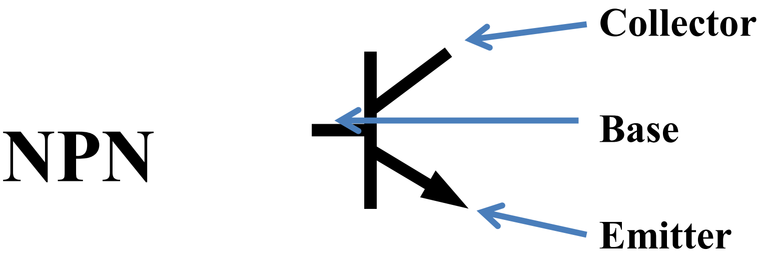


Figure 4.1 NPN transistor symbol

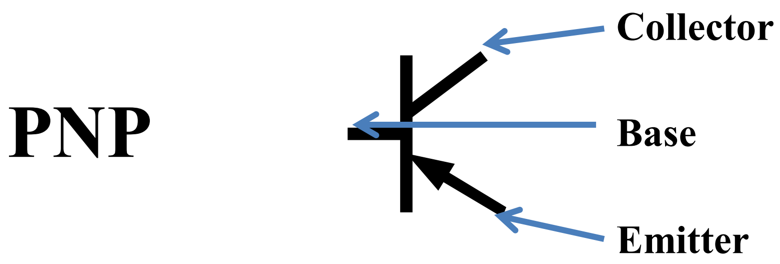


Figure 4.2 PNP transistor symbol

Inside each transistor there are 3 layers of semiconductor, as shown on Figure 4.3 and Figure 4.4.

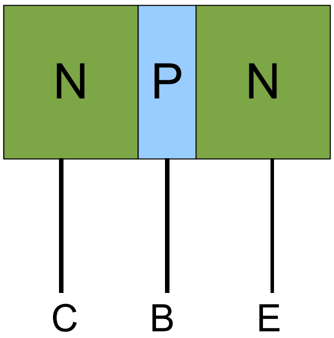


Figure 4.3 Internal structure of NPN transistor

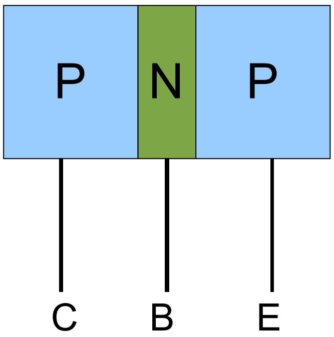


Figure 4.4 Internal structure of PNP transistor

The basic operation of a bipolar transistor is the following: the small current flowing through the base-emitter (BE) junction is controlling a much higher current flowing from collector (C) to emitter (E).

The current flow in the NPN transistor is shown on . The ratio between currents I_b and I_c is specified as a so called current gain, and is usually denoted as β. This coefficient is specific for a certain transistor in certain conditions and varies widely from transistor piece to piece and with the conditions.

The typical values of current gain are specified for selected different types of transistors in the table below.

Table 4.1 Typical current gains for transistors of selected different types

Transistor type	Typical current gain β
High power low frequency transistors	10 – 100
Low power multipurpose transistors	100 – 1000
Low power high frequency transistors	~100

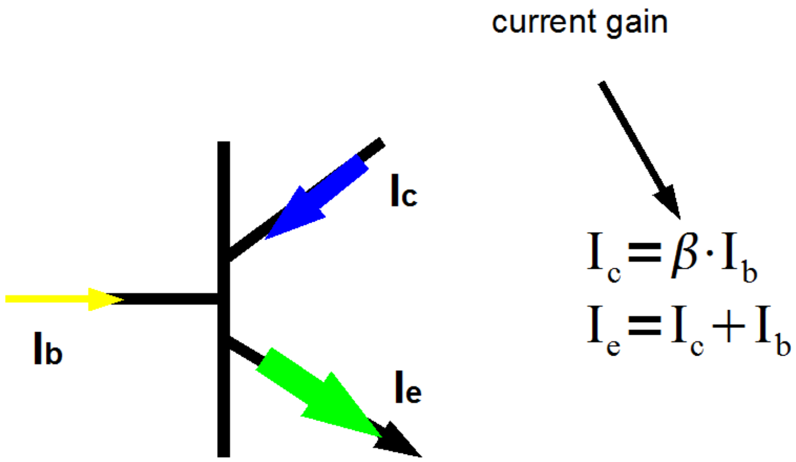


Figure 4.5 Currents in NPN transistor

In order for a transistor to operate, there must be a current flow through the base-emitter junction. Since this is a PN junction, it behaves much like a diode. Therefore, in order for the current to flow through this junction, a certain forward voltage U_{be} must be present. Usually for simple analysis, the value of this forward voltage can be regarded as close to **0.7V**. Please note, that for PNP and NPN transistors, the direction of this voltage is different. See Figure 4.6.

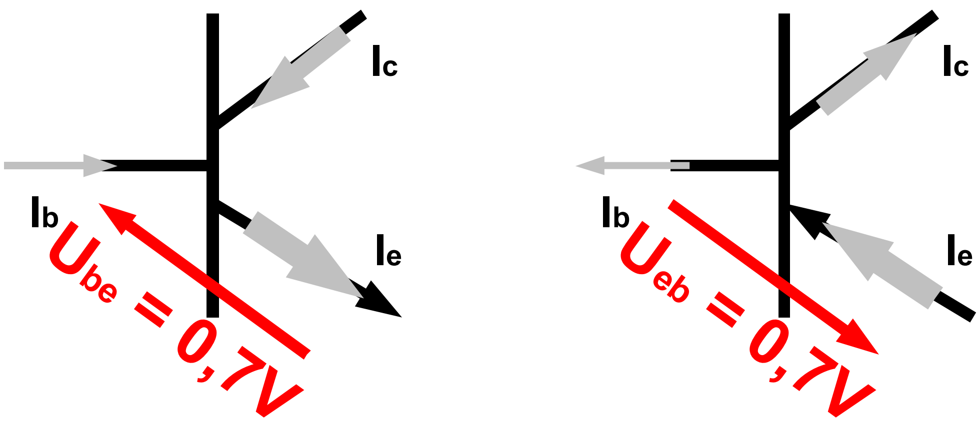


Figure 4.6 Polarization voltage for bipolar transistors NPN on the left, PNP on the right

The typical operating conditions for the bipolar transistors are schematically shown on Figure 4.7and on Figure 4.8. Please note current and voltage directions on each of figures. It needs to be stressed, that connecting a voltage source directly to the transistor base will result in a (sometimes spectacular) malfunction of the transistor and will damage it irreversibly.

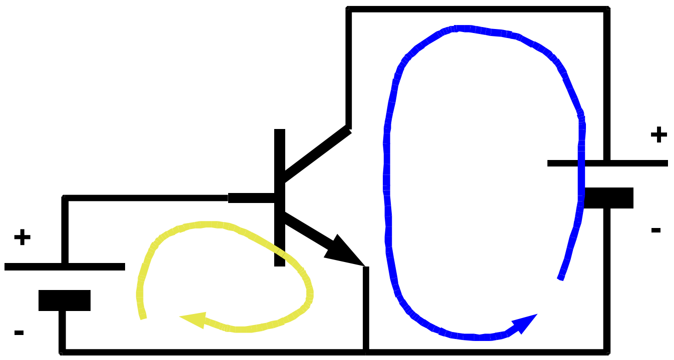


Figure 4.7 Schematical view of a typical NPN transistor circuit

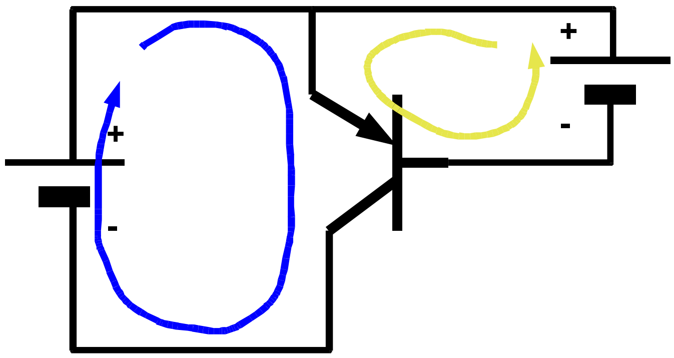


Figure 4.8 Schematical view of a typical PNP transistor circuit

The analysis of Figure 4.3 and Figure 4.4 suggest that a transistor is able to operate in reverse configuration, with E and C electrodes exchanged. That is in fact true, but in such a configuration the transistor presents much lower current gain, but, also, lower saturation voltage (explained later).

In principle, there are 3 modes of operation of a bipolar transistor:

- cutoff,
- linear region operation,
- saturation.

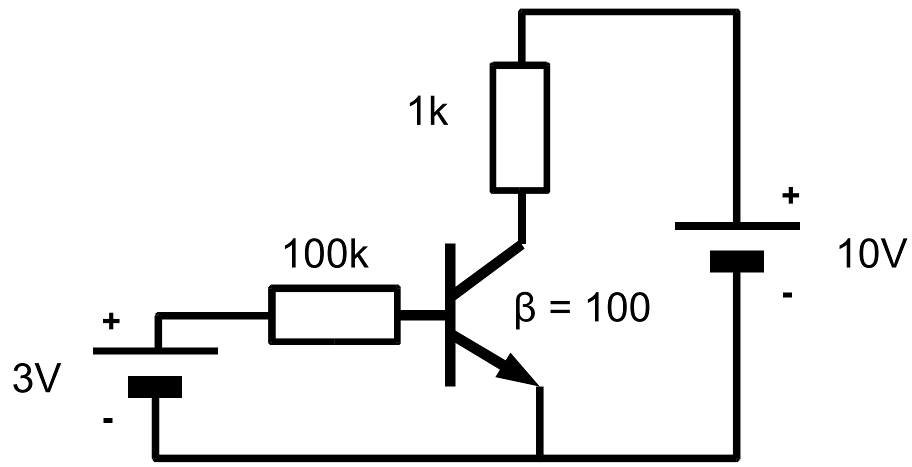
Those 3 modes of operation can be characterized as shown below in Table 4.2.

Table 4.2 Modes of operation of a bipolar transistor

Operation mode	**Collector current**	**Other**
cutoff	$I_c \approx 0$	$I_b = 0$
linear	$I_c > 0$ $I_c = \beta \cdot I_b$	$I_b > 0$
saturation	$I_c > 0$ $I_c < \beta \cdot I_b$	$I_b > 0$ $U_{bc} > 0$

Example:

What is the value of U_{ce} in the circuit shown below?



A typical graph showing relation between I_c and U_{ce} for different values of I_b is shown on Figure 4.9.

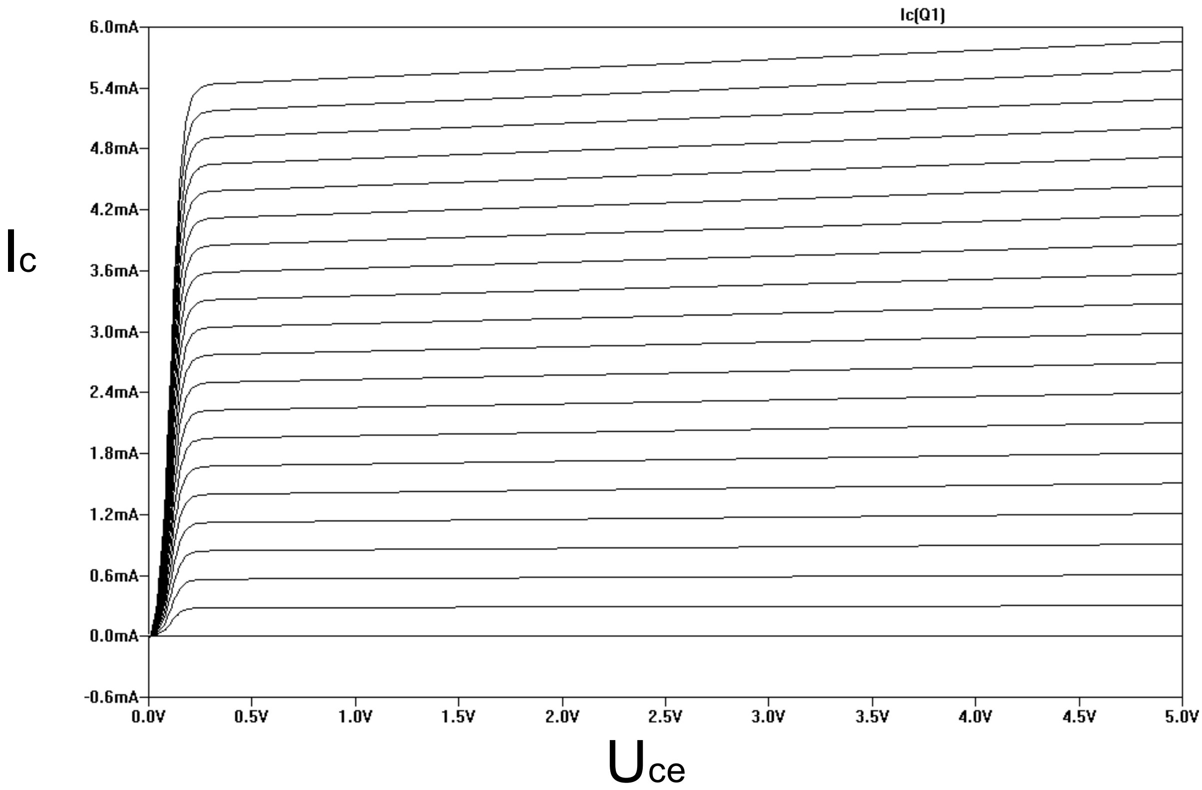


Figure 4.9 Bipolar transistor output characteristics

The most important parameters of a bipolar transistor, that one needs to consider when choosing a device for a specific application are the following:

- maximal collector current I_c
- collector – emitter breakdown voltage $U_{ce\ max}$

- collector – base breakdown voltage $U_{cb\ max}$
- maximum dissipated power
- typical current gain value
- typical saturation voltage $U_{ce\ sat}$
- transition frequency f_t
- other, specific to application

Typical applications of bipolar transistors include switches, amplifiers, integrated circuits and other.

4.2. Transistor as a switch

When operated as a switch, the transistor should be in one of the two states: saturation (when it is meant to conduct current) or cutoff (when it is meant not to conduct current).

A situation for the transistor in saturation (switch is conducting) is shown on Figure 4.10.

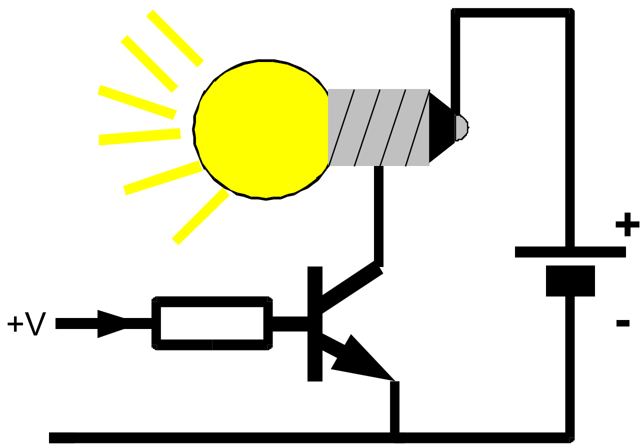


Figure 4.10 Transistor as a switch – conducting

The transistor in saturation can be modeled as shown on Figure 4.11. The voltage source with low voltage value models the non-zero saturation voltage of the transistor. The typical value of this voltage is about **0.2V**, but may vary widely with the transistor type and currents flowing in the circuit.

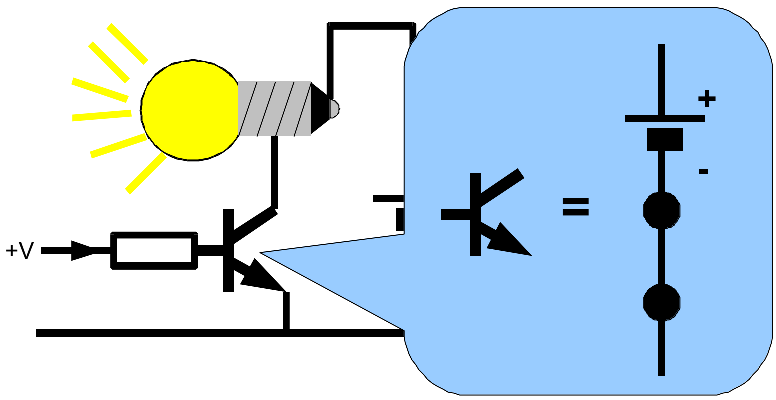


Figure 4.11 Model of a transistor in saturation

A situation for the transistor in cutoff (switch does not conduct current) is shown on Figure 4.12.

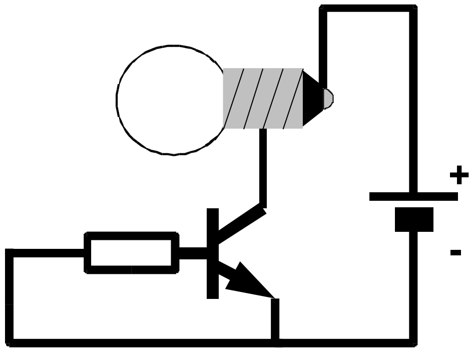


Figure 4.12 Transistor as a switch - not conducting

The transistor in cutoff can be modeled as shown on Figure 4.13.

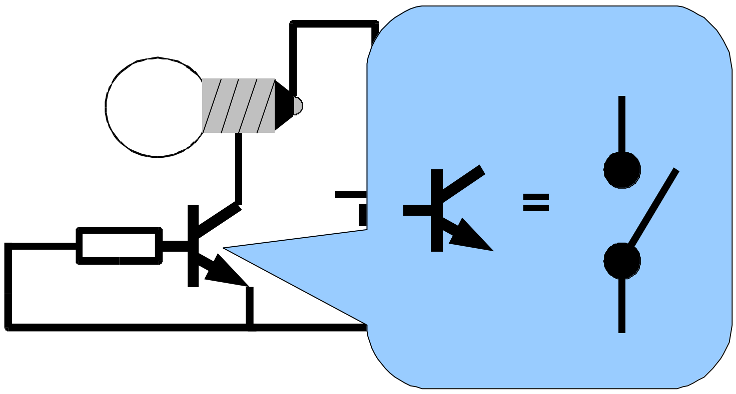


Figure 4.13 Model of a transistor in cutoff

4.3. Transistor as an amplifier

Another important application of a transistor is amplification of signals. In such applications the transistor works as an amplifier. Usually for such applications it is desirable for a transistor to work in the linear region of operation. It is therefore important to provide the proper polarization of base for this application. The proper polarization ensures the following:

- there is a desired current flow through transistor base,
- the transistor does not saturate,
- the sensitivity of the amplifier to surrounding conditions (mainly temperature) is as low as possible,
- the U_{ce} value is set to required value for steady state (quiescent point),
- the I_c value is set to required value for steady state (quiescent point).

Some circuits used to ensure the proper polarization of transistor for linear circuit operation are shown below.

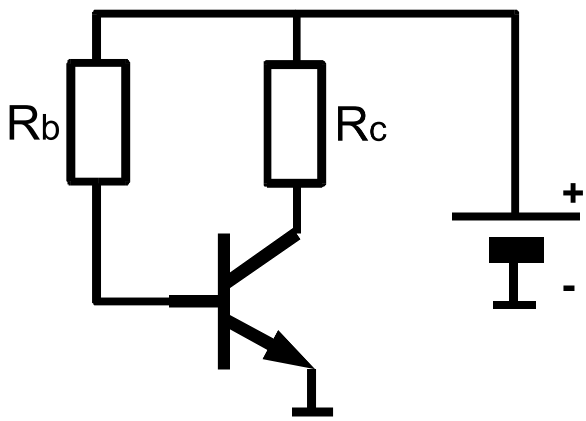


Figure 4.14 Constant base current circuit

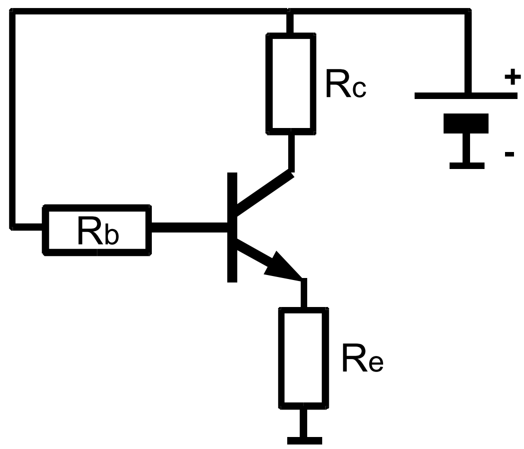


Figure 4.15 Emitter feedback circuit

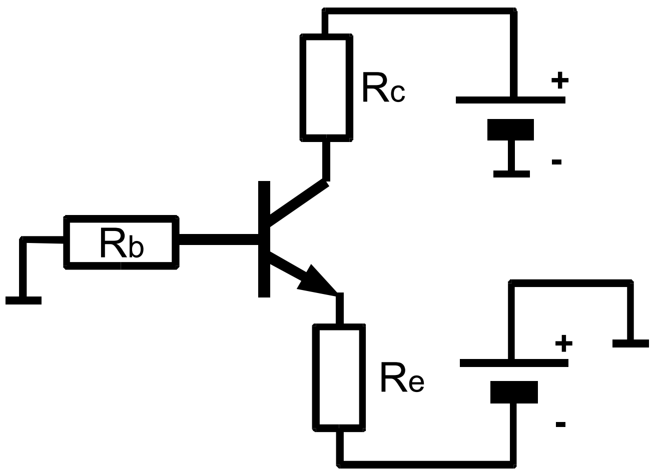


Figure 4.16 Constant emitter current circuit

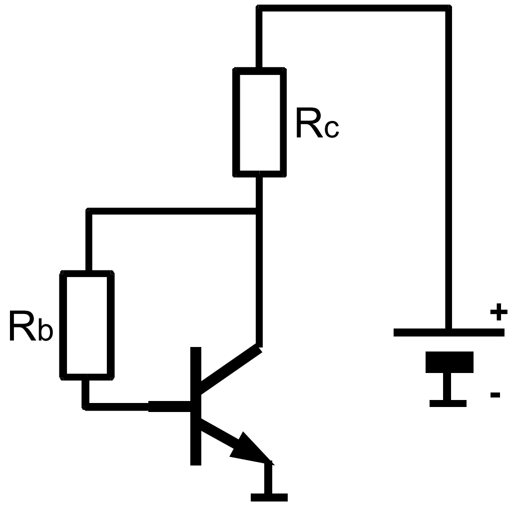


Figure 4.17 Collector feedback circuit

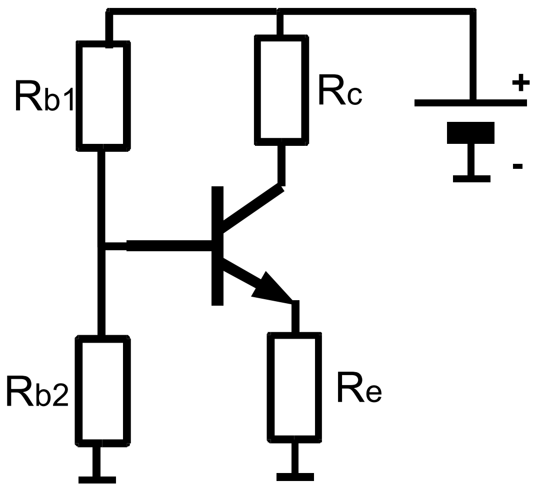
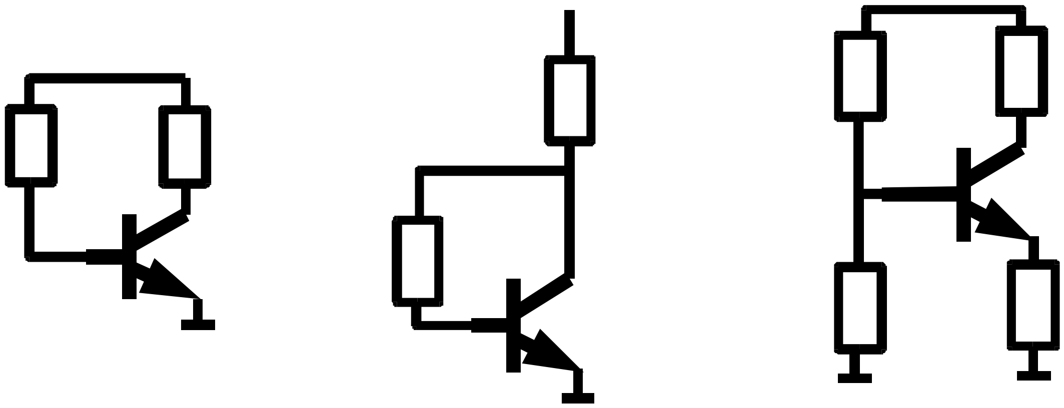


Figure 4.18 Voltage divider circuit (4 resistor circuit)

Example 4.1

In the circuits shown below, select the resistor values so that the collector potential with respect to ground is equal to **6V**. The collector current should be **1mA**. The supply voltage is **12V**. Assume that the current gain of the transistor is equal to **100**.



Example 4.2

How does the calculations from example 4.1 change for the value of current gain equal to **120**? And for **80**?

Example 4.3

How does the calculations from example 4.1 change for the value of supply voltage equal to **13V**? And for **11V**?

An example of a typical single transistor amplifier is shown on Figure 4.19. It should be noted that this amplifier is only able to amplify AC signals! For amplification of constant voltage values a different circuit has to be used.

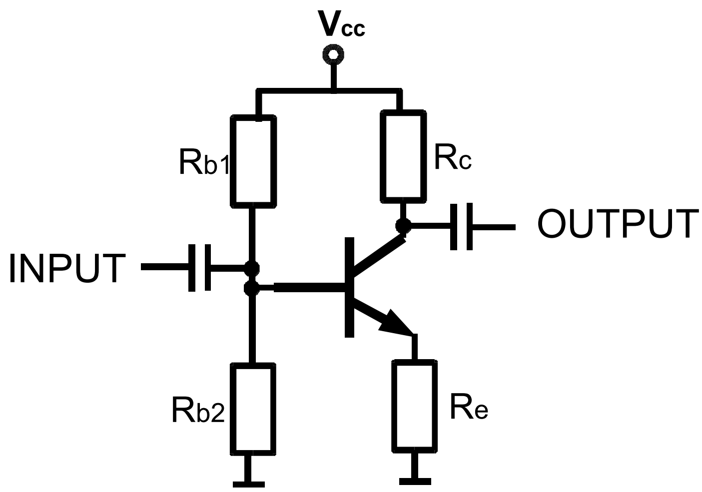


Figure 4.19 Typical single transistor amplifier

Calculating the basic properties of a transistor amplifier

The calculations of the transistor amplifier circuits progresses in two main steps. First, the DC operating point (quiescent point) is found, then, using the values calculated in the first step, the AC analysis of the amplifier is performed. For AC analysis, a new schematic of the amplifier is drawn, consisting only of components important for AC analysis and with transistor replaced by its AC model. For simple AC analysis, a linear model of a transistor is used, described in detail further on.

As this is extremely important to memorize, the 2 steps of transistor amplifier analysis is given again:

TRANSISTOR AMPLIFIER ANALYSIS

2 SEPARATE STEPS:

1. DC analysis of the circuit to find constant currents and voltages in the biasing circuit.
2. AC analysis of the circuit, using redrawn schematic and values calculated in step 1.

The two steps are explained below.

DC analysis

The DC analysis is explained using the very simple circuit shown below.

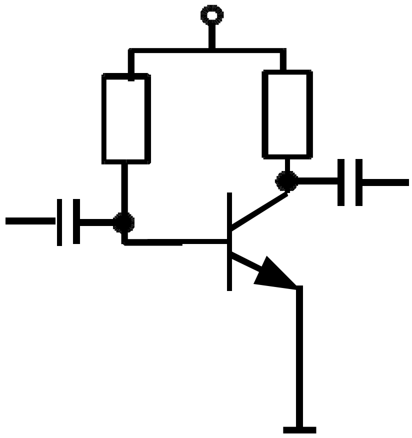


Figure 4.20 Example circuit for DC analysis of a transistor amplifier

The purpose is to find I_c and check, whether the transistor operates in the linear region. Usually for such circuits we aim for collector potential (with respect to ground) to be close to half of the supply voltage. This ensures large possible output voltage swing and usually reasonably linear operation.

AC analysis

For AC analysis, the transistor is replaced by its model. In this course, an extremely simple model is used. There are two equivalent variants of the model, they can be selected freely for each analyzed circuit. It is important to note lowercase names for resistance and voltage, denoting that only AC components are considered. The I_c value is calculated during DC analysis.

Transistor model PI

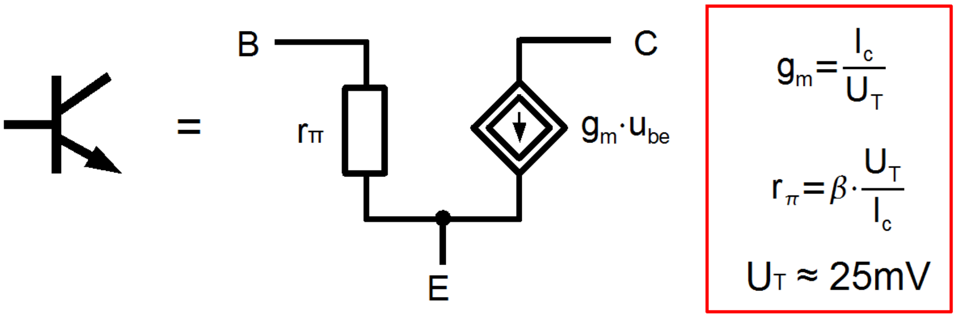


Figure 4.21 AC model of bipolar transistor - PI version

Transistor model T

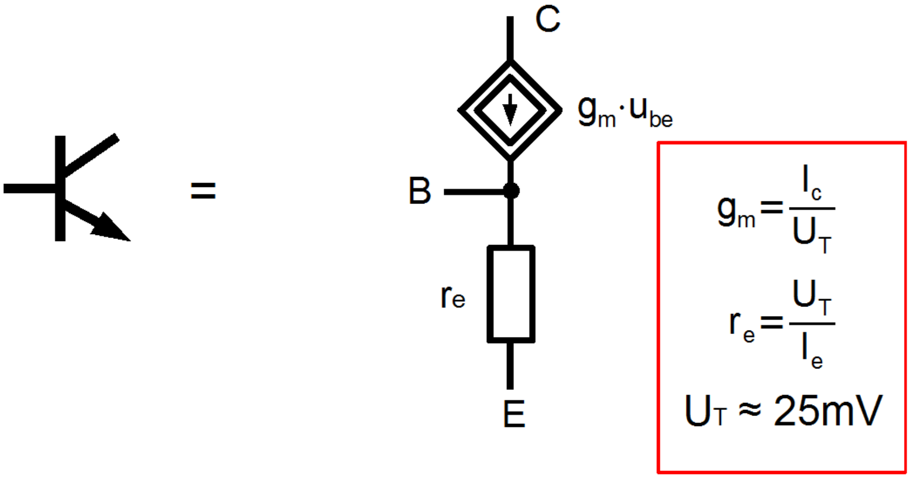


Figure 4.22 AC model of a bipolar transistor - T version

After the DC analysis, the schematic of the circuit is redrawn, following the algorithm given below, valid for simple analysis:

1. Replace the transistor with a selected AC model.
2. Replace capacitors with short circuits.
3. Replacing constant voltage sources with short circuits (including power supply voltage!), replacing constant current sources with open circuits.

The redrawn circuit schematic is the basis for further analysis. During this analysis, the following parameters of the amplifier can be calculated:

- **voltage gain** k_u,
- current gain k_i,
- power gain k_P,
- **input resistance** R_{in},

- **output resistance** R_{out}.

The model of an amplifier, depicting its basic parameters (k_u, R_{in}, R_{out}), is shown on Figure 4.23. Lowercase letters denote that only AC voltages are considered.

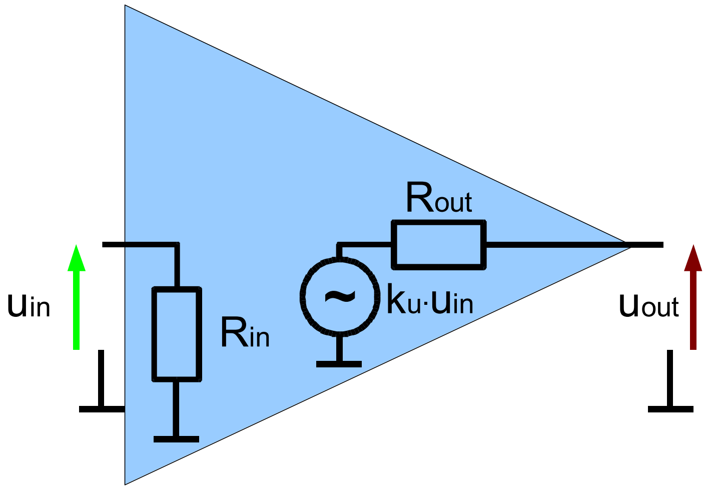
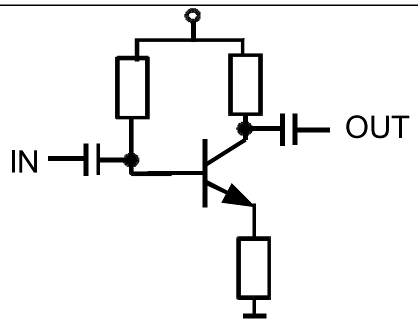
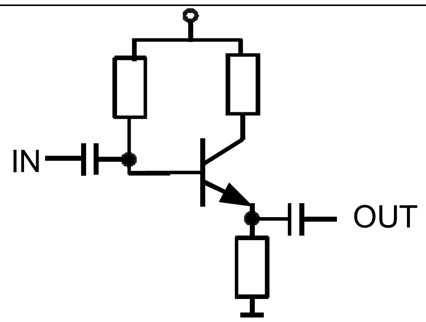


Figure 4.23 Basic amplifier model

Transistor amplifier configurations

There are 3 basic configurations for single transistor amplifier. They are listed in the Table 4.3, and their usual basic properties are listed in Table 4.4.

Table 4.3 Bipolar transistor amplifier configurations

Configuration name	Input	Output	Example schematic
Common Emitter (CE)	base	collector	
Common Collector (CC) also known as **Emitter Follower**	base	emitter	

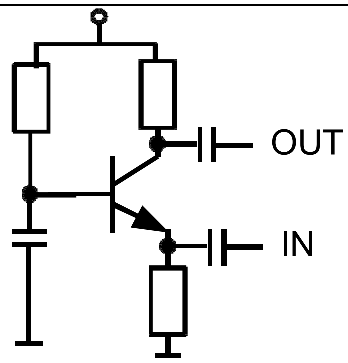
Common Base (CB)	emitter	collector	

Table 4.4 Bipolar transistor amplifier typical properties depending on configuration

	voltage gain	$\mathbf{R_{in}}$	$\mathbf{R_{out}}$	$\mathbf{f_{max}}$
CE	high (inverts phase)	medium	medium	medium
CC	~1	high	low	high
CB	high	low	high	high

4.4. Power dissipation in transistors

The power dissipated in a transistor must lay in the Safe Operation Area (SOA), limited by P_{max}, $U_{ce\ max}$, $I_{c\ max}$ and by the secondary breakdown phenomenon, as shown on Figure 4.24.

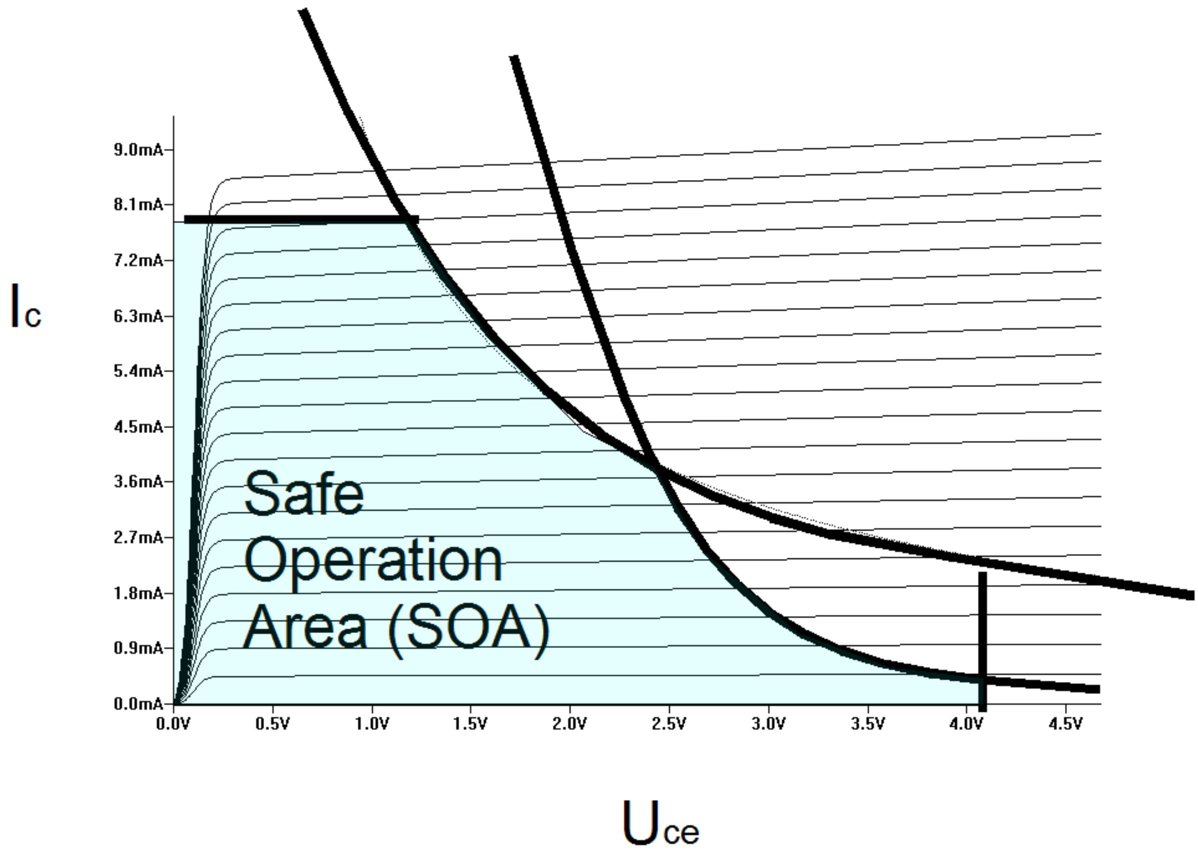


Figure 4.24 Power dissipation in bipolar transistors

4.5. Simple transistor circuits

Some examples of transistor circuits are given below.

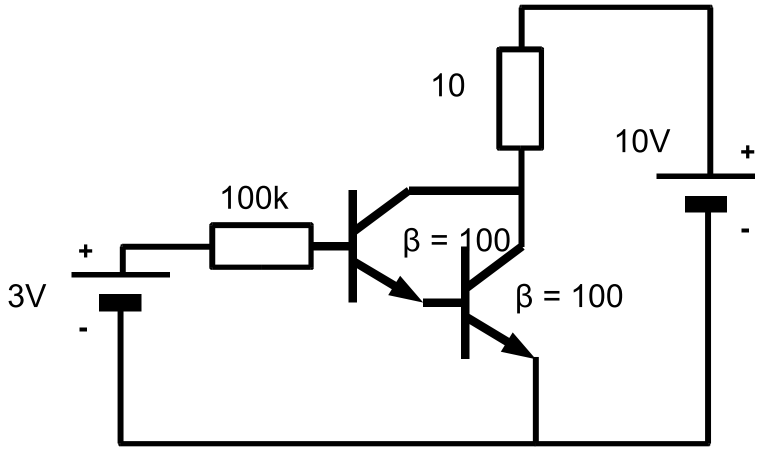


Figure 4.25 Two bipolar transistors connected together

The above circuit uses a special connection of transistors, known as a Darlington circuit (Figure 4.26). A different combination of transistors in such a connection is called a Sziklai circuit (Figure 4.27). It has slightly different properties.

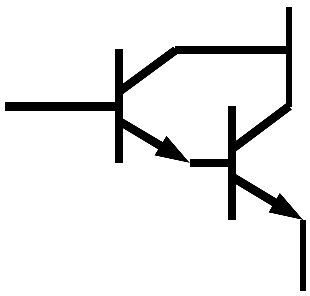


Figure 4.26 Darlington circuit

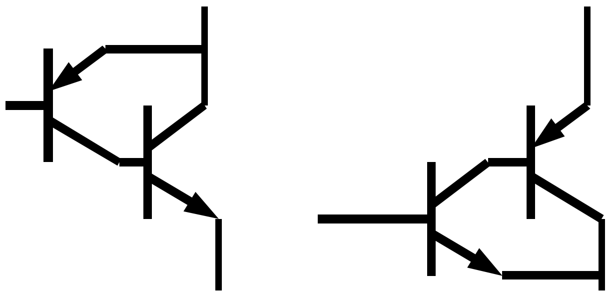
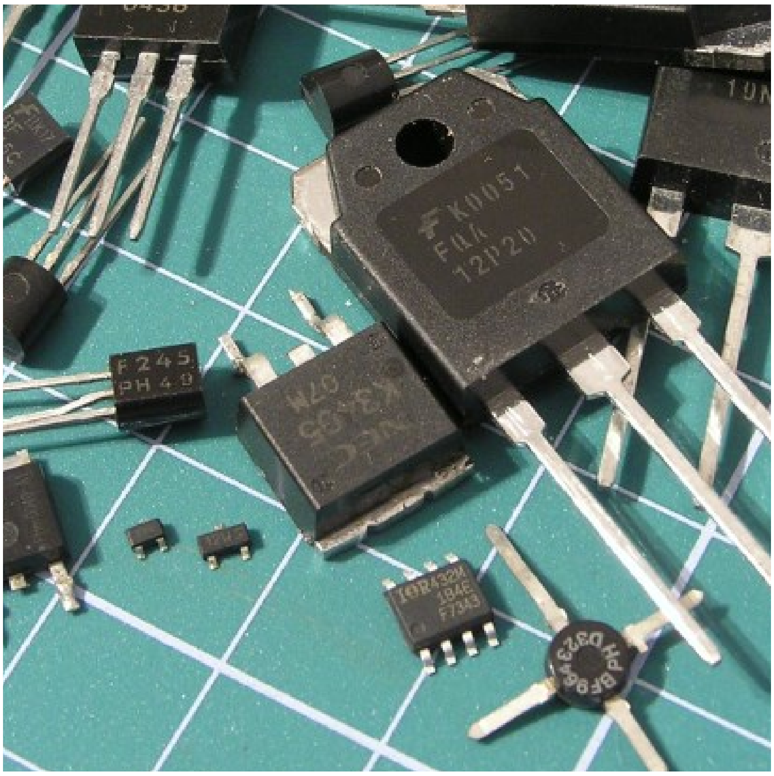


Figure 4.27 Sziklai circuits



5. Field effect transistors

5.1. Field effect transistors basics

The Field Effect Transistors (FET) are a large family of transistors working on a slightly different principle than bipolar transistors. Due to their properties, they are the basic building blocks for modern electronics.

The typical FET usually has 3 terminals, namely: Gate (G), Source (S), Drain (D). There are, however, some FETs that have two gates. They are used only in very specific applications, like in radios. Other FETs have a fourth connection, Bulk (B). The detailed description of different types of FETs will be given below.

The different types of FETs are shown on Figure 5.3. The more popular the type, the thicker the surrounding ellipse.

5.2. JFET transistor

The Junction Field Effect Transistors (JFET) have 3 terminals and have two versions – with P doped channel (JFET-P) - Figure 5.2, or with N doped channel (JFET-N) - Figure 5.1.

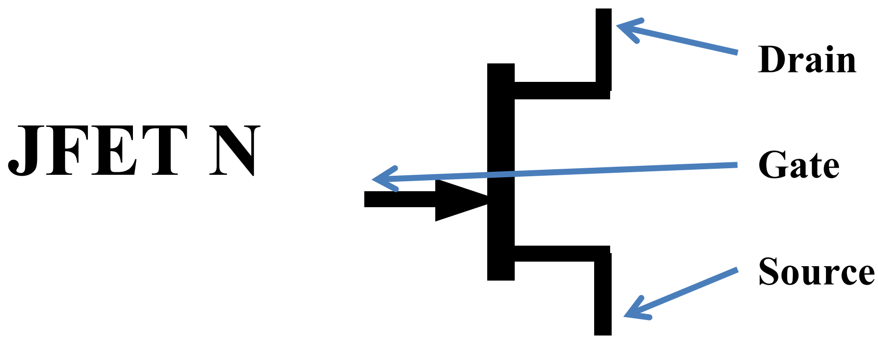


Figure 5.1 JFET-N transistor

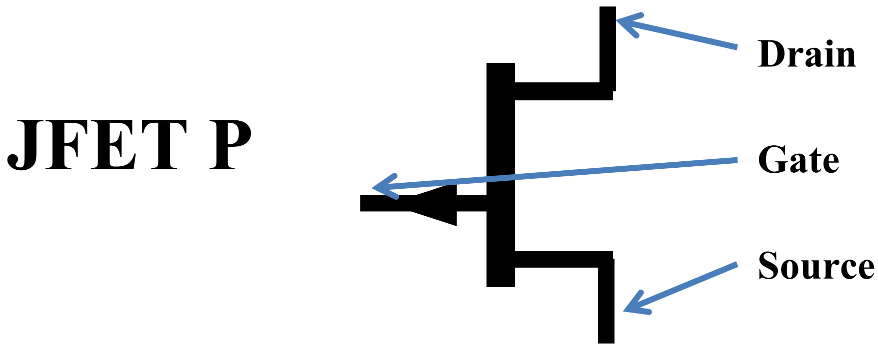


Figure 5.2 JFET-P transistor

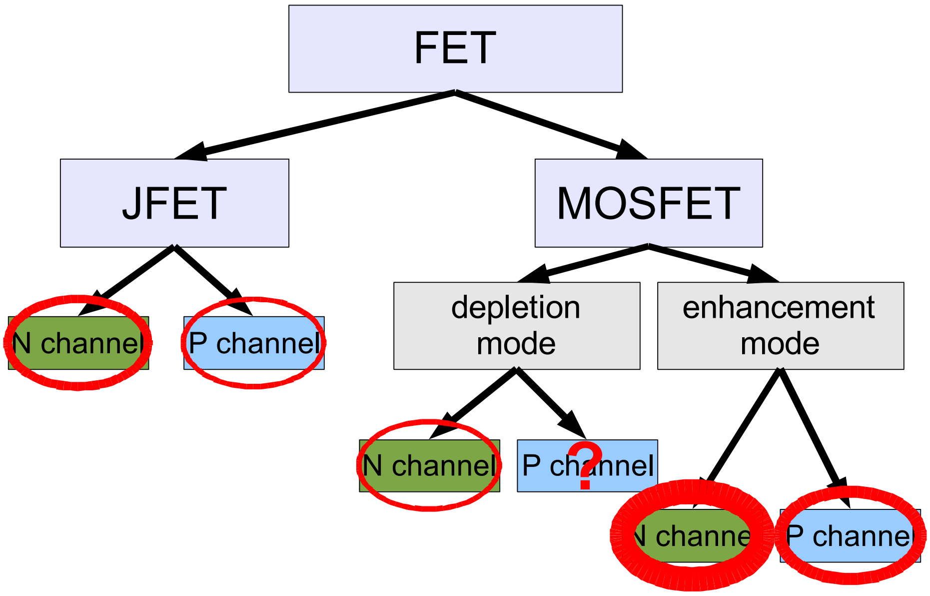


Figure 5.3 FET transistor types

The approximate internal structure of the JFET transistor is shown below, on Figure 5.4 and Figure 5.5.

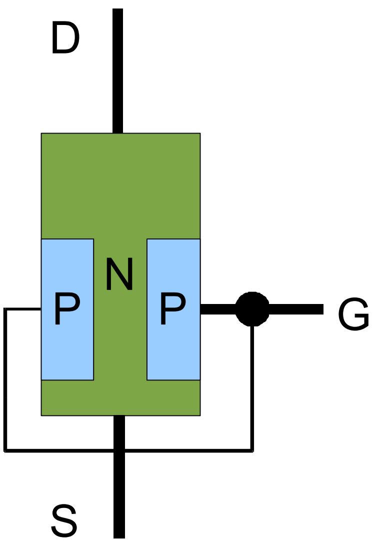


Figure 5.4 N channel JFET transistor internal structure

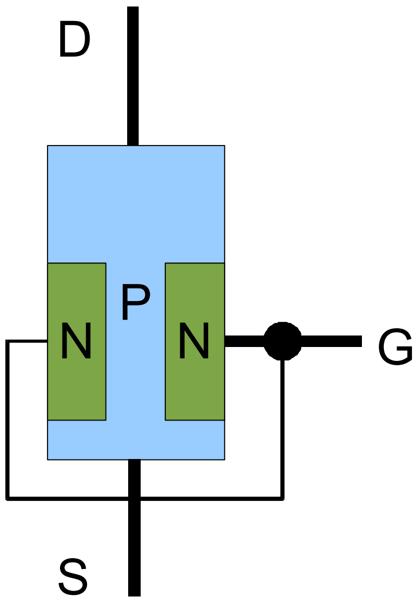
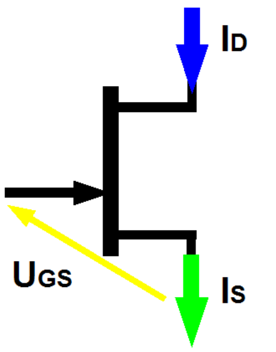


Figure 5.5 P channel JFET internal structure

The operation principle of the JFET is the following – the voltage applied to the gate – source (GS) junction in the reverse direction is controlling the drain current. This current flows inside the transistor from drain to source. No current flows through the gate terminal.

The drain current can be calculated by the following formula, valid for the most of the cases of use of a JFET. Other formulas will be given further on.



$$I_D = I_{DSS} \cdot \left(1 - \frac{U_{GS}}{U_P}\right)^2$$

$$I_D = I_S$$

Figure 5.6 Currents and voltages in JFET-N

The threshold voltage U_P varies from piece to piece, and usually is within the range of a few volts negative for JFET-N. Values between -1V and -5V are very common.

The I_{DSS} current also is device dependent and can vary from piece to piece. Usual value is in the range of several mA to several tens of mA, depending on the device. Please see Figure 5.7 for example.

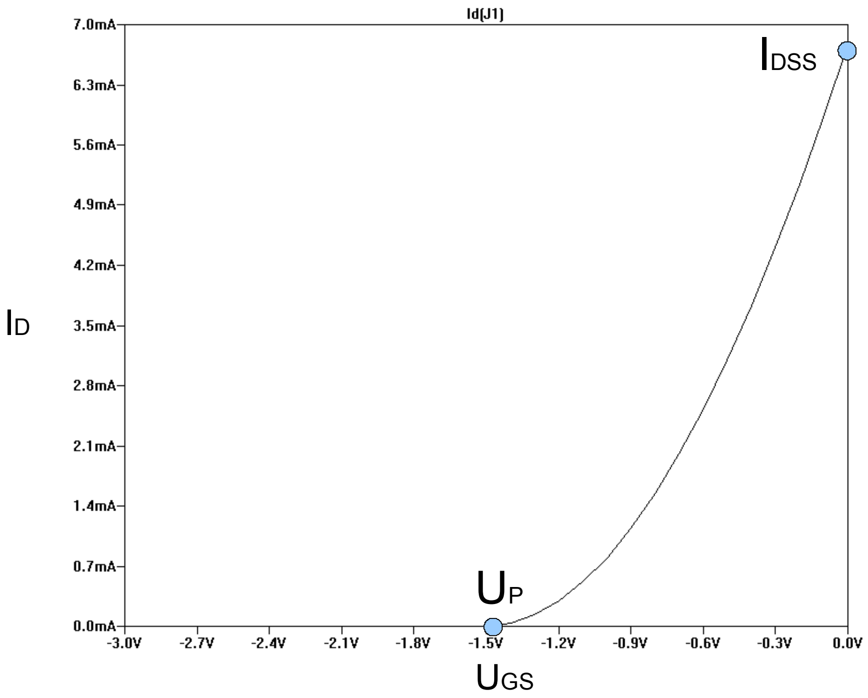


Figure 5.7 Example curve of drain current dependency on U_{GS} for JFET-N

The schematic of a typical circuit utilizing JFET-N is depicted on Figure 5.8, while for JFET-P is depicted on Figure 5.9. Please note the polarity of the voltage sources.

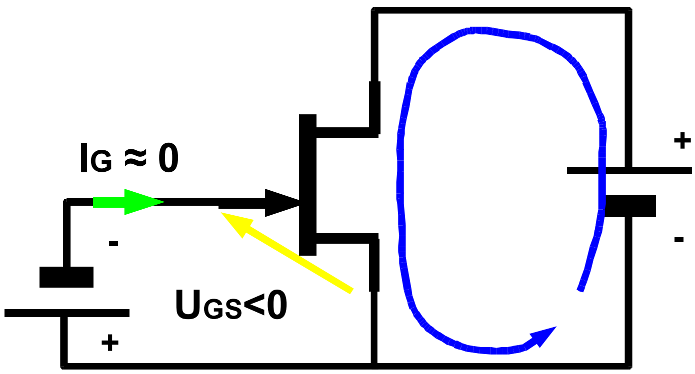


Figure 5.8 Schematical view of a typical JFET-N circuit

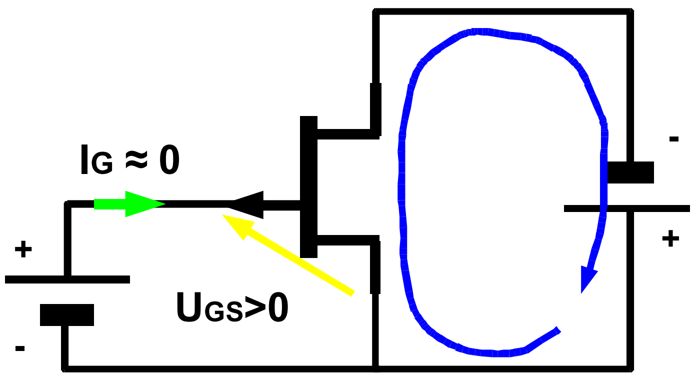


Figure 5.9 Schematical view of a typical JFET-P circuit

In principle, there are 3 modes of operation of a JFET transistor:

- cutoff,
- triode region,
- saturation.

Those 3 modes of operation can be characterized as shown below in Table 5.1.

Table 5.1 Modes of operation of a bipolar transistor

Operation mode	Drain current	Other
cutoff	$I_D \approx 0$	$\lvert U_{GS}\rvert > \lvert U_P\rvert$
triode	$I_D = \frac{I_{DSS}}{U_P^2}\cdot\left(2\cdot(U_{GS}-U_P)\cdot U_{DS}-U_{DS}^2\right)$	$\lvert U_{DS}\rvert + \lvert U_{GS}\rvert < \lvert U_P\rvert$ for low U_{DS}: $I_D \approx U_{DS}/r_{DS}$
saturation	$I_D = I_{DSS}\cdot\left(1-\frac{U_{GS}}{U_P}\right)^2$	$\lvert U_{DS}\rvert + \lvert U_{GS}\rvert > \lvert U_P\rvert$

A typical graph showing relation between I_D and U_{DS} for different values of U_{GS} is shown on Figure 5.10.

The most important parameters that one needs to consider when selecting a JFET for the specific application are the following:

- typical I_{DSS} value range,
- typical U_P value range,
- maximum drain to source voltage U_{DS},
- maximal frequency of operation f_T,
- noise figure (i.e. for radio receivers),
- other, specific for application.

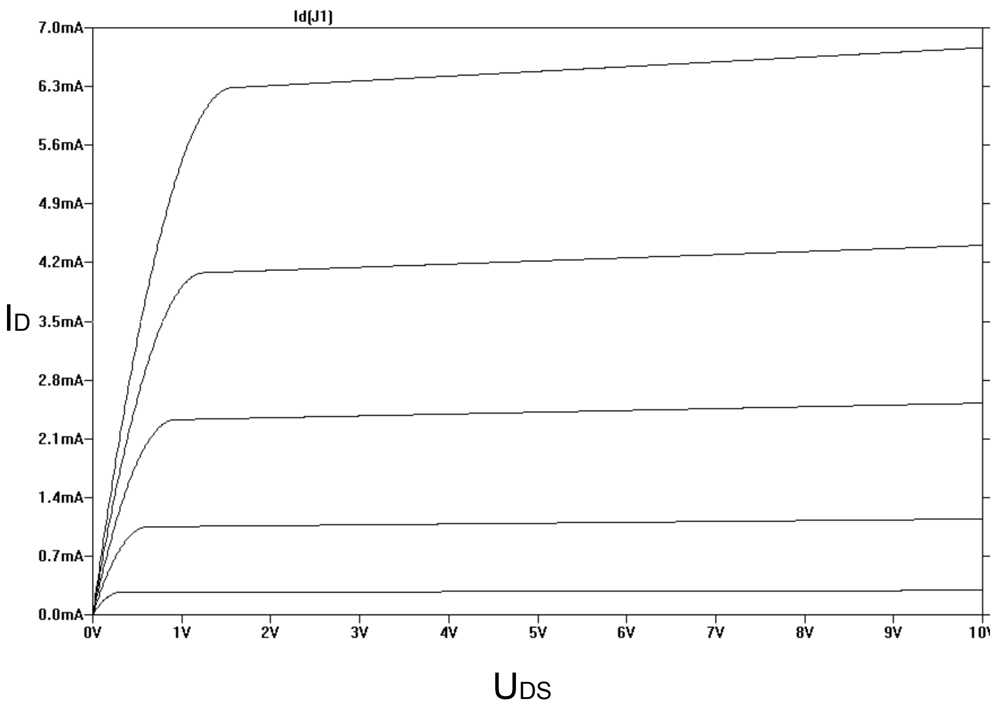


Figure 5.10 JFET transistor output characteristics

It is important to note that the JFETs do not have high power nor high current types. For applications requiring switching of high voltages or currents other transistors have to be used. When used as a switch, the JFET can conduct only low currents. However, JFETs can be successfully employed as amplifiers.

JFET as an amplifier

When working as an amplifier, the JFET needs a polarization circuit, to ensure the following:

- a proper polarization of U_{GS} is ensured,
- the polarization circuit should prevent any undesirable changes of quiescent point resulting from the change of conditions (mainly temperature),
- the circuit should work with any piece of the same type transistor (wide variety of I_{DSS} and U_P),
- there is a desired value of current flowing through the drain I_D in a steady state (quiescent point),
- the U_{DS} is set to a desired value for steady state (quiescent point).

Some circuits used to ensure the proper polarization of transistor for linear circuit operation are shown below.

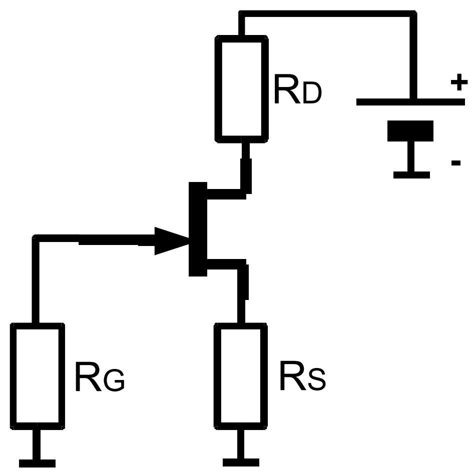


Figure 5.11 Automatic polarization circuit for JFETs - the most popular

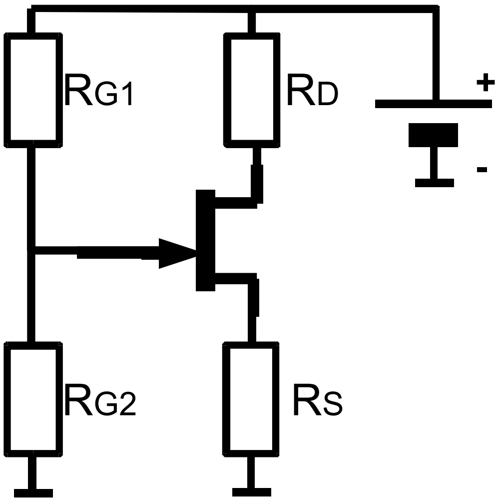
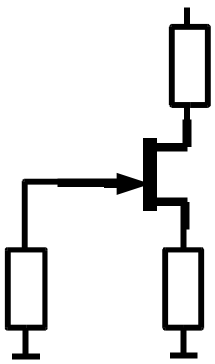


Figure 5.12 JFET polarization circuit with a voltage divider

Example 5.1

In the circuits shown below, select the resistor values so that the drain potential with respect to ground is equal to **6V**. The drain current should be **1mA**. The supply voltage is **12V**. Assume that the I_{DSS} is equal to **10mA** and U_P is equal to **-2V**.



Example 5.2

How does the calculations from example 5.1 change for the value of I_{DSS} equal to **12mA**? And for **8mA**?

Example 5.3

How does the calculations from example 5.1 change for the value of U_P equal to **-1V**? And for **-4V**?

Example 5.4

How does the calculations from example 5.1 change for the value of supply voltage equal to **13V**? And for **11V**?

An example of a typical single transistor amplifier is shown on. It should be noted that this amplifier is only able to amplify AC signals! For amplification of constant voltage values a different circuit has to be used.

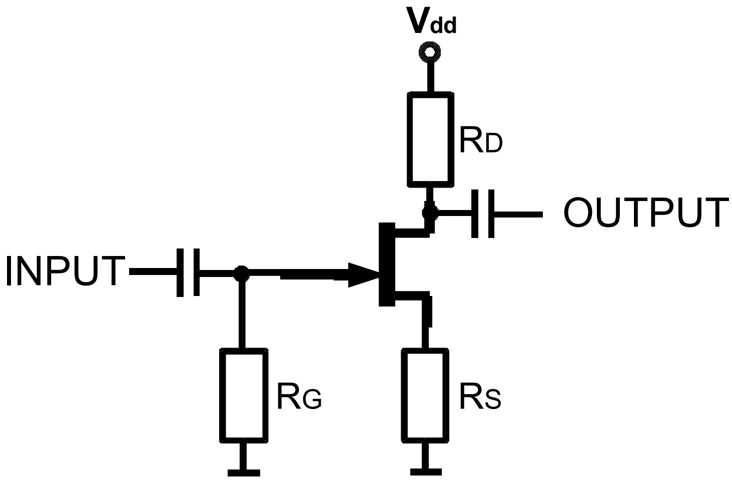
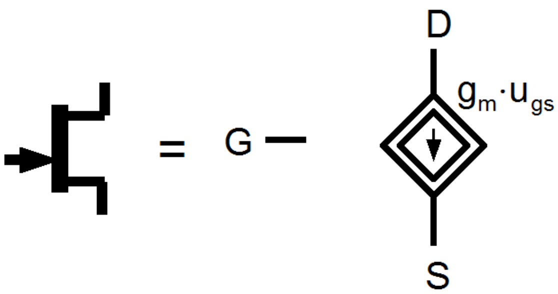


Figure 5.13 JFET transistor amplifier

The process of calculating the properties of this kind of amplifier follows the same two steps as were defined for bipolar transistor. First, the quiescent point has to be established and U_{GS} needs to be calculated.

Then the circuit is redrawn using AC model of the transistor and following the same rules as those specified for bipolar transistor amplifier. The very simplified AC model of a JFET transistor is shown and explained below.



$$g_m = g_{m0} \cdot \left(1 - \frac{U_{GS}}{U_P} \right)$$

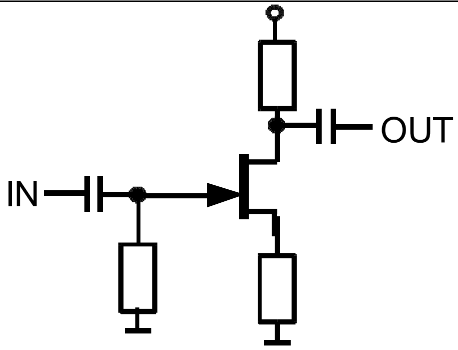
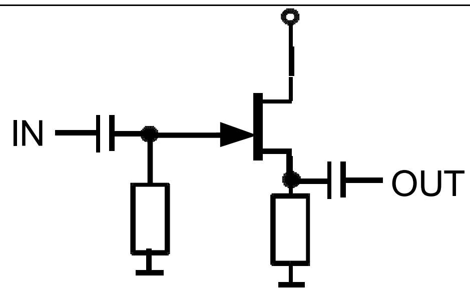
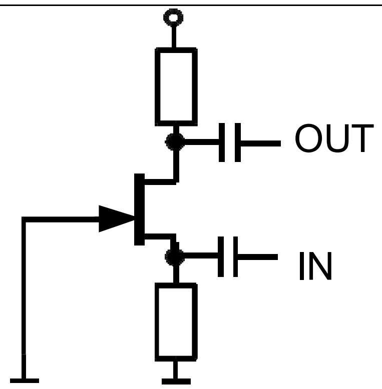
$$g_{m0} = \frac{2 \cdot I_{DSS}}{|U_P|}$$

Figure 5.14 AC model of a FET transistor

Transistor amplifier configurations

There are 3 basic configurations for single transistor amplifier. They are listed in the Table 5.2.

Table 5.2 JFET transistor amplifier configurations

Configuration name	Input	Output	Example schematic
Common Source (CS)	gate	drain	
Common Drain (CD)	gate	source	
Common Gate (CG)	source	drain	

JFET current source

A standalone JFET transistor, sometimes with a single resistor, can be used as a current source for less demanding applications. The schematic of this simple current source is given below.

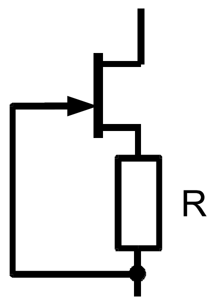


Figure 5.15 JFET current source

5.3. MOSFET transistors

Another variety of FETs are MOSFETs – Metal-Oxide-Semiconductor Field Effect Transistors. There are 4 basic kinds of those transistors – with N or P channel, enhancement or depletion mode.

The most distinctive features of those transistors are the following: the gate is completely insulated from the rest of the transistor by a very thin layer of insulator and the transistor has a fourth terminal, Bulk (B). For most transistors it is internally connected to source. Due to this connection, there is a parasitic diode in all of those MOSFET transistors.

The symbols used for the more popular versions, enhancement mode MOSFETs are shown below. Usually the diode symbol is omitted on the schematic symbol, but it is always present in a 3 terminal MOSFET.

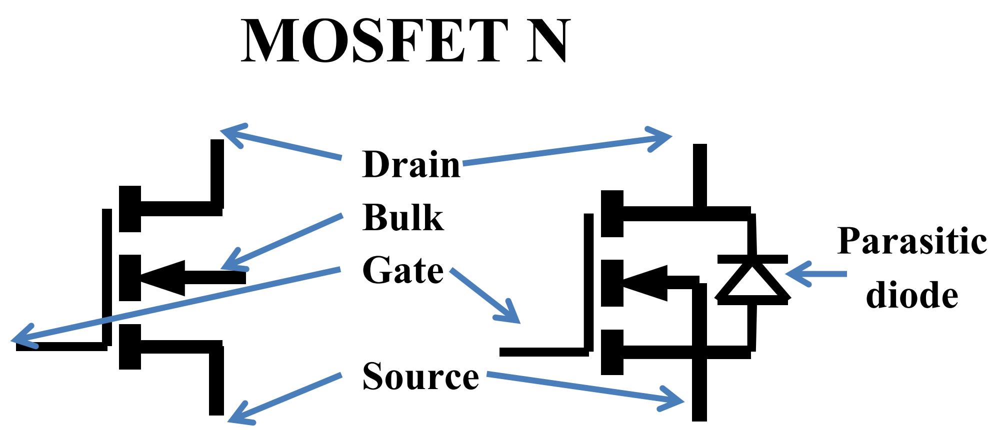


Figure 5.16 MOSFET N terminals

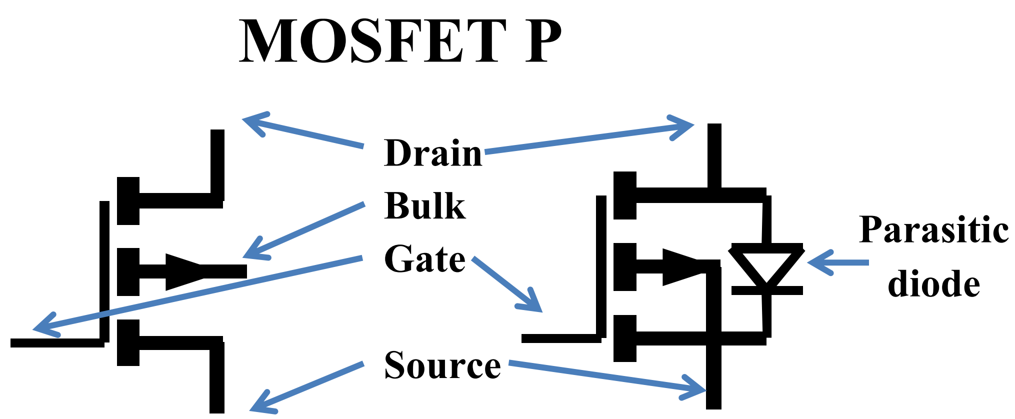


Figure 5.17 MOSFET P terminals

The symbol for another type of MOSFET transistor – depletion mode N channel, is shown on Figure 5.18.

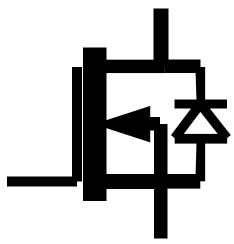


Figure 5.18 Depletion mode N channel MOSFET symbol

In different schematics, different symbols may be used for MOSFETS, the most popular are presented on Figure 5.19 and on Figure 5.20. Please note the symbol conflicting with depletion mode transistor described further on – this is due to the fact that depletion mode transistors are rarely used, mainly in very specific applications.

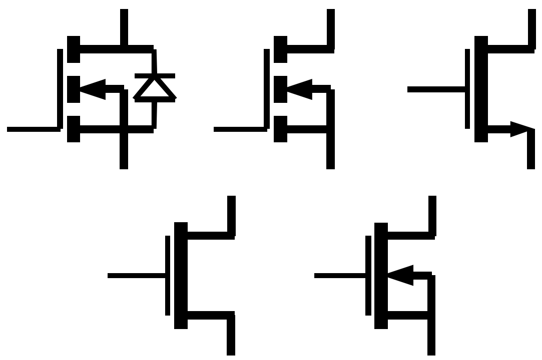


Figure 5.19 Different symbols used for N channel enhancement mode MOSFET

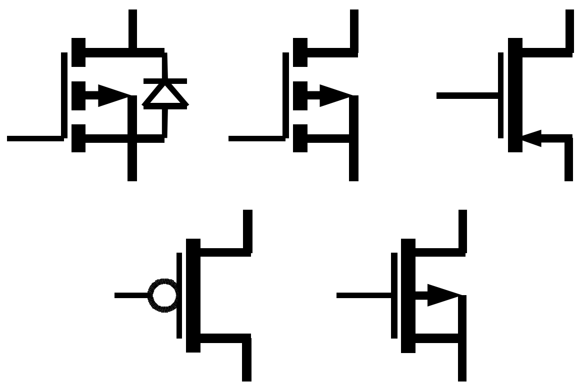


Figure 5.20 Different symbols used for P channel enhancement mode MOSFET

The schematic internal structure of a N channel enhancement mode MOSFET transistor is shown on Figure 5.21.

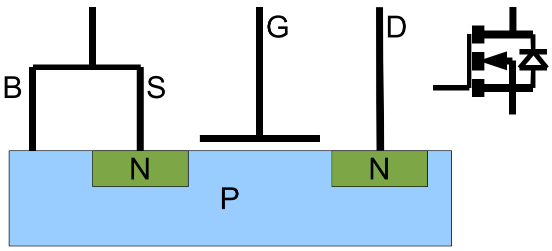


Figure 5.21 Internal structure of N channel enhancement mode MOSFET – no current flow from D to S

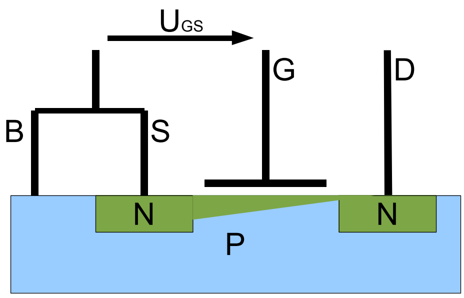


Figure 5.22 Internal structure of N channel enhancement mode MOSFET – current can flow from D to S through the induced channel

The current flowing through the transistor is controlled by the voltage applied to the gate. The example graph showing the correspondence is presented on Figure 5.23. The formula for current I_D value is presented below.

For saturation region the formula is:

$$I_D = K \cdot (U_{GS} - U_P)^2$$

while for the triode region the formula is:

$$I_D = 2 \cdot K \cdot \left((U_{GS} - U_P) \cdot U_{DS} - \frac{1}{2} U_{DS}^2 \right)$$

The K coefficient is constant for a given transistor, and depends mostly on the technology used during manufacturing of the transistor and on its physical dimensions (channel width to length ratio).

An example characteristic of a N channel enhancement mode MOSFET is shown on Figure 5.23, for P channel enhancement mode – on Figure 5.24. The characteristics for an N channel depletion mode MOSFET is shown on Figure 5.25

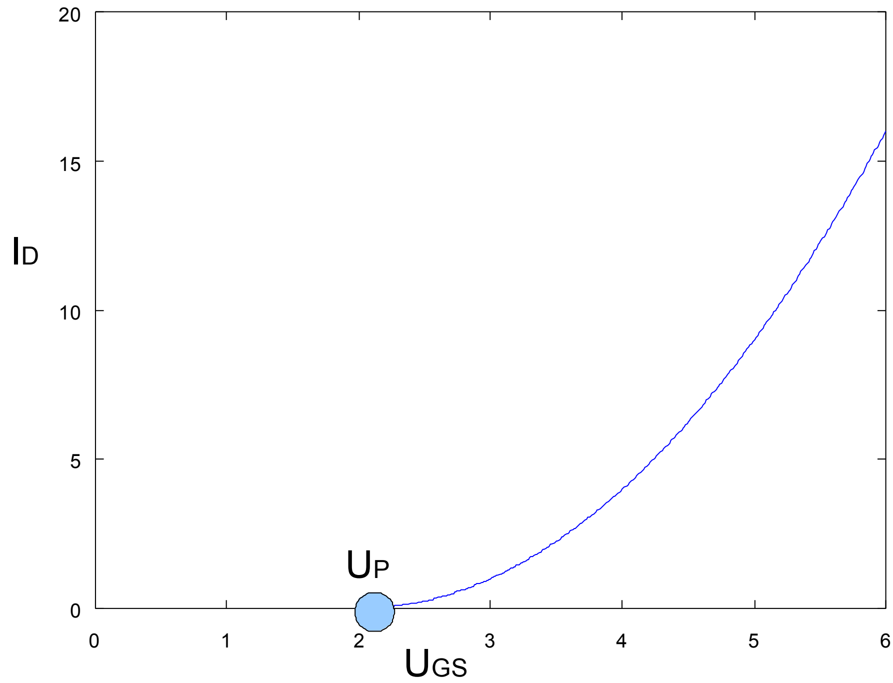


Figure 5.23 Enhancement mode N channel MOSFET transfer characteristics

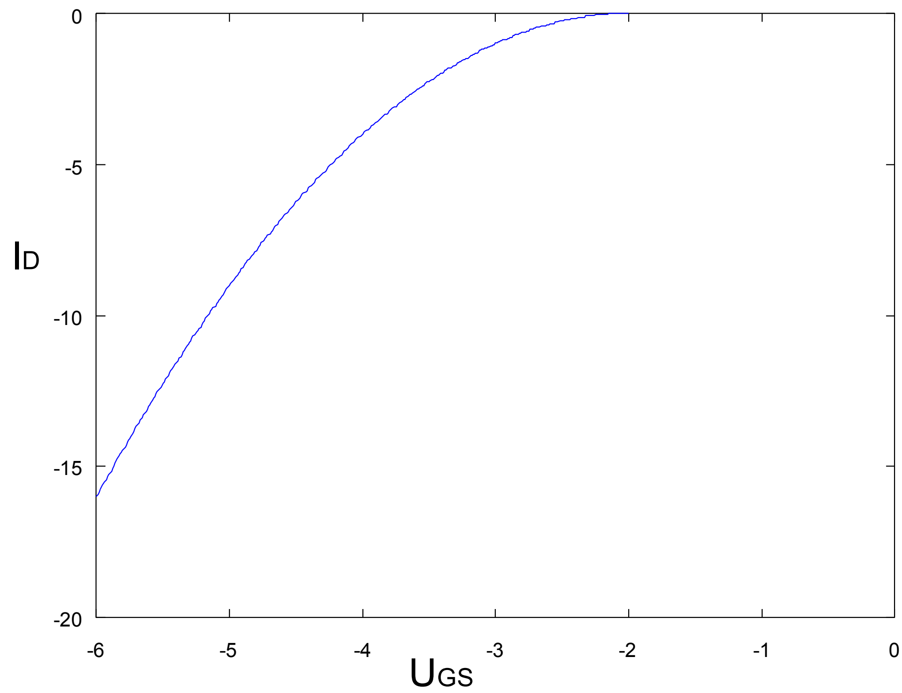


Figure 5.24 Enhancement mode P channel MOSFET transfer characteristics

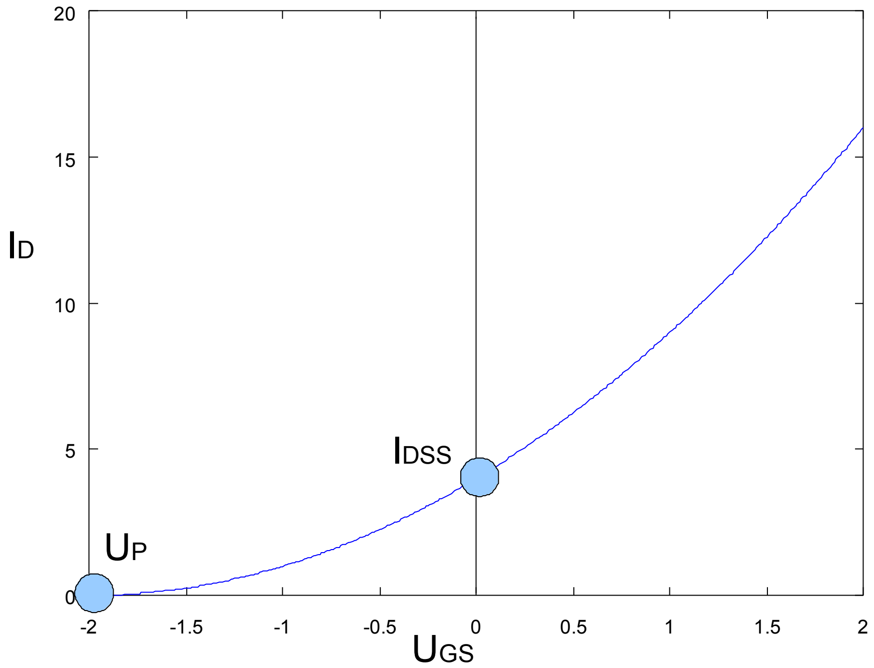


Figure 5.25 Depletion mode N channel MOSFET transfer characteristics

For depletion mode transistors, there is additional formula, specifying drain current for gate shorted to source.:

$$I_{DSS} = K \cdot U_P^2$$

When considering the use of a FET in an application, the following basic characteristic value of a transistor must be observed:

- maximal drain current I_D,
- maximal drain-source voltage U_{DS},
- maximal gate-source voltage U_{GS} (often much lower than other voltages, observe carefully),
- maximal power dissipation,
- threshold voltage U_P.

For specific applications also other parameters may be of importance, like the gate input-capacitance (important for fast switching applications), drain to source channel resistance in on state R_{DSon}, transition frequency f_T for amplifiers.

MOSFET as a switch

The main use of discrete MOSFET devices are switching applications (Figure 5.26). In such applications, the MOSFET operates in fully on or in fully off state.

For fully on state, like on Figure 5.27, the transistor acts mostly like a resistor of a resistance equal to R_{DSon}, specified for each type of a transistor. There is a certain power dissipated by the transistor due to the drain current flowing through this resistance.

For fully off state, like on Figure 5.28, the transistor does not conduct any significant (for given application) current.

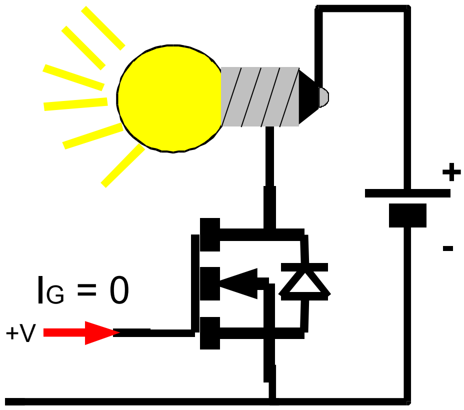


Figure 5.26 MOSFET working as a switch

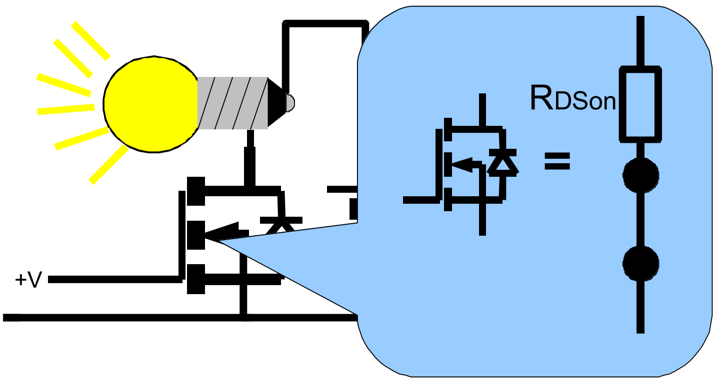


Figure 5.27 MOSFET as a switch - fully on

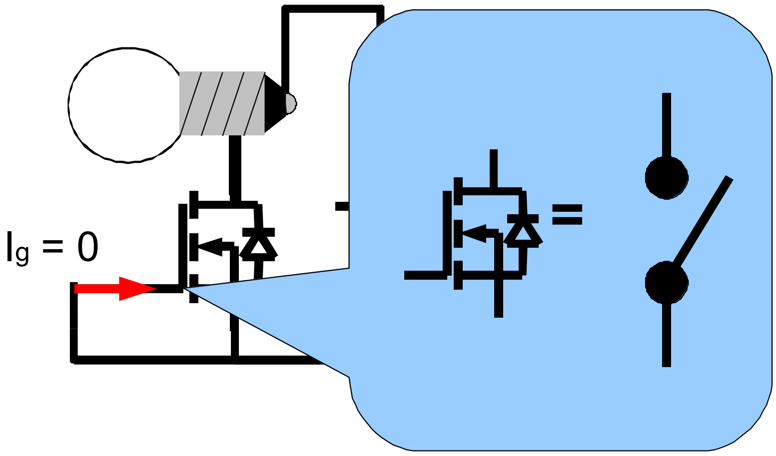


Figure 5.28 MOSFET as a switch - fully off

Integrated circuits

Another very important application of FETs, especially MOSFETS is integrated circuits. Most modern integrated circuits are manufactured with the use of MOSFET transistors. The design of integrated circuits will not be described here.

An example of a very simple circuit using MOSFET is a digital gate – inverter, shown on

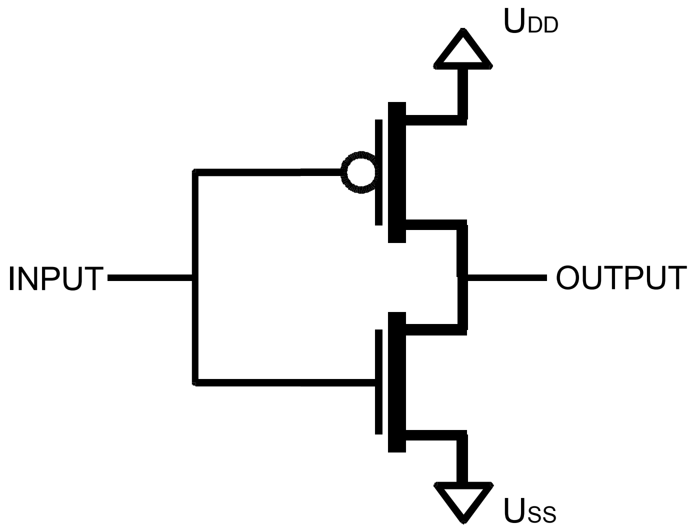
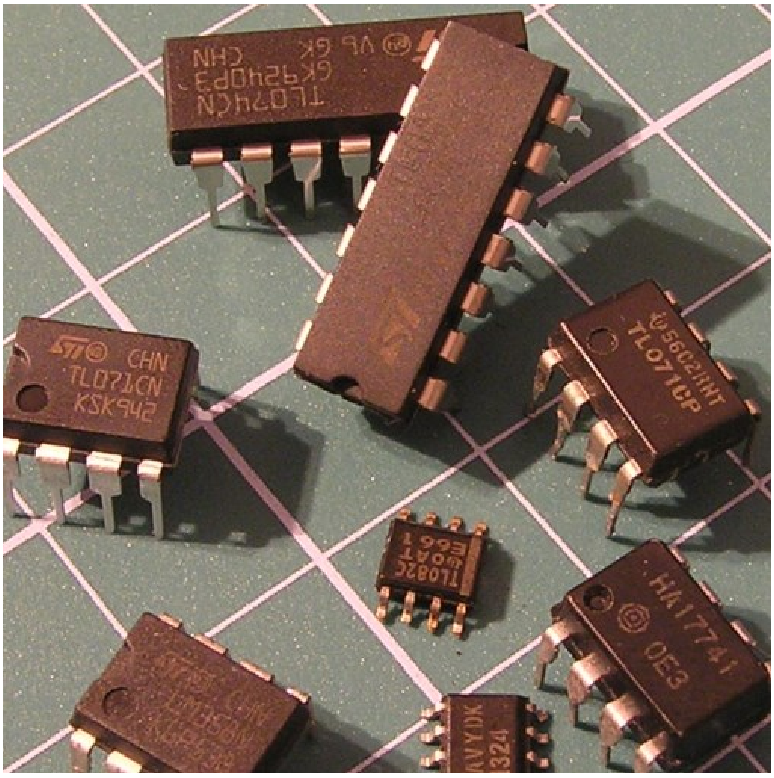


Figure 5.29 Inverter



6. Operational amplifiers

6.1. Operational amplifier basics

The operational amplifiers are the integrated circuits, therefore they are much more complex than the devices described earlier. Their importance in electronics is, however, that large, that they are often used as a simple building block. It can be sometimes seen that it is referenced as an “opmap” or “OA” (short for operational amplifier).

The name of this part is taken from one of the applications the device was used in – as a building block of analog computers. They were a basic block for performing simple operations, like addition, subtraction, integration, differentiation.

The most basic versions of a schematic symbols for operational amplifier are shown on Figure 6.1.

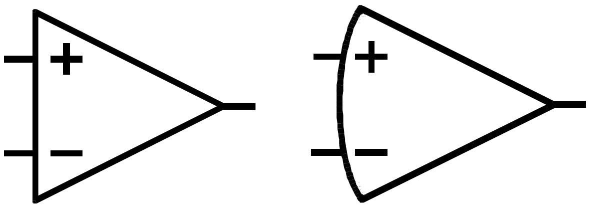


Figure 6.1 Operational amplifier - basic symbol

The regular operational amplifier has 2 inputs (inverting and non-inverting) and 1 output, as shown on Figure 6.2.

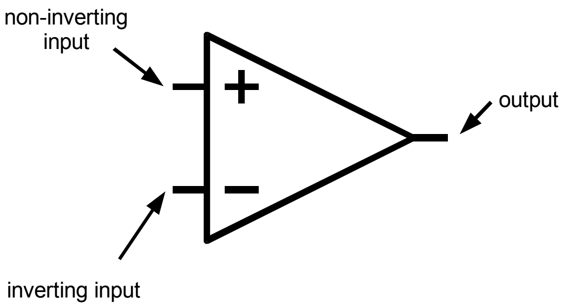


Figure 6.2 Operational amplifier terminals

It needs to be stressed, that despite of the fact that usually it is not marked on the schematic in an obvious way, each operational amplifier needs a power supply for its proper operation. Therefore, a more complete version of the symbol would be similar to the one depicted on Figure 6.3. In an usual arrangement, the values of voltages U+ and U- are symmetrical – the U- is equal to U+ with the minus sign.

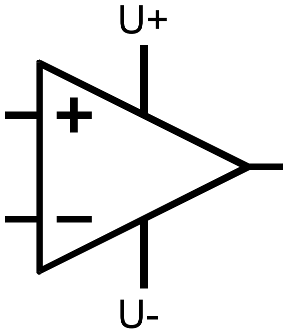


Figure 6.3 Operational amplifier with power supply pins visible

The value of supply voltages determines the possible output voltage swing – the output voltage cannot exceed the limits set by the values of power supply voltage rails. Usually, the output voltage range is smaller. There is a group of operational amplifiers that can provide voltages on their outputs close to the supply voltage values – they are called “rail to rail”. Similar limitations need to be observed when it comes to input voltages – they cannot exceed the supply voltages. Detailed information about voltage limits can be always found in the documentation (“datasheet”) of a certain operational amplifier.

The principle of operation of the operational amplifier is the following, depicted on Figure 6.4. The amplifier amplifies the difference of voltages on its inputs ΔU and presents on its output the voltage equal to ΔU multiplied by the factor of k (operational amplifier gain, so called “open loop gain”).

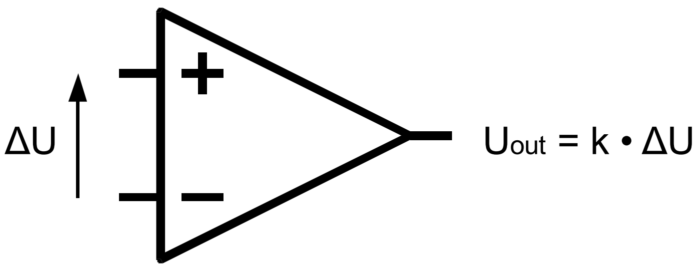


Figure 6.4 Principle of operation of an operational amplifier

6.2. Ideal operational amplifier

To understand the operation of circuits with operational amplifiers, it is very practical to use the simple model, so called ideal operational amplifier. Although the parameters of real amplifiers are not ideal, usually for many applications the idealized model is sufficient.

For an ideal operational amplifier, the gain k is infinite.

The idea of a device with infinite gain seems to be troubling, but in fact, the operational amplifier is rarely used as a standalone device. Usually, it is connected in a specific way in a circuit.

First, the linear applications of an operational amplifier will be considered. Please note that for those circuits there is a connection between output and inverting input. This connection constitutes a so called negative feedback. For such circuits, two following rules must be observed during analysis of a circuit.

IDEAL OPERATIONAL AMPLIFIER
LINEAR CIRCUIT ANALYSIS

2 RULES:

1. The ideal operational amplifier forces the voltage difference ΔU between its inputs to be 0.
2. No current flows into nor out of the inputs of the operational amplifier.

Further on, a short review of basic operational amplifier circuits is presented. They are all linear circuits, therefore the two rules given above will apply to those circuits. Please note, that those circuits work for both – alternating and constant voltages.

The most basic circuit is the inverting amplifier.

6.3. Ideal amplifier circuits

Inverting amplifier

The schematic of an inverting amplifier built using an operational amplifier is shown on Figure 6.5.

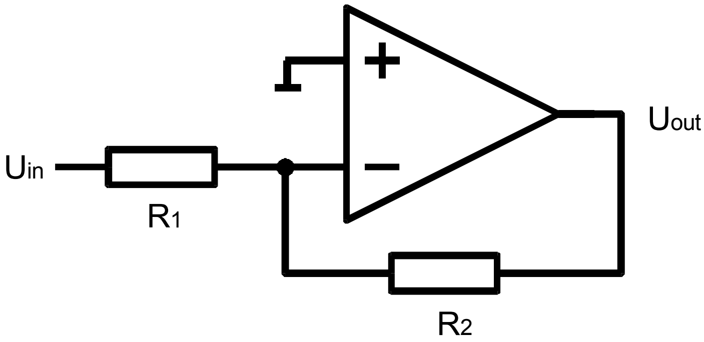


Figure 6.5 Inverting amplifier

For inverting amplifier, the output voltage is defined by the formula given below

$$U_{out} = -U_{in} \cdot \frac{R_2}{R_1}$$

Non-inverting amplifier

Below is presented another simple operational amplifier circuit – non inverting amplifier.

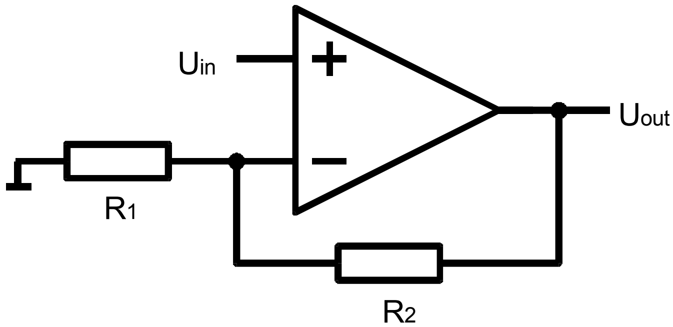


Figure 6.6 Non-inverting amplifier

The gain of such a circuit is given by the formula

$$U_{out} = U_{in} \cdot \frac{R_1 + R_2}{R_1}$$

Voltage follower

The circuit presented below is a voltage follower. It provides on ins output exactly the same voltage as is present on its input. It can be perceived as a non-inverting amplifier of a gain 1.

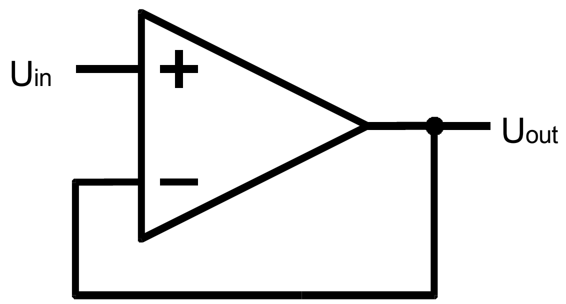


Figure 6.7 Voltage follower

Such a circuit is useful for connecting high output resistance sources to lower input impedance loads.

$$U_{out}=U_{in}$$

Summing amplifier

The circuit presented below can be used to add two (or more – the extension is straightforward) voltages with different or the same weights.

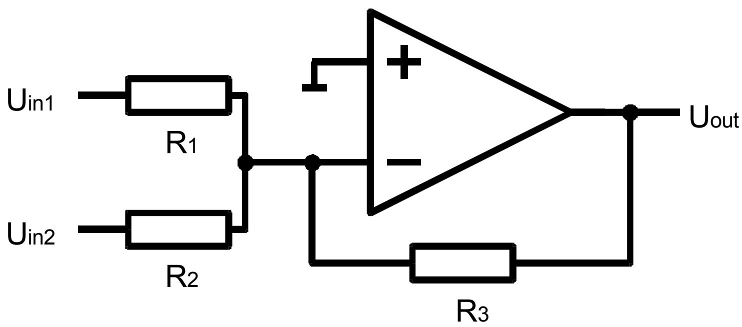


Figure 6.8 Summing amplifier

The output voltage of such a circuit is defined as follows

$$U_{out}=-R_3\left(\frac{U_{in1}}{R_1}+\frac{U_{in2}}{R_2}\right)$$

Differential amplifier

To subtract two voltages, a different circuit may be used. There are different circuits used as a differential amplifier, but the one presented below is the most basic one.

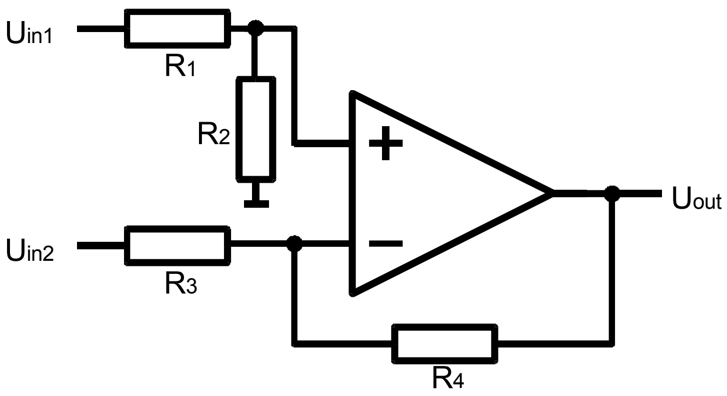


Figure 6.9 Differential amplifier

The output voltage of this circuit is defined as follows

$$U_{out}=U_{in1}\left(\frac{R_4}{R_3}+1\right)\frac{R_2}{R_1+R_2}-U_{in2}\frac{R_4}{R_3}$$

When the resistor ratios satisfy the following requirement

$$\frac{R_2}{R_1}=\frac{R_4}{R_3}$$

then the output voltage becomes

$$U_{out}=\left(U_{in1}-U_{in2}\right)\frac{R_2}{R_1}$$

and the subtraction of voltage values can be easily performed. For precise applications this circuit has limited use, due to some of its shortcomings. Therefore another differential amplifier is shown further on.

Differential amplifier 2

The more advanced and complicated circuit used for subtracting voltages is shown below. It is much more complicated, but does not have the drawbacks of the previous circuit.

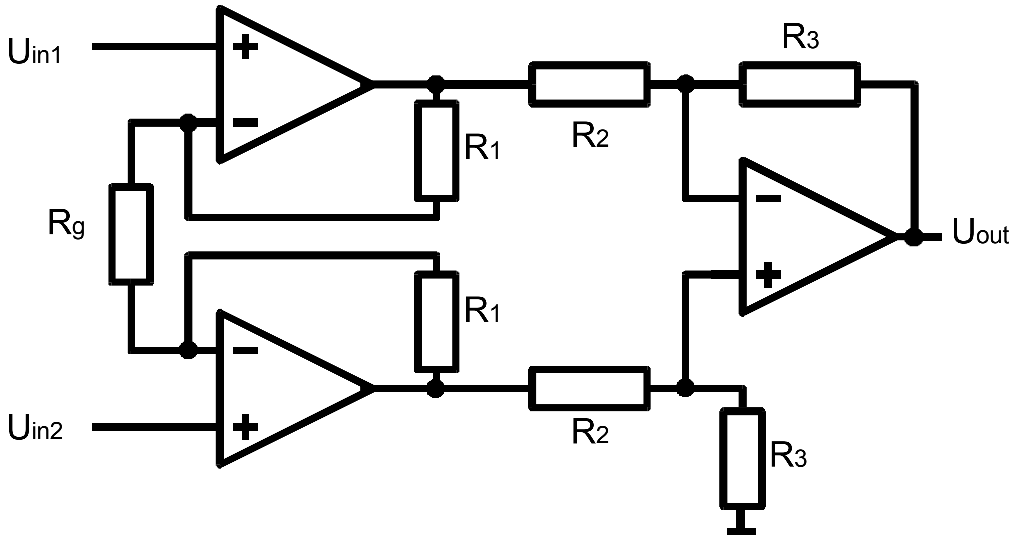


Figure 6.10 Differential amplifier 2

The output voltage from this circuit follows the formula

$$U_{out} = (U_{in2} - U_{in1}) \cdot \left(1 + \frac{2 \cdot R_1}{R_g}\right) \frac{R_3}{R_2}$$

Integrator

Another basic operational amplifier circuit is an integrator, shown on the Figure 6.11.

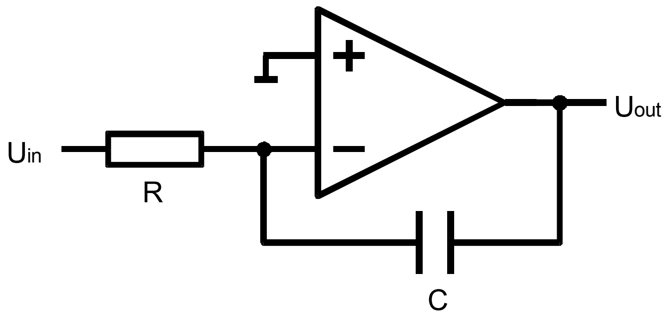


Figure 6.11 Integrator

The output of the integrator follows the formula given below

$$U_{out} = -\frac{1}{RC} \int_t U_{in} \, dt$$

Differentiator

A circuit performing the differentiation operation is shown below.

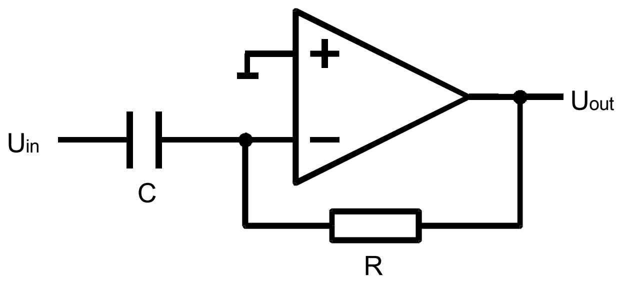


Figure 6.12 Differentiator

The output of a differentiator is defined by the formula

$$U_{out} = -RC\frac{d\,U_{in}}{dt}$$

Other simple circuits

The simple blocks shown above are often used in many applications. Below some more simple circuits are shown. All of them can be analyzed using the two basic rules for ideal operational amplifier circuits.

Voltage controlled current sources

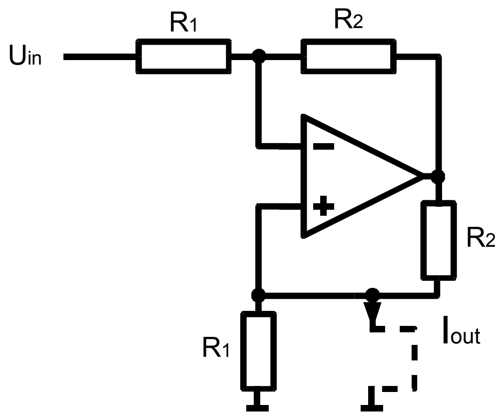


Figure 6.13 Voltage controlled current source 1

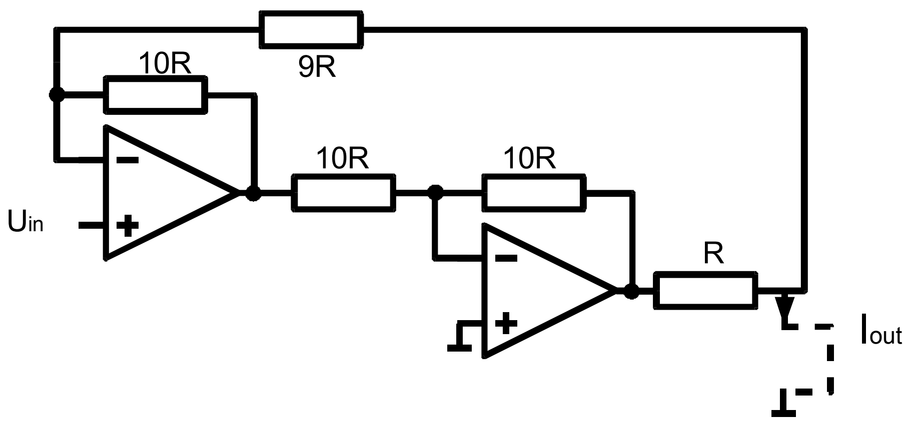


Figure 6.14 Voltage controlled current source 2

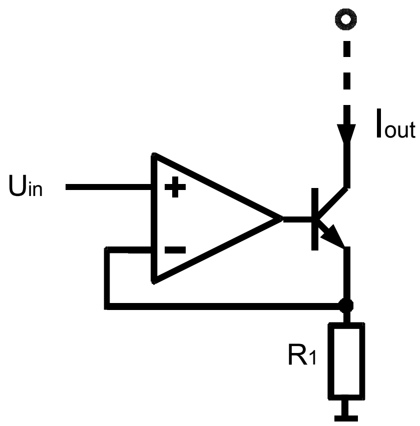


Figure 6.15 Voltage controlled current source 3

Current controlled voltage source

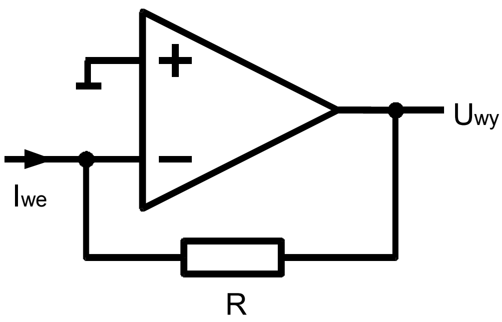


Figure 6.16 Current controlled voltage source

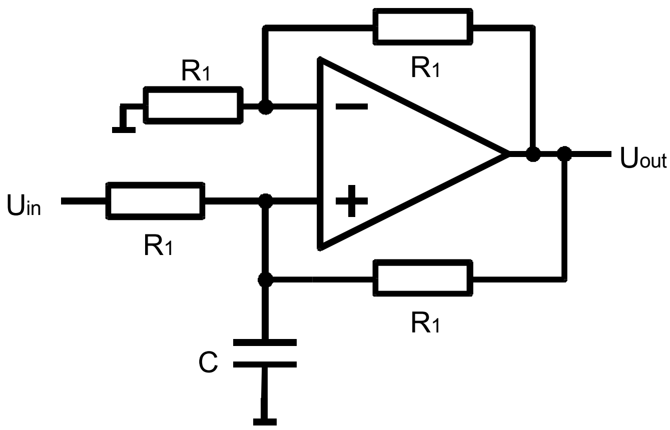


Figure 6.17 Non inverting integrator

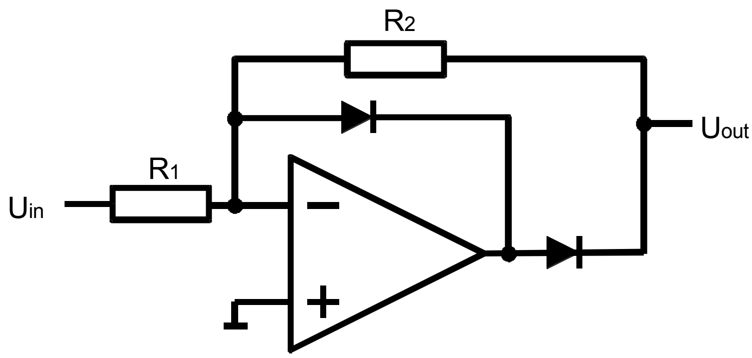


Figure 6.18 Half wave rectifier

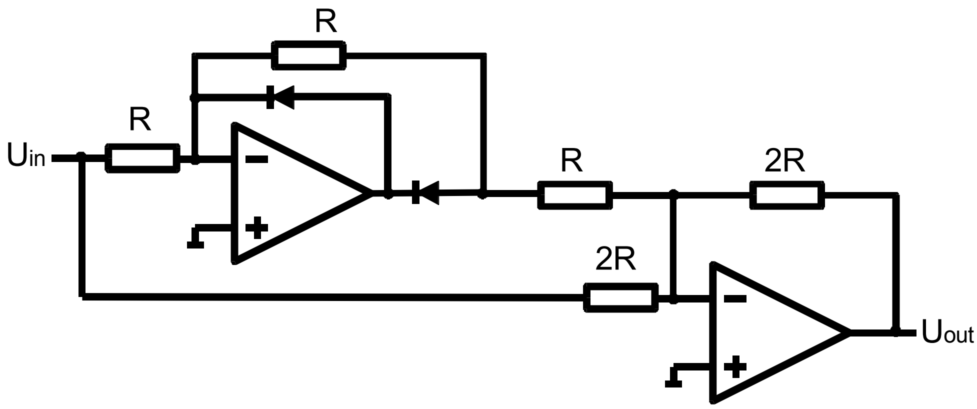


Figure 6.19 Full wave rectifier

A pair of more complicated circuits

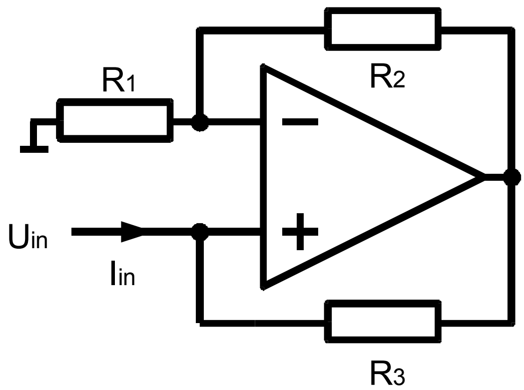


Figure 6.20 Simple impedance converter

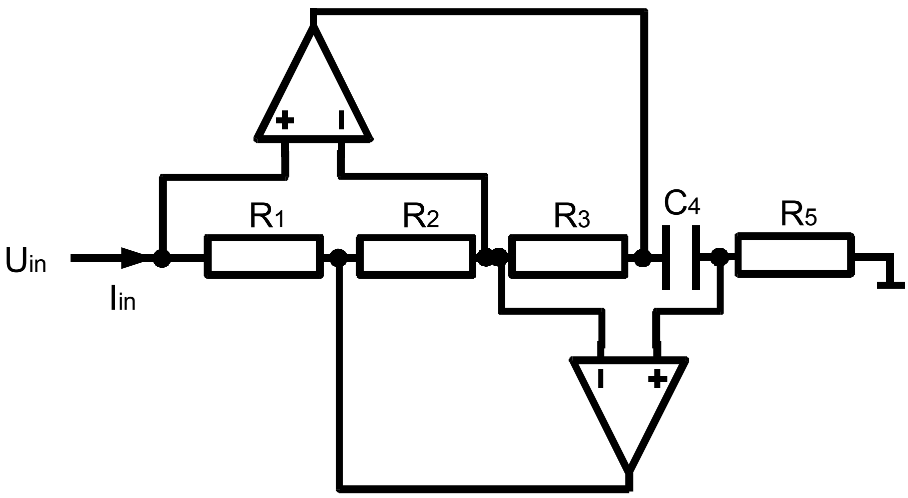


Figure 6.21 General impedance converter

6.4. Real operational amplifier

The ideal operational amplifier is a useful concept for simple circuits where requirements for accuracy are not very strict. For precise applications, the properties of real-life parts must be considered.

First of all – the real operational amplifier gain is less than infinity. Usually, the voltage gain of modern parts is in $10^5 \div 10^6$ V/V range.

The consequences of this fact will be shown on the simple inverting amplifier. Let us still assume, that current does not flow through the inputs of amplifier, only the k value is less than infinity.

The Figure 6.22 depicts the situation.

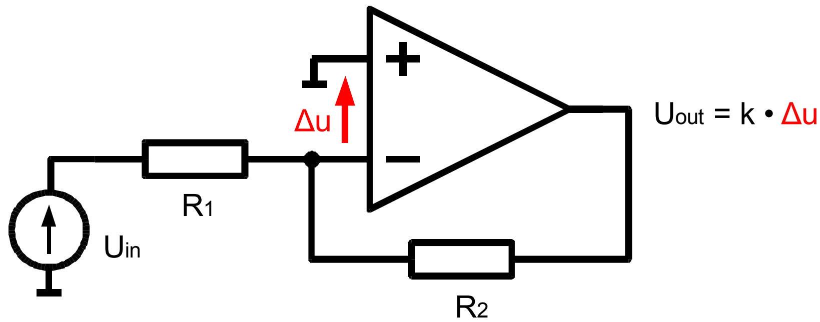


Figure 6.22 Real inverting amplifier

For this situation, the Δu is equal to:

$$\Delta u = -U_{in} \cdot \frac{\frac{R_2}{R_1}}{k + 1 + \frac{R_2}{R_1}}$$

and the output voltage is:

$$U_{out} = -U_{in} \cdot \frac{\frac{R_2}{R_1}}{1 + \frac{1 + \frac{R_2}{R_1}}{k}}$$

Example
Please check what is the difference between output voltage of the real operational amplifier and ideal operational amplifier circuit for: $k = 100\ 000$ V/V $R_1 = 1k\Omega$ $R_2 = 10k\Omega$ $U_{in} = 100mV$ What is the Δu value? Is it much different than 0V for an ideal operational amplifier?

Apart from finite gain, the real operational amplifier differs from the ideal one by the following, depicted on Figure 6.23:

- less than infinity input impedance Z_{in} – as a consequence, current does flow through the inputs,
- larger than zero output impedance – as a consequence, the output current capability of an operational amplifier is limited, in most cases to a few miliamperes only.

In real amplifier, the voltage gain is also dependent on the frequency of the input signal – the higher the frequency, the lower the gain. This issue will be discussed later.

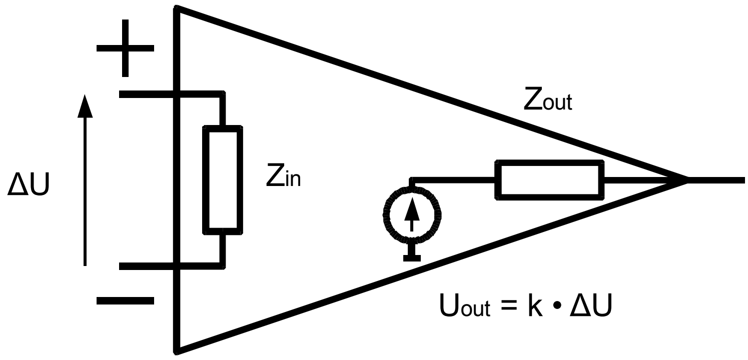


Figure 6.23 Input and output impedances of a real operational amplifier

The input circuitry of operational amplifiers is not ideal, therefore there are some imbalances in the internal circuitry. Due to this, the amplifier is sensitive to common mode voltage and has less than infinity Common Mode Rejection Ratio (CMRR), as shown on the Figure 6.24. For the figure, the voltages are defined as shown in Table 6.1.

Table 6.1Differential and common mode voltages

Voltage	Value
Common mode	$U_c = \frac{U_1 + U_2}{2}$
Differential mode	$U_d = 2 \cdot (U_c - U_1) = 2 \cdot (U_2 - U_c) = U_2 - U_1$

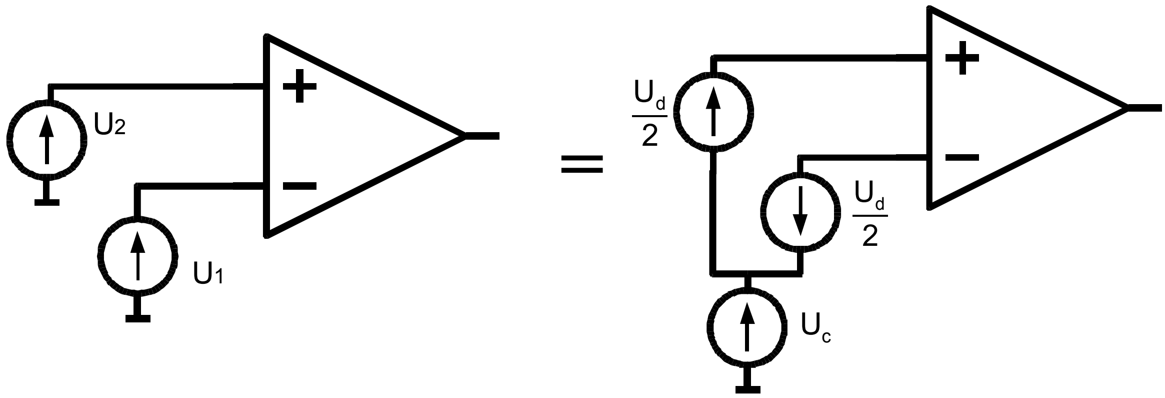


Figure 6.24 Differential and common mode voltages

The output voltage of the amplifier is then defined as follows:

$$U_{out} = U_c \cdot k_c + U_d \cdot k_d$$

where:
kc is the gain for the common mode voltage (equal to 0 for the ideal operational amplifier),
kd is the gain for the differential voltage.

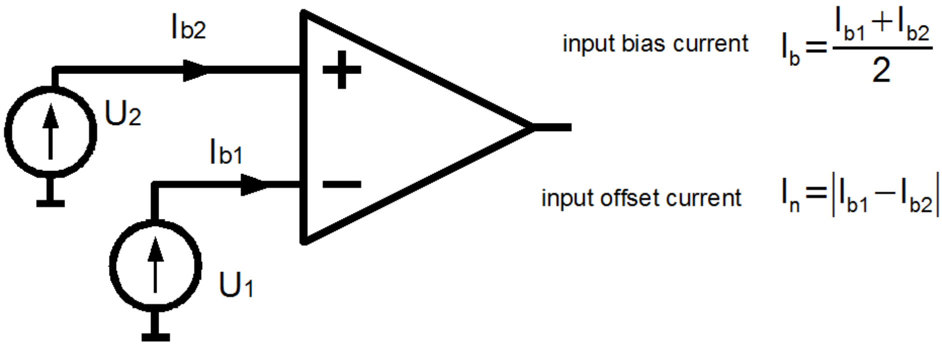
The already mentioned CMRR is a coefficient defined as follows, expressed in decibels:

$$CMRR = 20 \log_{10} \frac{k_d}{k_c}$$

Usually, this value is in the range of 100dB.

The real operational amplifier has also some other important properties:

- input bias current and input offset current – the current that flows in (or sometimes out of) the inputs, as shown on Figure 6.25

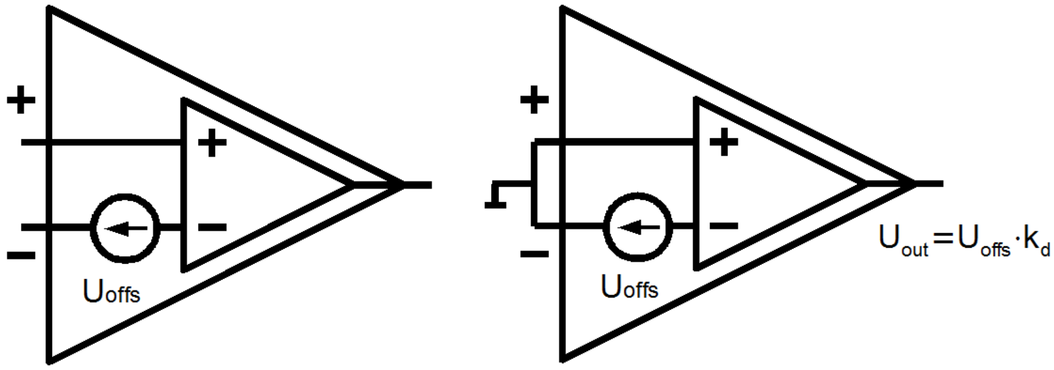


$$I_b = \frac{I_{b1} + I_{b2}}{2}$$

$$I_n = |I_{b1} - I_{b2}|$$

Figure 6.25 Input bias current

- input offset voltage, as shown on Figure 6.26



$$U_{out} = U_{offs} \cdot k_d$$

Figure 6.26 Input offset voltage

6.5. Comparator

The operational amplifier can also be used to compare voltages. In such application, the operational amplifier works without feedback at all, or with a positive feedback (connection from output to non-inverting input). Due to the fact that comparing voltages usually needs to be performed fast, some modifications are introduced in the internal structure of a standard operational amplifier to speed up its operation, sacrificing some other properties.

Let us consider an operational amplifier in the circuit shown on Figure 6.27.

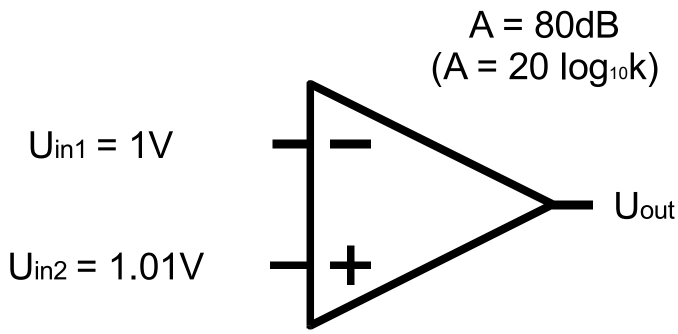
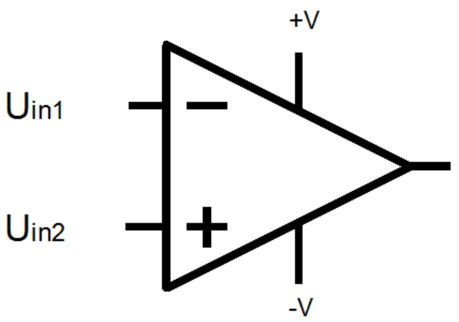


Figure 6.27 Comparator example

The voltage difference ΔU_{in} is $U_{in2} - U_{in1} = +0.01V$. Since the gain is 80dB (that is 10 000), the output voltage in such a case will be +100V. However, since the output voltage is limited by the supply rail voltage value, the output will saturate at the voltage level close to +V supply voltage. In practice, the gain of operational amplifier is so large, that even very small difference between voltages on the inputs will cause the output to saturate. Overall, the operation of a comparator is described on Figure 6.28.

PLEASE NOTE!

The comparator is not a linear circuit (does not meet the additive nor multiplicative criterions). In comparator circuit, the operational amplifier will not be able to maintain 0V difference between its inputs!

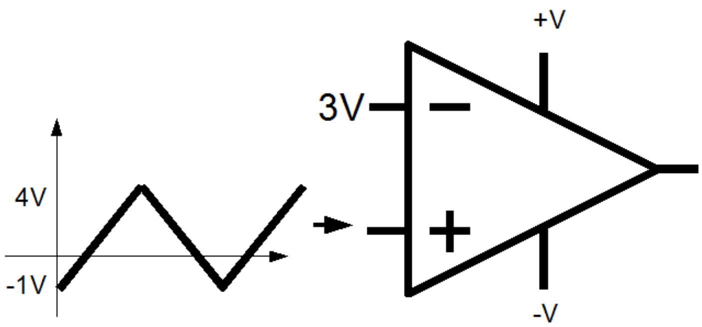


$$U_{out} = \begin{cases} +V & \text{for } U_{in2} > U_{in1} \\ -V & \text{for } U_{in1} > U_{in2} \end{cases}$$

Figure 6.28 Comparator operation

Example

Consider the comparator circuit from the figure. What will the output be?



$$U_{out} = \begin{cases} +V & \text{for } U_{in} > 3V \\ -V & \text{for } U_{in} < 3V \end{cases}$$

In practice, the input signal is noisy, therefore there will be multiple switching of output level when input signal approaches the threshold value, as seen on Figure 6.29.

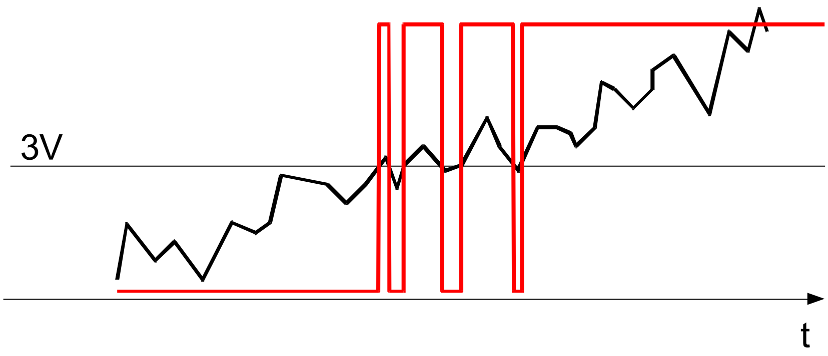


Figure 6.29 Noisy input signal (black) and comparator output (red)

To overcome the problem with multiple crossing of threshold voltage, a small shift of threshold voltage is introduced each time the crossing occurs. This is called hysteresis. A comparator with hysteresis is sometimes called a comparator with Schmitt trigger.

Inverting Schmitt trigger

The inverting Schmitt trigger is shown on Figure 6.30. Please note the input markings – the schematic is the same as for inverting amplifier, only the inputs are exchanged.

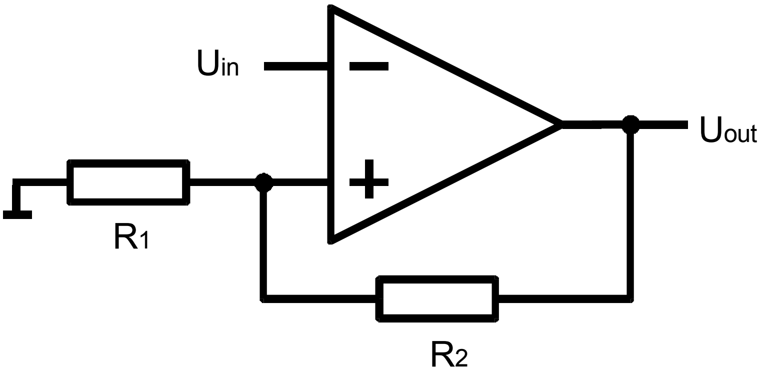


Figure 6.30 Inverting Schmitt trigger

The operation of this circuit is shown on Figure 6.31, and the curve depicting the hysteresis loop is shown on Figure 6.32 and on Figure 6.33.

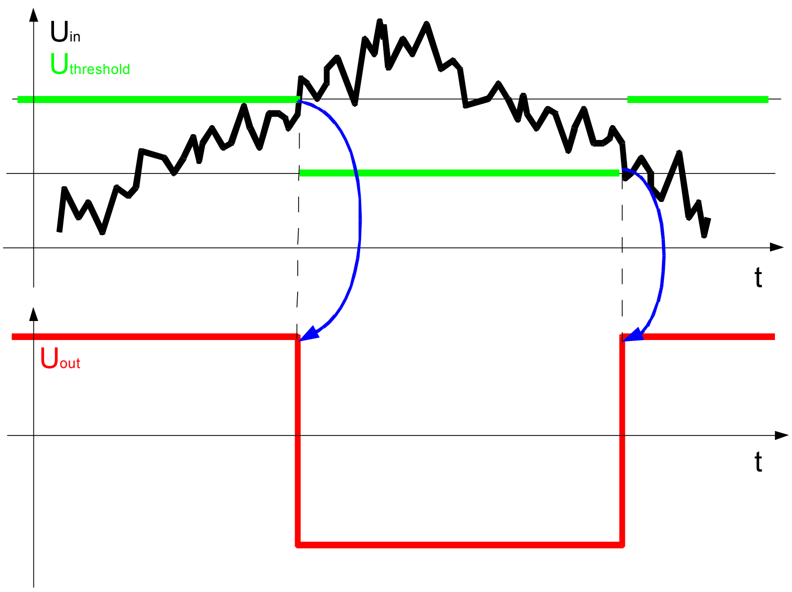


Figure 6.31 Inverting Schmitt trigger operation

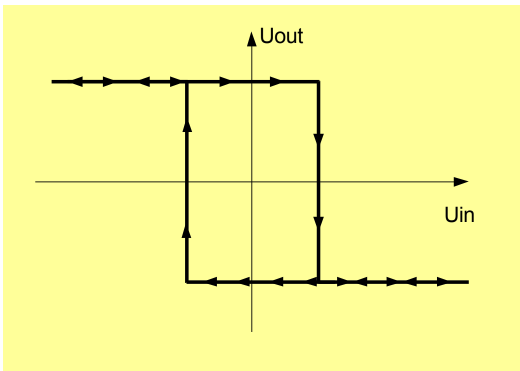


Figure 6.32 Inverting Schmitt trigger example operation curve

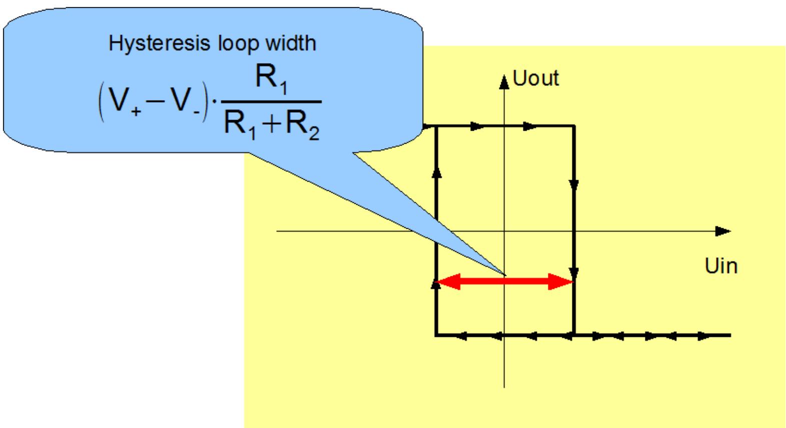


Figure 6.33 Hysteresis loop width - inverting Schmitt trigger

Non-inverting Schmitt trigger

A non-inverting version of the Schmitt trigger is shown on Figure 6.34, along with the operation example (Figure 6.35) and hysteresis curve (Figure 6.36 and Figure 6.37).

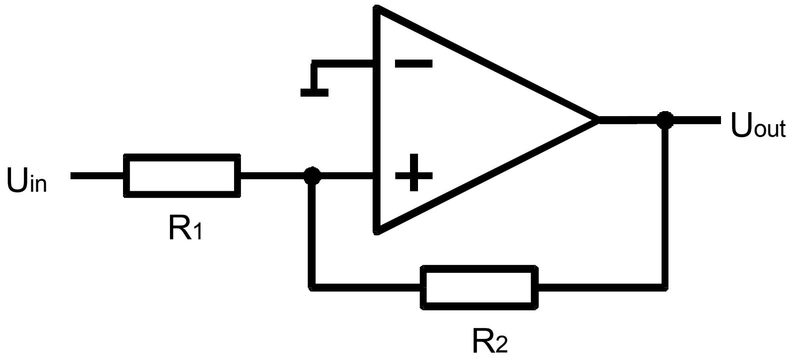


Figure 6.34 Non-inverting Schmitt trigger

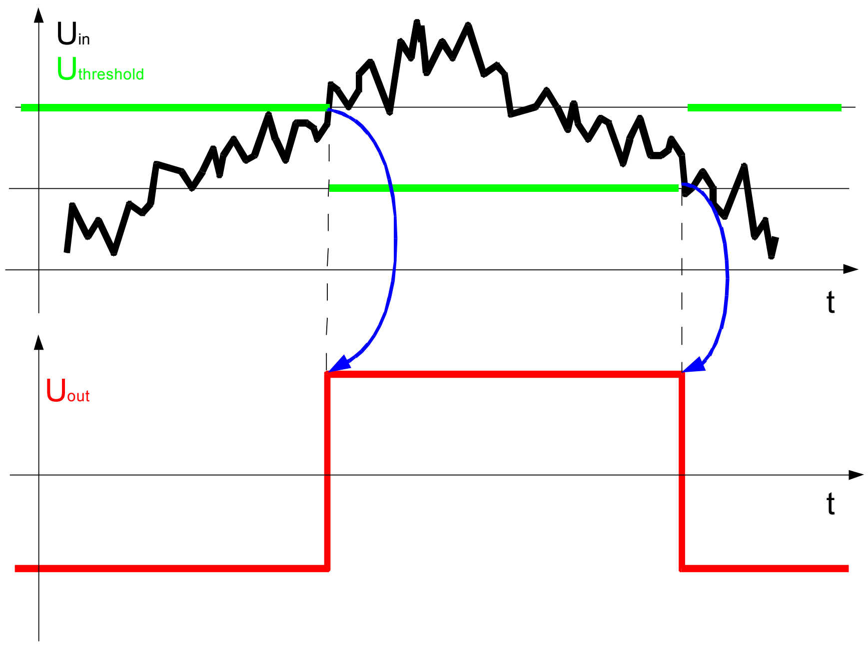


Figure 6.35Non-inverting Schmitt trigger operation

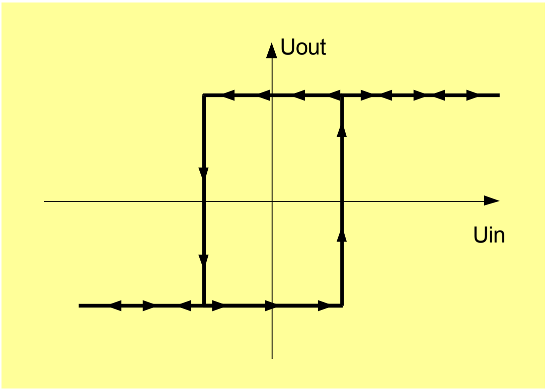


Figure 6.36 Non-inverting Schmitt trigger example operation curve

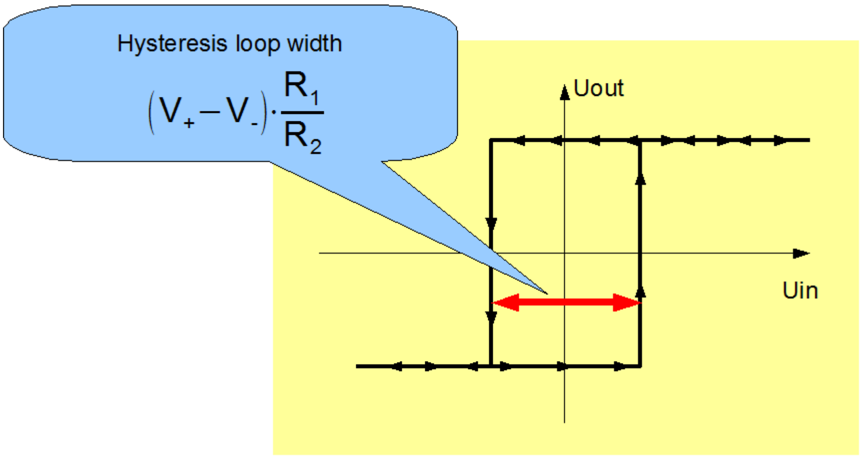


Figure 6.37 Hysteresis loop width - non-inverting Schmitt trigger

6.6.Inside the operational amplifier

A very simplified structure of operational amplifier is shown on Figure 6.38.

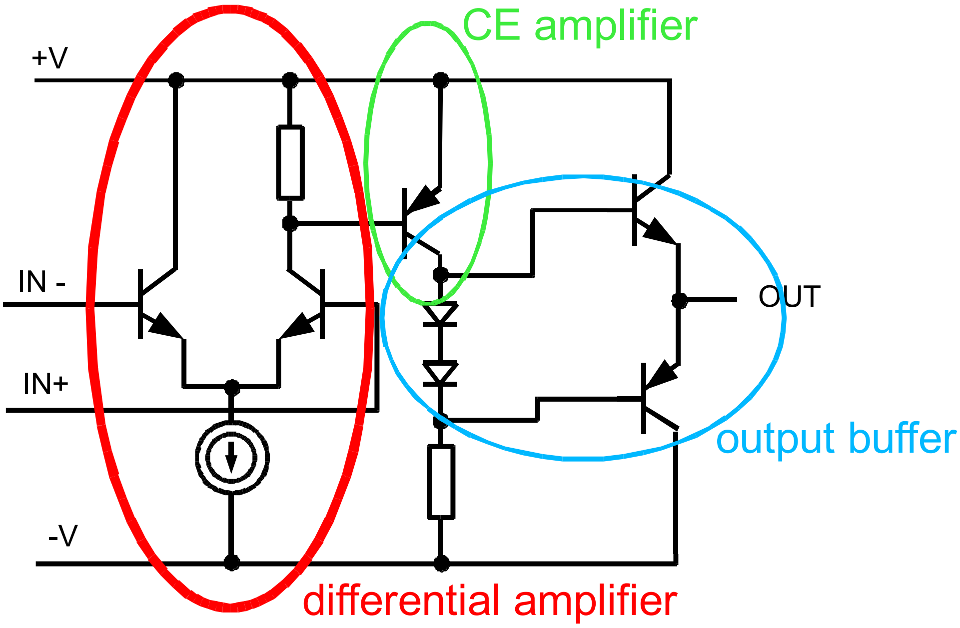


Figure 6.38 Simplified schematics of internal structure of an operational amplifier

Due to the need to ensure stability of the operational amplifier, often a capacitor is added, that limits the gain of the amplifier for higher frequencies.

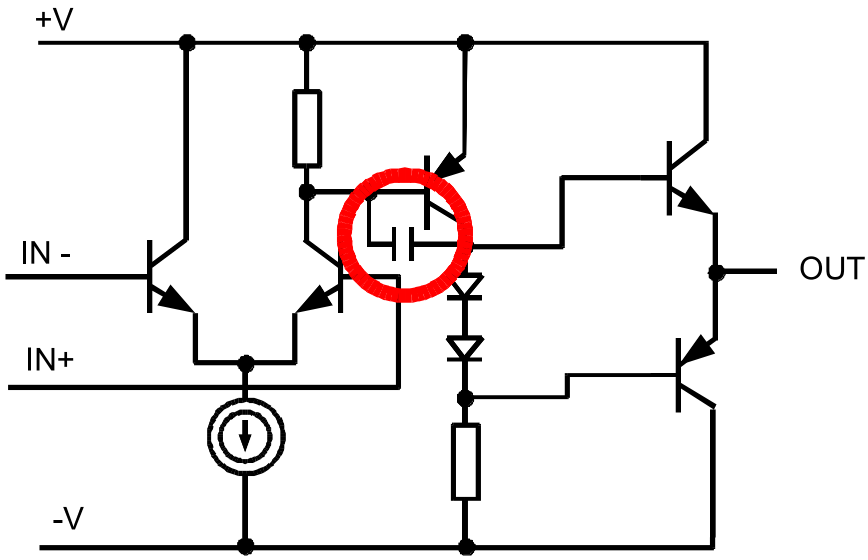


Figure 6.39 Frequency compensation of operational amplifier

The current source visible on the schematic is usually implemented as a current mirror. A current mirror circuit is shown on Figure 6.40 and its version with multiple outputs is shown on Figure 6.41. When the transistors have the same sizes and are held in the same temperature (those requirements can be easily met in integrated circuits), the input and output currents are the same, accurately to twice the base current value. More precise current mirrors are shown on Figure 6.42 and on Figure 6.43.

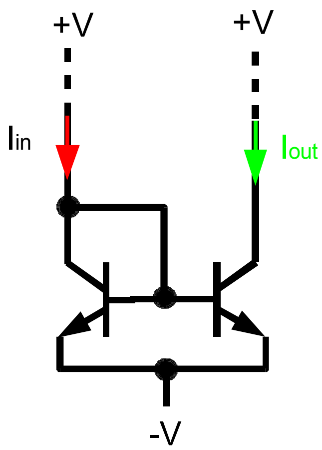


Figure 6.40 Simple current mirror

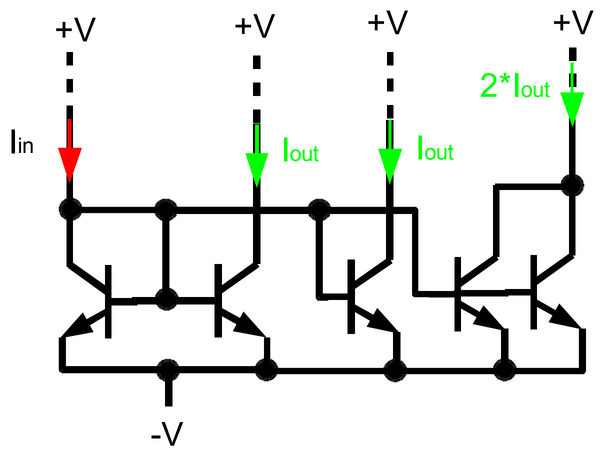


Figure 6.41 Multiple output current mirror

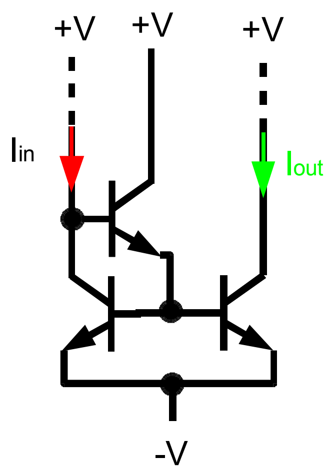


Figure 6.42 Current mirror with additional transistor improving symmetry

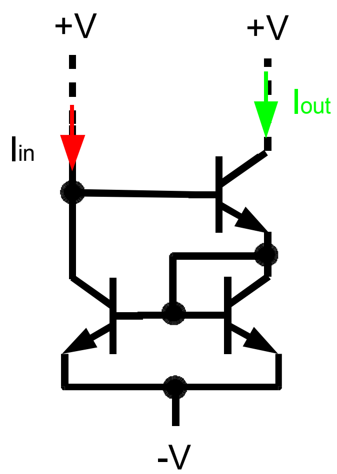
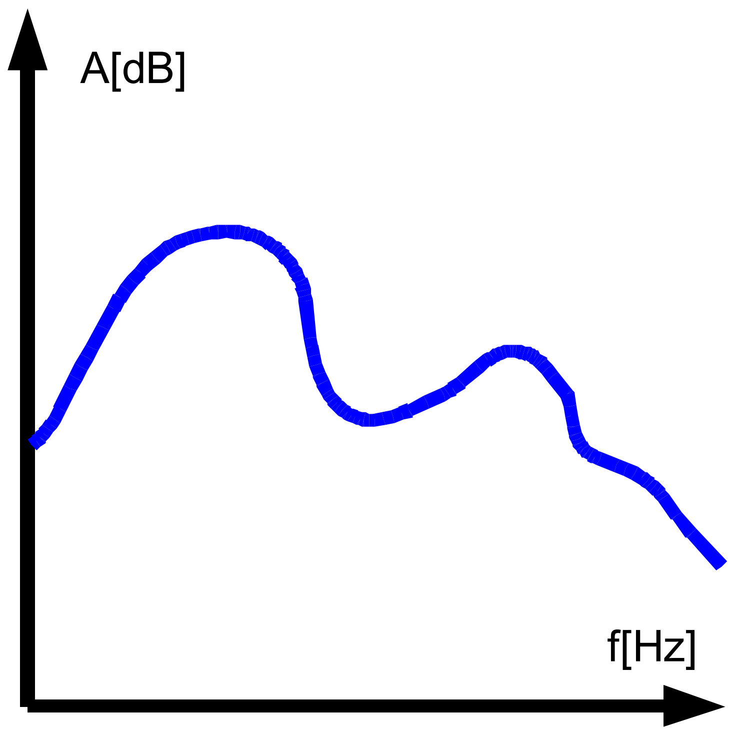


Figure 6.43 Current mirror with buffered output



7. Frequency characteristics

In chapters 4, 5 and 6 the properties of the amplifiers were considered to be independent from the frequency of input signal. In real circuits, however, the frequency of input signal has a large impact on the circuit operation. Not only does the gain of the amplifier change, but also the phase offset of output signal with respect to input signal changes with frequency. This chapter gives a brief introduction into the frequency properties of amplifiers.

7.1. Operational amplifier frequency behavior

The operational amplifier, as already stated, works for input signals of frequency range from 0Hz. The upper limit is, however, dependent on the given part properties. The open loop gain (the gain denoted as "k" in chapter 6) depends on the frequency, as shown on

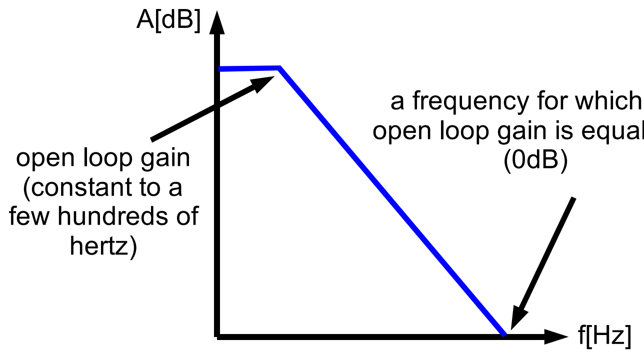


Figure 7.1 Open loop gain dependency on frequency

As it can be seen, without the negative feedback, the 3dB bandwidth of an operational amplifier is a mere few hundreds of hertz.

The frequency for which the open loop gain is equal to 1 is usually called in the datasheets a Gain-BandWidth Product (GBWP, GBW, sometimes only “bandwidth”). This is a very important value defining the capabilities of a given operational amplifier type.

This value is used to determine the bandwidth of an amplifier of a specific gain. It is so, that the product of gain and bandwidth is constant for a given operational amplifier type, as defined by the formula

$$f_T = k_{cl} \cdot f_{cl}$$

For a given circuit, a bandwidth may be determined using this formula. The idea of a gain-bandwidth product is shown, for a non-inverting amplifier, on Figure 7.2.

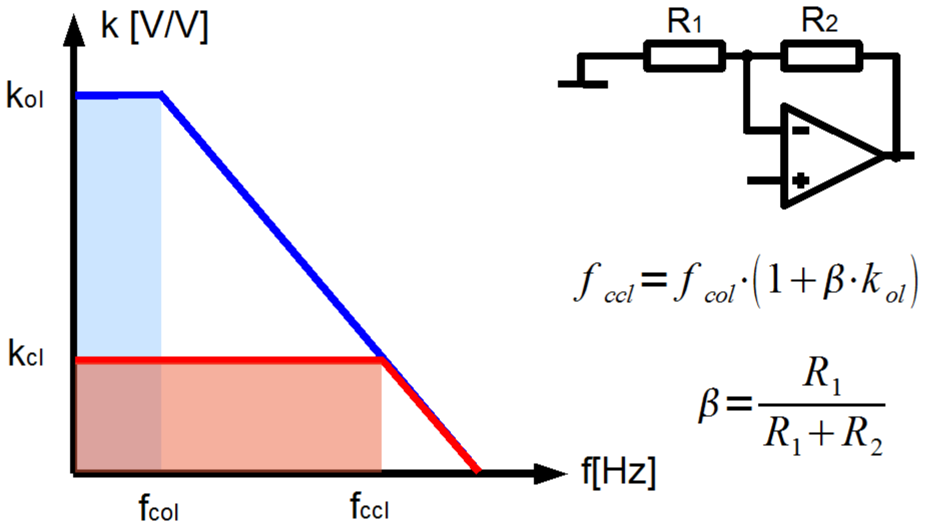


Figure 7.2 Gain-bandwidth product for an amplifier (ol = open loop, cl = closed loop)

Example

An amplifier with the GBW equal to 1MHz is used in an amplifier of a gain equal to 100 V/V. What is the bandwidth of such an amplifier?

1 000 000 / 100 = 10 000

Another important characteristic value of an operational amplifier is the slew rate – the fastest rate at which the voltage on the operational amplifier can change. This is important for amplifying fast changing signals, like impulses or high frequency signal. It is not directly connected with GBW, but also limits the range of frequencies of input signals that the amplifier can operate with. The importance of the slew rate value can be seen on Figure 7.3 where a step voltage is fed to the input of a voltage follower.

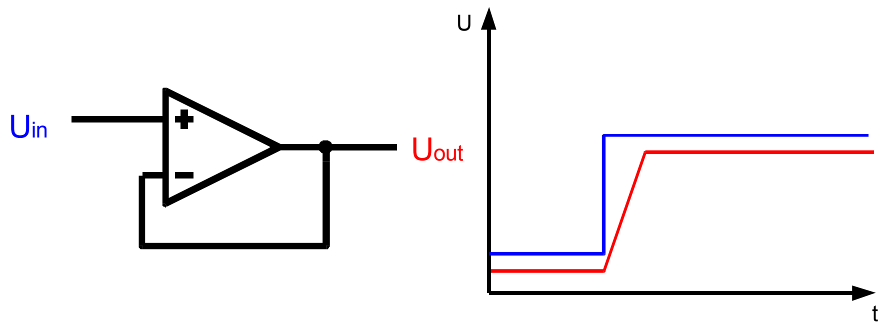


Figure 7.3 Operational amplifier output - slew rate limit. A slight offset of the signals is applied for clarity only.

Usually, the operational amplifier is built as a multi-stage amplifier. Each stage introduces its own gain, but also has a certain frequency characteristics. Usually the transmittance of a single stage can be modeled as a first order lowpass filter.

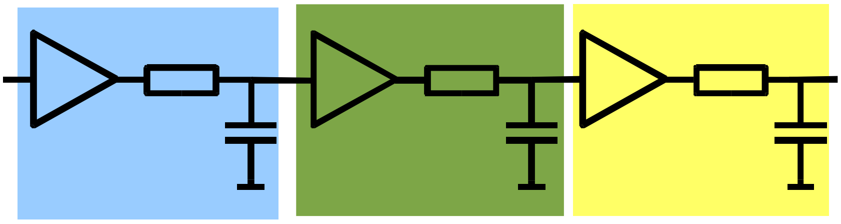


Figure 7.4 Multi stage amplifier

Each of the stages has an amplitude spectrum and a phase spectrum, as shown on Figure 7.5.

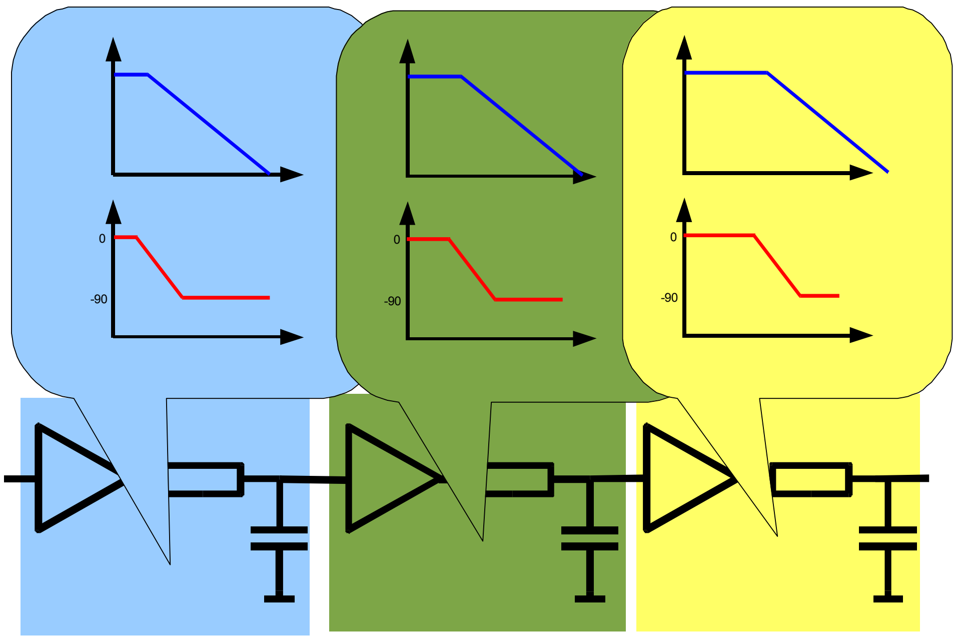


Figure 7.5 Multi stage amplifier frequency characteristics

The overall characteristics of the amplifier is a sum of characteristics of consecutive stages, as shown on Figure 7.6. The resulting characteristics is shown on Figure 7.7.

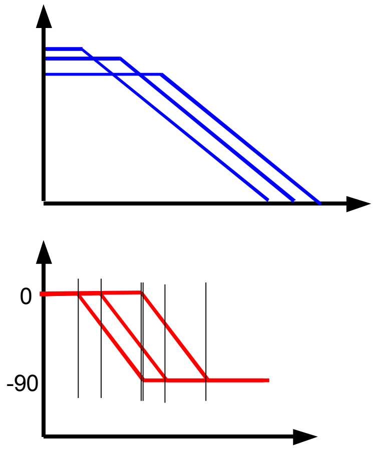


Figure 7.6 Frequency characteristics of consecutive stages

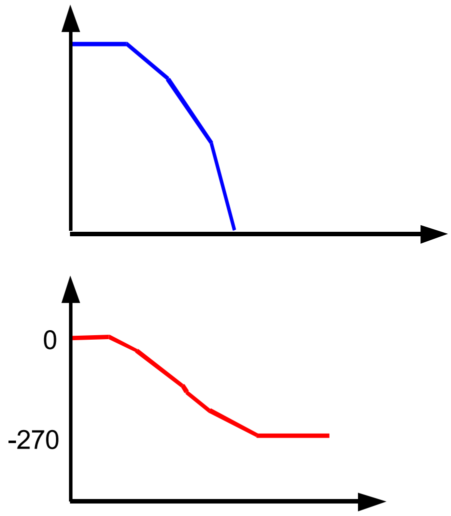


Figure 7.7 Frequency characteristics of a 3 stage amplifier

When the phase spectrum of the amplifier drops to -180 degrees for lower frequency than the amplitude spectrum drops below 0dB (as on Figure 7.8), the amplifier is unstable and a mean of stabilizing it has to be provided.

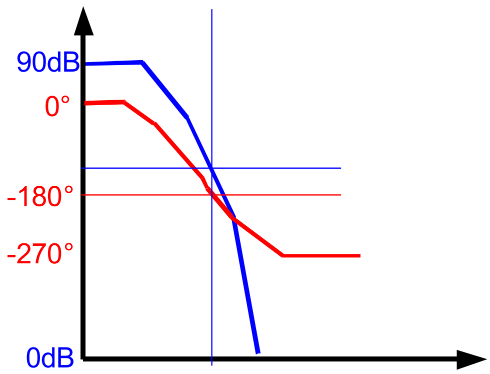


Figure 7.8 Uncompensated amplifier frequency response

The stabilization involves reducing the gain below 0dB for the frequencies above the one in question, and is usually done by introducing a negative feedback, like the capacitor on Figure 6.39. After compensation, the frequency response can be as shown on Figure 7.9.

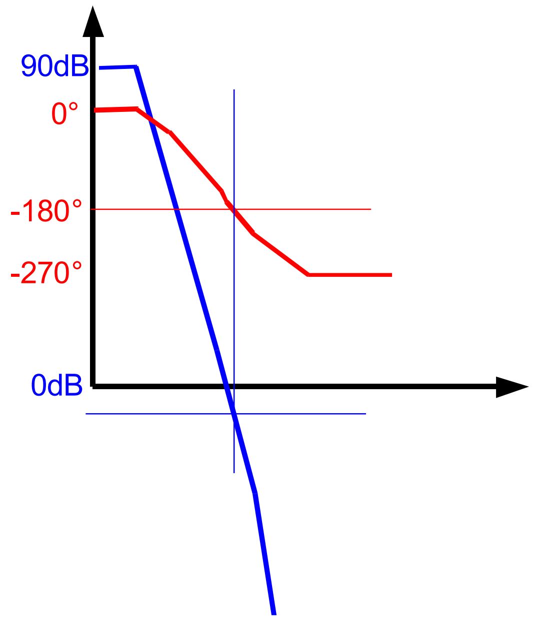


Figure 7.9 Compensated amplifier frequency response

7.2. Transistor amplifier frequency behavior

A transistor amplifier, discussed in chapters 4 and 5, also has a certain bandwidth. It is, however not only limited from the high frequency side, but also, due to its construction, from the low frequency side. Below the simple explanation of these limitations is given.

Let us consider the amplifier shown on Figure 7.10.

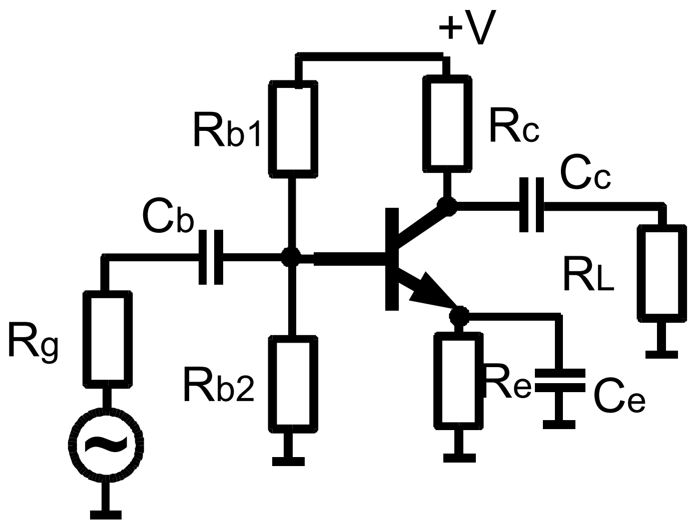


Figure 7.10 Transistor amplifier

The first source of frequency limitation is marked on . This is a first order highpass filter.

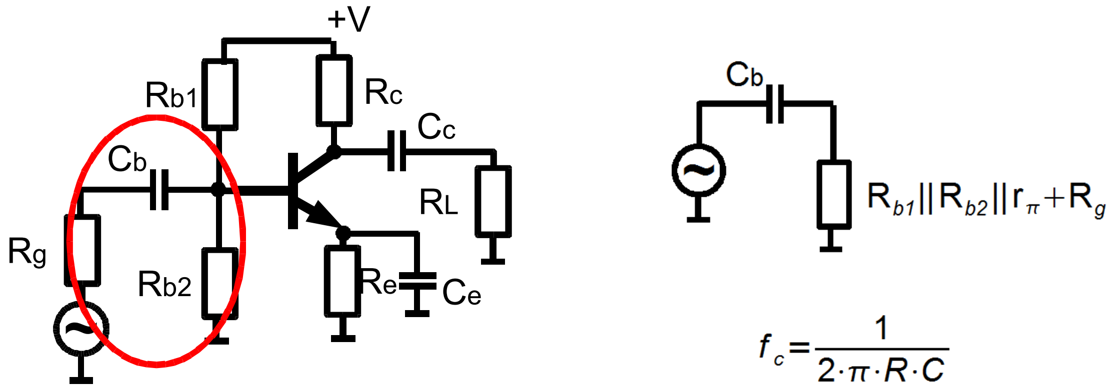


Figure 7.11 Input highpass filter

The next filter is marked on Figure 7.12. It is also a highpass filter.

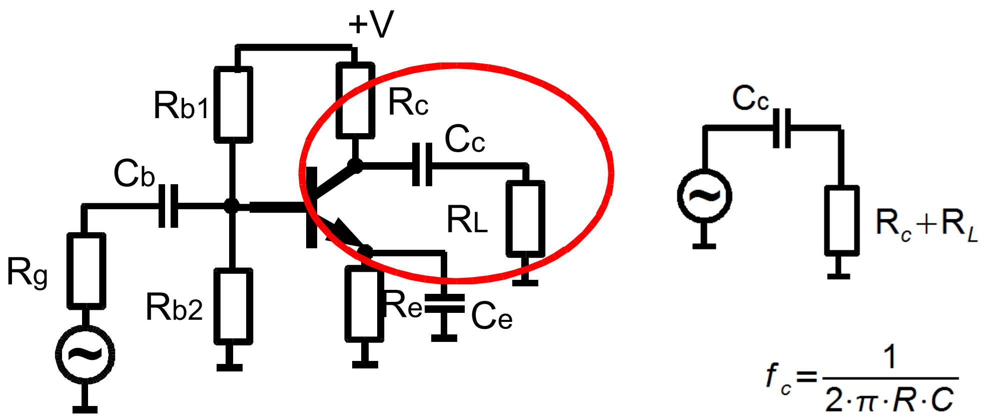


Figure 7.12 Output highpass filter

Another frequency limiting circuit is marked on Figure 7.13. This time, it is a lowpass circuit, but since it operates in a negative feedback of the amplifier, it limits the frequency behavior of the whole amplifier in a highpass way.

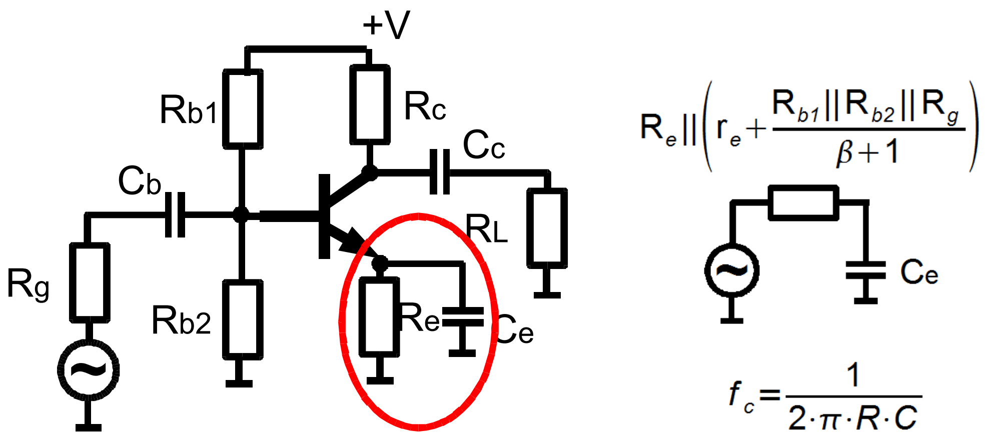


Figure 7.13 Emitter circuit frequency limit

So far all the three mentioned circuits make the overall frequency response of the amplifier from the side of low frequencies. The high frequency limit is imposed mainly by the internal parasitic components of the transistor. The simple model used in chapter 4 does not reflect the frequency dependent elements, therefore a need for a more precise model. A so called full hybrid-pi model is presented on Figure 7.14. The two components used in model from Figure 4.21 can be easily identified.

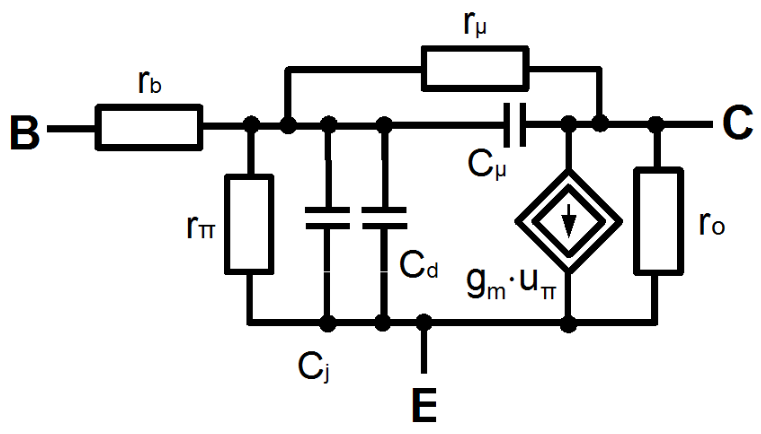


Figure 7.14 Full hybrid-pi bipolar transistor model

The capacitors present in the model impose limit on a high frequency operation, as will be shown further on. A simplified model will be used, as seen on Figure 7.15.

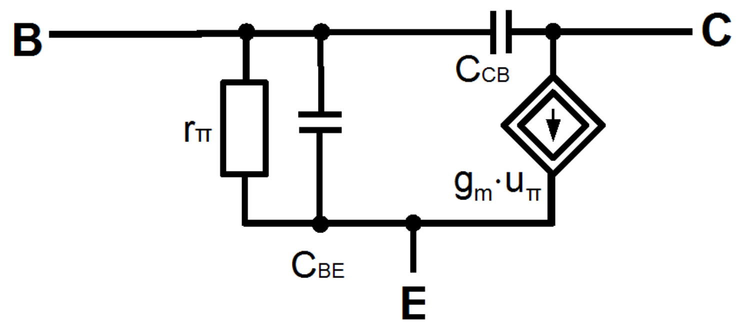


Figure 7.15 A simpler model of a transistor

For high frequencies, the 3 capacitors that are marked on Figure 7.11, Figure 7.12, Figure 7.13 can be replaced by short circuits, due to the fact that their capacitances are sufficiently high, resulting in a circuit shown on Figure 7.16.

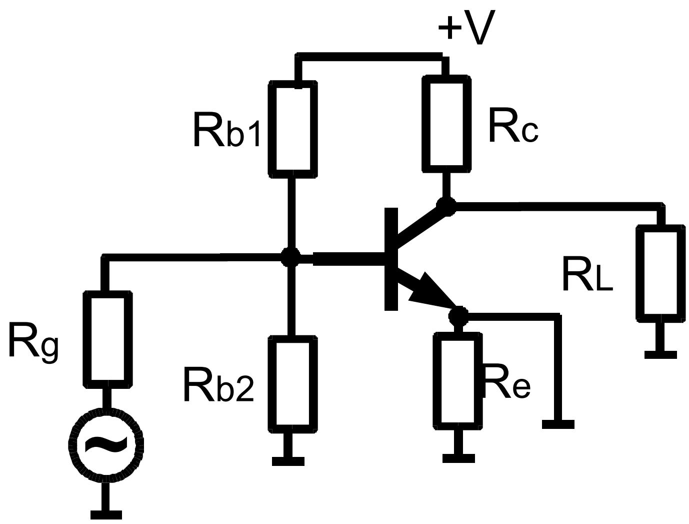


Figure 7.16 High frequency model of the transistor amplifier 1

Now let us insert the model from Figure 7.15 to the circuit from Figure 7.16 to form the Figure 7.17:

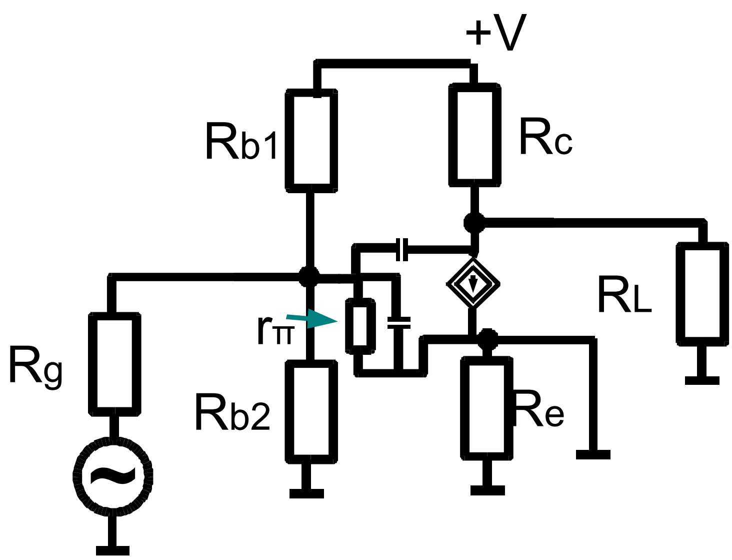


Figure 7.17 High frequency model of the transistor amplifier 2

Now let us consider the capacitor marked in red on Figure 7.18.

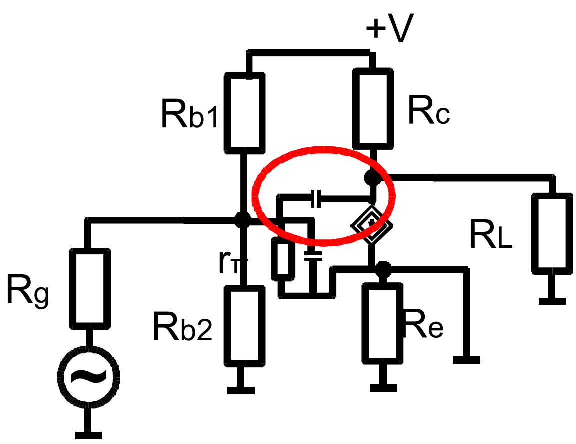


Figure 7.18 High frequency model of the transistor amplifier 3

This capacitor is forming a negative feedback. The Miller's theorem will be used to remove the feedback.

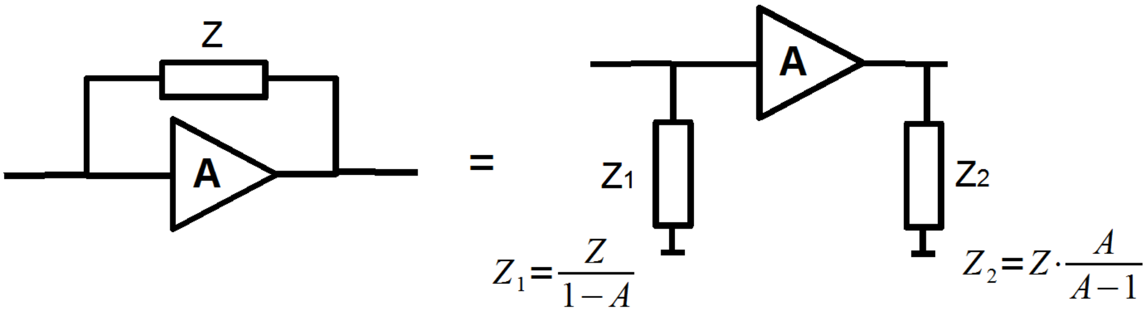


Figure 7.19 Miller's theorem

After applying the Miller's theorem, the resulting circuit is simpler to analyze. There are 2 capacitors that contribute to high frequency limit, by forming a lowpass filters. The first one is marked on Figure 7.20, the second on the Figure 7.21.

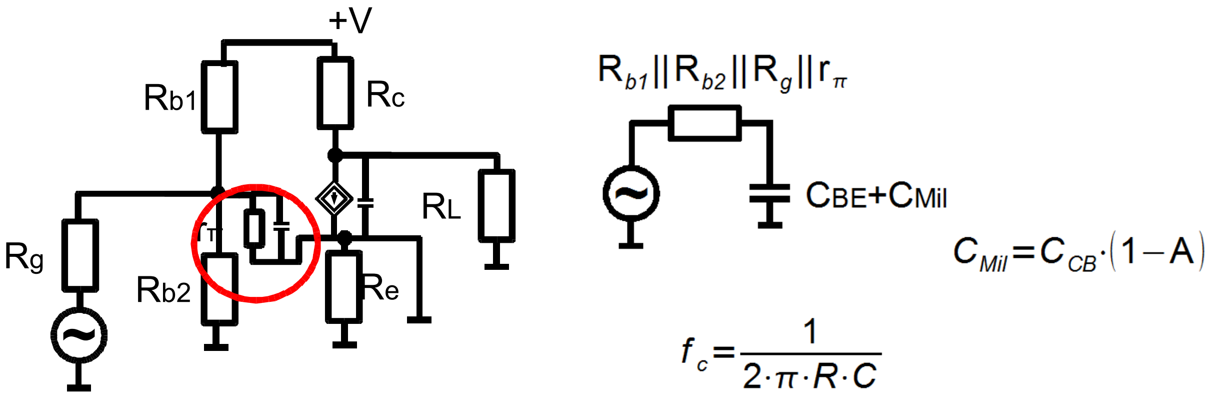


Figure 7.20 High frequency limit - base side

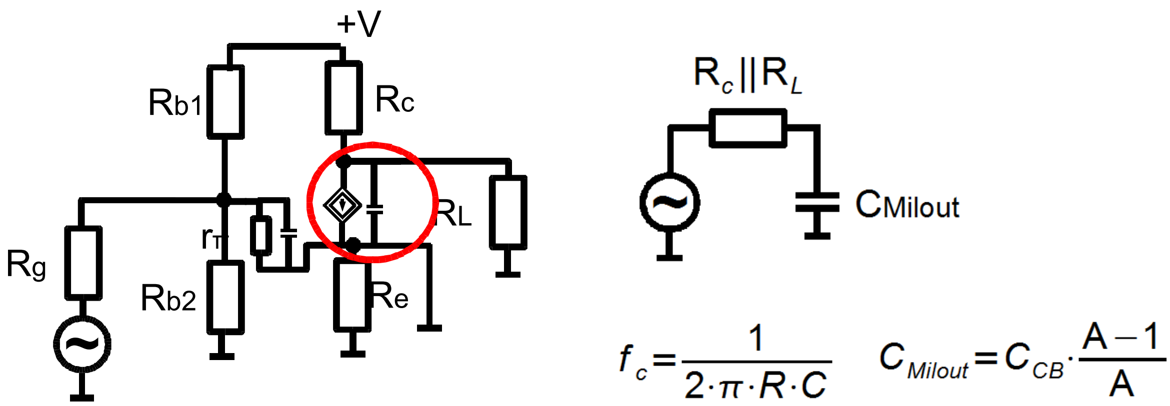


Figure 7.21 High frequency limit - collector side

When the 5 corner frequencies are marked on a single graph, the overall amplitude spectrum of the amplifier can be presented, as on Figure 7.22.

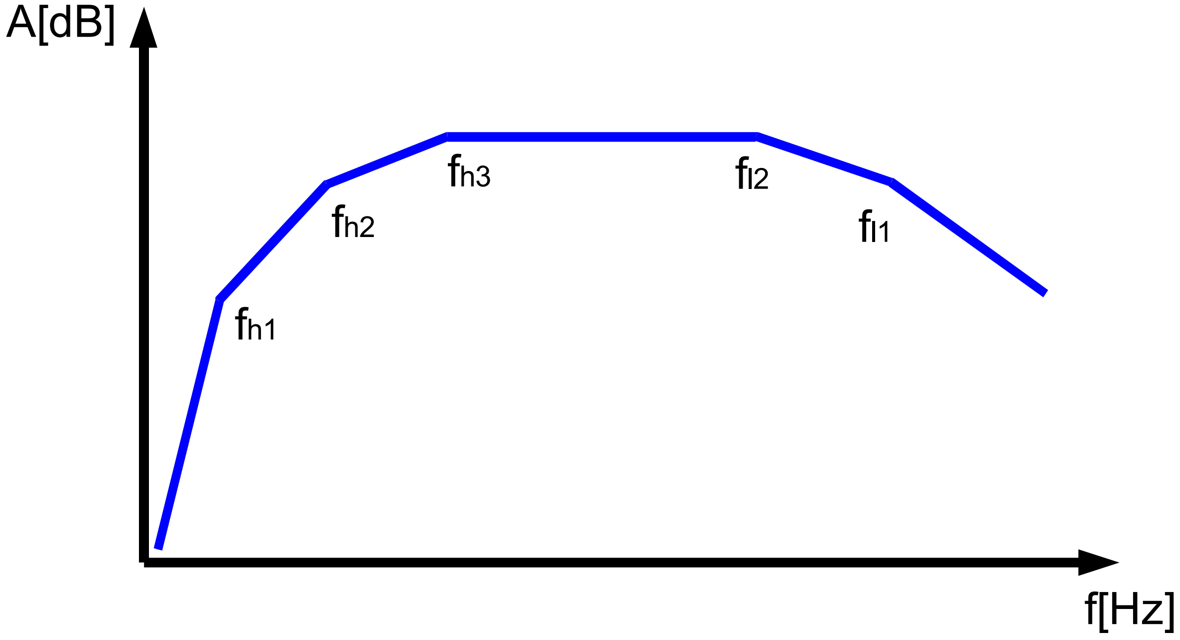


Figure 7.22 Frequency spectrum of a transistor amplifier