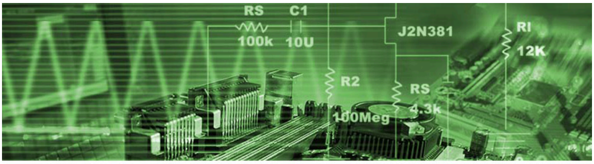
ELECTRONICS
DESIGN AND MANUFACTURING
SERIES

GUIDE TO ELECTRONIC COMPONENTS

(Part I)

Nanotech Elektronik is an EMS company with a wide range of services

- PCB Services
- SMT and THT assembly
- Electronic components
- BOM Services
- Prototypes
- Turnkey manufacturing



Our technological capabilities in the scope of assembly

Production and assembly of printed circuit boards	
Minimum order quantity	from 1 piece upwards
Maximum PCB size (X x Y)	automatic SMT assembly - 610 mm x 510 mm; THT assembly - no restrictions
Minimum PCB Size (X x Y)	automatic SMT assembly - 50 mm x 50 mm; THT assembly - no restrictions
SMD components assembly	
Component size range	from 0,4 mm x 0,2 mm (01005) to 45 mm x 100 mm
Component height (max)	15 mm
Types of components	Chips: 01005, 0201, 0402, 0603, 0805, 1206, 1210, 1812, 2010, 2225, 2512
	IC: PLCC18-PLCC84, LCC20-LCC84, SO, HSOP, SOJ18-SOJ44, MSOP8-MSOP10, SSOP8-SSOP64, HSOP20-HSOP44, TSSOP8-TSSOP80, TSOP28-TSOP56, TQFP32-TQFP176, LQFP32-LQFP256, QFP44-QFP304, CSP40-CSP56 (0,5), BGA46-BGA100 (0,75-0,8), LBGA48-LBGA280 (0,75-0,8), BGA81-BGA324 (1,0) up to LBGA1936 (1,0), BGA208(1,27) up to LBGA1225 (1,27), BGA169 (1,5) up to LBGA400, CBGA121 - CBGA1089
Assembly accuracy (X, Y)	50µm for chips 01005, 0201, 0402
	75µm for chips > 0402, SOIC
	30µm for QFPs

Product quality is assured by a multi-level control system at every stage of the production cycle. The manufactured product will fully comply with the provided technical requirements and standards of the international association of electronics manufacturers (Institute of Printed Circuits - IPC).

Contents

Part I

Part II (*comes as additional booklet*)

4. **Optoelectronic components**

   4.1 LED diodes
   4.2 Opto-isolators
   4.3 Displays
   4.4 Photoelements
   4.5 Other optoelectronic components

5. **Electromechanical elements**

   5.1 Connectors
   5.2 Relays
   5.3 Buttons and switches
   5.4 Wires and cables
   5.5 Other electromechanical elements

Contacts

Feel free to contact us if you have further questions. You will always obtain comprehensive information both in the scope of designing and producing printed circuit boards, as well as practical information specifying the product manufacture and delivery time. We are always happy to share our knowledge and experience, in addition to taking care of the highest quality the projects implemented by us, which can be confirmed by the line-up of our clients in the EU and worldwide.

We are always willing to prepare a detailed cost estimate for the production of printed circuit boards, purchase of electronic components, assembly works consisting in mounting components on PCBs and other additional works. Owing to this, you will be able to find out about the production cost of both the first prototype batch and the cost of serial production after sending us the technical documentation of the project.

You can also contact us by phone: **+48 338 338 338**
or write to the e-mail address: **office@nanotech-elektronik.com**
(we communicate in English, German and Polish).

Sincerely,
The Team of Nanotech Elektronik Sp. z o.o.

1. Basic information about electronic components

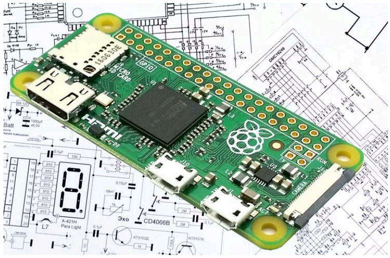
An electronic component (electronic part) is a part of an electronic device that performs a specific function and has a separate packaging.

An electronic circuit (electronic device) is a set of components (electronic components, connecting elements, mechanical elements) connected according to a circuit diagram in a way enabling them to carry out a specific task by manipulating electrical signals and their parameters, such as current, voltage, frequency, etc.

A circuit diagram (schematics) is a drawing containing graphic symbols of electronic components and the connections between them.

Within an electronic circuit, individual electronic components are connecting elements, usually appearing as wires and copper conductors (traces) on a printed circuit board.

A printed circuit board (PCB) is a rigid (or less commonly flexible) dielectric substrate with electrical connections (conductive traces and metallised holes, known as vias) and pads (the exposed region of metal on a circuit board to which the leads of the components are soldered).



1.1 Classification of electronic components

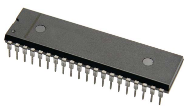
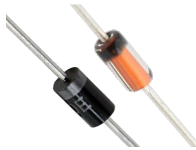
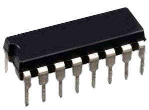
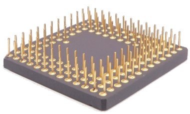
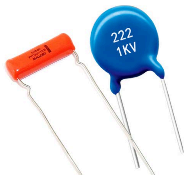
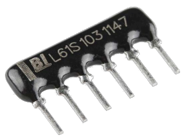
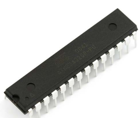
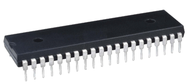
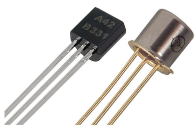
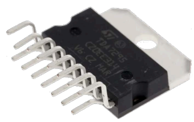
The most common electronic components can be classified into three main categories:

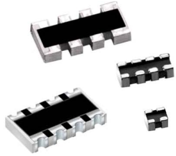
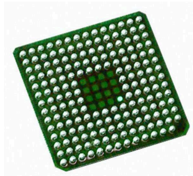
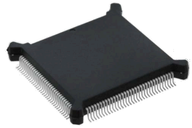
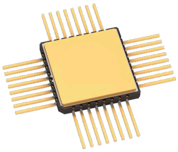
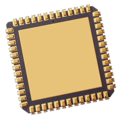
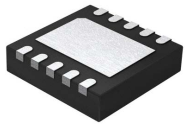
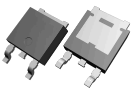
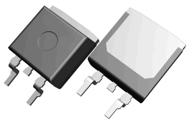
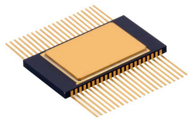
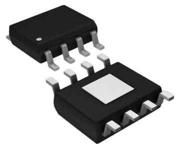
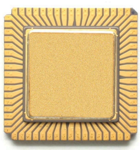
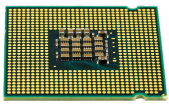
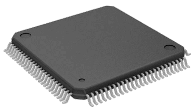
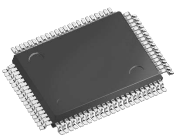
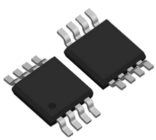
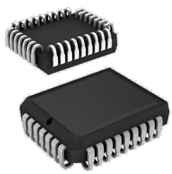
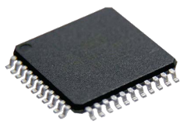
- **Active components** - elements of an electric circuit which can amplify electrical signals, control voltage, current, and switch signals in the presence of an energy source. The current-voltage characteristic of the active element is non-linear. Examples: diodes, transistors, integrated circuits.
- **Passive components** - elements that cannot amplify signals in an electrical circuit. Some passive elements can store energy, but in each passive element there occur energy losses (to varying degrees). The current-voltage characteristic of a passive element is linear. Examples: resistors, capacitors, inductors, transformers.
- **Electromechanical components** - mechanical components that control or transmit electrical signals in one or more electronic or electrical devices. Electromechanical components may have moving parts. Examples: connectors, relays, buttons, cables, wires.

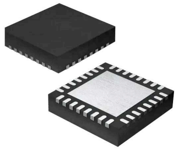
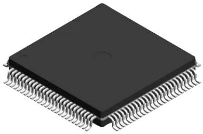
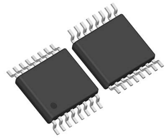
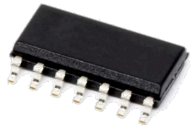
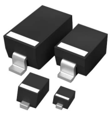
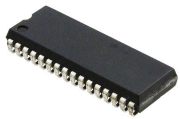
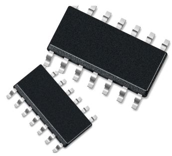
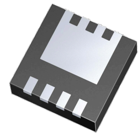
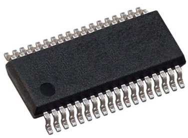
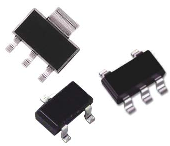
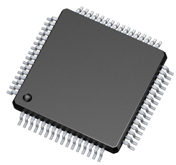
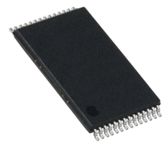
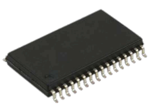
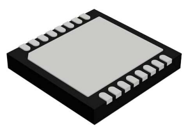
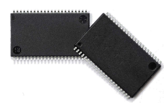
All components from those categories can be classified into additional two groups, according to the method of mounting: through hole or THT components (THT - Through Hole / Through Hole Technology) and SMD components (SMD or SMT - Surface Mount Device / Surface Mount Technology). The difference is such that in order to mount THT components on a PCB, holes are required in which the component leads are soldered, while SMD components are soldered directly to the flat pads on the PCB surface.

Some components may appear in mixed technology - THT+SMD, for example the following connectors:

1.2 Types of electronic component packaging

THT component packages			
Axial	**CERDIP, CDIP** - Ceramic Dual In-line Package	**DIL, dip** - Dual-In-line Package	**DO** - Diode Outline
			
PDIP – Plastic Dual-In-line Package	**PGA** - Pin Grid Array	**Radial**	**SIL, SIP** - Single In-line Package
			
SDIP - Skinny Dual In-line Package	**SPDIP** - Shrink Plastic Dual-In-line Package	**TO** - Transistor Outline	**ZIP** - Zig-zag In-line package
			

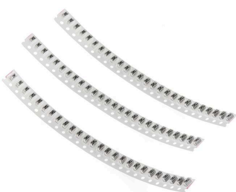
Packages of SMD components			
Chip - Capacitors, Resistors, Inductors	**Chip Array** - Multi Elements	**BGA** * - Ball Grid Array	**BQFP** - Bumper Quad Flat Pack
			
CQFP - Ceramic Quad Flat Pack	**CLCC** - Ceramic Leaded Chip Carrier	**CSP** - Chip Scale Package	**DFN** - Dual Flat No Lead
			
DPAK - Device Package	**D2PAK** - Device Squared Package	**FP** - Flat Pack, Dual Side	**HSOP** – Heatsink Small Outline Package
			
LCC - Leadless Chip Carrier	**LGA** - Land Grid Array	**LQFP** - 1.4mm Low Quad Flat Pack	**MELF, MiniMELF, MicroMELF** - Metal electrode leadless face
			
MQFP - Metric Quad Flat Pack	**MSOP** - Mini Small Outline Package	**PLCC** - J-Lead Plastic Leaded Chip Carrier	**PQFP, QFP** - Plastic Quad Flat Pack
			

QFN - Quad Flat No Lead	**QFP** - Quad Flat Pack	**QSOP** - Quarter Small Outline Package	**SO, SOIC, SOP** - Small Outline IC
			
SOD - Small Outline Diode	**SOJ** - Small Outline J-Lead	**SOL, SOM** - Small Outline Large / Small Outline Medium	**SON** - Small Outline Non-leaded package
			
SSOP - Shrink Small Outline Package	**SOT** - Small Outline Transistor	**TQFP** - 1.0mm Thin Quad Flat Pack	**TSOP** - Thin small-outline package
			
TSSOP - Thin Shrink Small Outline Package	**WLCSP** - Wafer Level Chip Scale Package	**VSON** - Very-thin Small Outline Non-leaded package	**VSOP** - Very Small Outline Package
			

* *You can find out more about BGA components in our booklet **"PCB Layout Recommendations for BGA packages"**, which you can download from our website or get a free printed copy by contacting our office directly.*

1.3 Packaging and shipping methods for electronic components

Electronic components shipped to the customer are usually packed in the following ways:

<table>
<tr><td rowspan="2">Factory packaging, suitable for automated assembly</td><td>Tube, Rail, Stick</td><td>Tray</td><td>Tape and Reel</td></tr>
<tr><td></td><td></td><td>
</td></tr>
<tr><td rowspan="2">Factory packaging, suitable for automated assembly</td><td>Cut Reel
Custom reel with start and ending sections</td><td>Cut Tape
Cut tape with ending sections (sections without elements at the ends, at least 10-15 cm long)</td><td>Ammo Pack
Tape and Box
Tape placed in a box</td></tr>
<tr><td></td><td></td><td></td></tr>
<tr><td rowspan="2">Non-factory packaging, not suitable for automated assembly</td><td>Cut Tape
Too short cut tapes, without ending sections (sections without elements at the ends)</td><td>Packed in individual packages (e.g., foil bags)</td><td>Bulk
Packed together in one package</td></tr>
<tr><td></td><td>
</td><td>
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</table>

While ordering electronic components, it is advisable to check in advance what packaging options are available from suppliers. It is important in terms of the suitability of the ordered elements for assembly on automatic lines. It is also an additional security in the case of first orders from unknown suppliers.

For example, if the supplier of components sends them in non-factory packaging when ordering larger quantities, it may be a signal of their suspicious origin (remains from different batches, elements refurbished or rejected after tests, etc.).

Depending on the dimensions (packages) of the components, the factory packaging may contain different standard quantities of components. For example, the reel of 0603 resistors contains 5,000 pcs of resistors as standard, while the reel of 0402 or 0201 resistors - 10,000 pcs. If the components are ordered in quantities that differ from the factory quantities, they will most often be delivered in the form of cut tapes (with ending sections charged extra) or non-standard reels (with end and initial sections also charged extra).

The ending sections without elements are important with regard to automated assembly (they are needed for the correct fastening of the tape in the assembling machines). The requirements for the length of such end sections may differ in various assembly plants, while the average is 10-15 cm.

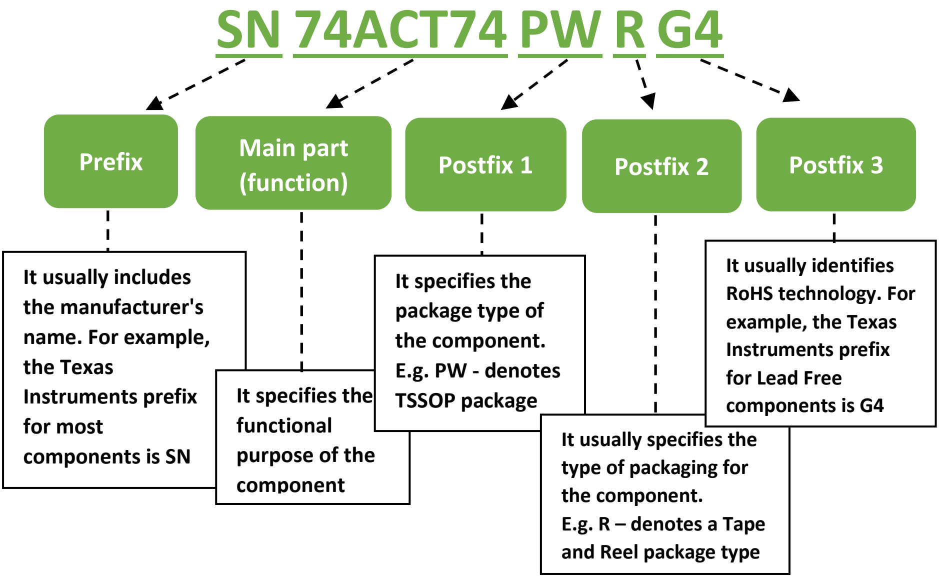
The bad news is that suppliers usually charge for ending section preparation, or sometimes they do not even offer this option at all. In this case, it is possible to consider ordering a greater quantity of elements (if they are cheap) than required for the assembly, and some of these elements will be lost in the sections used to fasten tapes in machines. One should take into account the fact that the assembly plant will have to prepare end sections on its own (there are materials and tools for this), which involves additional costs.

Knowledge of packaging types is also useful when identifying the names of components from different manufacturers, because Part Numbers often contain affixes in which packaging options are coded. You can find more about this topic in the next chapter.

1.4 Structure of component names (Part Number)

When selecting and purchasing electronic components, the main criterion for identification is the manufacturer's catalogue name (Part Number), whose structure depends on the type of component. Unfortunately, there is no unified standard for catalogue names, so various manufacturers have their own approach to its creation.

In most cases, the catalogue name consists of a prefix, main part, postfixes (using the example of a component from the manufacturer Texas Instruments):



Examples of prefixes in catalogue names

Manufacturer	Prefix
Advanced Micro Devices	AM
Altera	EP
Analog devices	AD
Atmel	AT
Cypress Semiconductor	CY
Dallas Semiconductor	DS
Fairchild Semiconductor	UA
Hitachi	HA, HD
Infineon	PEB
Intel	TN
International Rectifier	IR
Intersil	ISL
ISSI	IS
Linear Technology	LT, LTC

Manufacturer	Prefix
Maxim Integrated	MAX
Microchip	PIC
Micron	MT, IT
Motorola	MC
National Semiconductor	LM, DM
NXP Semiconductors	NE, TDA
ON Semiconductor	MC, N
Philips	HEF
Renesas Technology	HM
ST Microelectronics	ST
Taiwan Semiconductor	TS
Texas Instruments	LM, SN
Toshiba	TC
Xilinx	XC, XA

Examples of postfixes defining the type of package

Manufacturer	Package DIP type	Package SOIC type	Package TSSOP type
Analog devices	N	R, RW	RU
Fairchild Semiconductor	N	M, WM	MTC
Intersil	P	B	V
Linear Technology	N, N8	S, SW	F, FW
Maxim Integrated	P	S	U
Microchip	P	SN, SL	ST
NXP Semiconductors	N	0	PW
ON Semiconductor	N	D, DW	DT
Renesas Technology	P	RP	T
ST Microelectronics	N / B	D, M	P, DW
Texas Instruments	N	D, DW	PW
Toshiba	P	FN, FW	FT

Examples of postfixes defining the packaging type

Manufacturer	Postfix	Packaging type
Analog devices	Reel, Reel 7	Tape & Reel
Atmel	T	Tape & Reel
Fairchild Semiconductor	X	Tape & Reel
Intersil	TR	Tape & Reel
Linear Technology	TR	Tape & Reel
Maxim Integrated	T	Tape & Reel
National Semiconductor	X	Tape & Reel
NXP Semiconductor	115, 118, 135	Tape & Reel
	133, 143	Tape & Box
	112	Tube
ON Semiconductor	R2, T1, T3, T4	Tape & Reel
ST Microelectronics	RM13TR	Tape & Reel
Texas Instruments	R	Tape & Reel
Vishay	GS08	Tape & Reel 7”
	GS18	Tape & Reel 13”
	TR	Tape & Reel (TH)

Prefix examples for lead free technology (RoHS Lead Free)

Manufacturer	Prefix
Altera	**N**
Analog devices	**Z**
Cypress Semiconductor	**X**
Fairchild Semiconductor	**NL**
Infineon	**G**
International Rectifier	**PBF**
Intersil	**Z**

Manufacturer	Prefix
Linear Technology	**PBF**
Maxim Integrated	**+**
National Semiconductor	**NOPB**
ON Semiconductor	**G**
Texas Instruments	**E4, G4**
Toshiba	**G**
Vishay	**E3, GE3**

1.5 Pro-electron / EECA, JEDEC, JIS standards for naming components and their packages

There exist thousands of different types of diodes, bipolar and field effect transistors. These devices have different parameters depending on the materials and technologies used. To avoid confusion in the variety of these components, several standards have been created which apply to the naming of semiconductor components.

In fact, there exist several standards for semiconductor numbering (schemes):

- **EECA/PRO ELECTRON (EU)** - This is numbering scheme for diodes, bipolar transistors and FETs was created in Europe and it is widely used for semiconductors manufactured in the EU.

- **JEDEC (USA)** - this numbering scheme is widely used for diodes and transistors from North America.

- **JIS (Japan)** - this system for numbering semiconductor devices applies to semiconductors from Japan.

- **Original manufacturer's scheme** - there are some devices, especially specialised bipolar transistors and some FETs, for which manufacturers may want to reserve production rights. In these and similar cases, manufacturers will use their own numbering schemes which do not conform to industry standard schemes and therefore do not disclose specifications and production methods.

Below we show how the names of semiconductor elements are created according to each standard:

EECA/PRO ELECTRON (UE)

<letter> <letter> <letter> <serial number>[suffix]

The marking consists of four elements:

- The first element is a letter which indicates the type of semiconductor material used in the device:
  - A - Germanium;
  - B - Silicon;
  - C - Gallium Arsenide;
  - R - Other semiconductor materials;
- The second element is a letter specifying the type of semiconductor device:
  - A - Low-power and universal pulse diodes;
  - B – Varicap diodes;
  - C – AF (Audio frequency) low power transistors;
  - D - AF power transistors;
  - E - Tunnel diodes;
  - F - HF (High frequency) low-power transistors;
  - G - Special-purpose devices and complex devices containing several different elements in one package;
  - H - Magnetic sensitive diodes;
  - K - Hall-effect modulators;
  - L - HF power transistors;
  - N - Optocouplers;
  - P - Light-sensitive devices (photodiodes, phototransistors, etc.)
  - Q - Light emitting devices (LEDs, IR LEDs, etc.);
  - R - Low-power switching devices - thyristors (SCR or Triac);
  - S - Low-power switching transistors;
  - T - High-power switching devices - thyristors (SCR or Triac);
  - U - Switching power transistors;
  - X - Multiplication diodes;
  - Y - High power rectifier diodes;
  - Z - Zener diodes, TVS diodes
- The third element is a letter which appears only for special purpose devices (industrial, professional, military, etc.). Usually the letters "Z", "Y", "X" or "W" are used. This element does not appear in the markings of general-purpose devices.

- The fourth element is a two-, three- or four-digit serial number of the device. If the number contains two digits (e.g., BCV26): the product is usually used in industrial or professional equipment. If the product number contains three digits (e.g., BF194): this device is usually used in consumer equipment (e.g., entertainment, etc.)

Additional elements may also be included in the markings of some semiconductors. For example, a suffix denoting division of devices of the same type into different versions by parameters.

In this case, an additional code is added to the main notation (it can also be a hyphen or a fraction).

In the case of transistors, the following additional codes may be used: A – low gain factor, B – medium, C – high.

Using the numbering scheme, it can be concluded that the transistor bearing number BC107 is a low power silicone audio transistor, while the BC847C is a low power silicone audio transistor with high gain.

In the case of components such as Zener diodes, an additional code is often used containing information about the stabilization voltage and its tolerance ("A" - 1%, "B" - 2%, "C" - 5%, "D" - 10%, "E" - 15%). If the stabilization voltage is not an integer number, then the letter V is placed instead of a decimal point. In the additional code for rectifier diodes, the maximum value of the reverse voltage will be indicated.

For example, BZY88C4V7 is a special silicon Zener diode with registration number 88, stabilization voltage of 4.7 V with a maximum deviation of this voltage of ± 5% from the rated value.

JEDEC (USA)

<digit> <letter> <serial number> [suffix]

- The first digit is used to identify the type of semiconductors – 1 for diodes, 2 for BJT transistors, 3 for FET transistors, 4 for optocouplers.
- The letter - always the letter "N".
- The serial number is a two-, three-, or four-digit number which mirrors the sequential registration number of a semiconductor component in the EIA.
- Suffix - indicates the division of components of the same type into different versions according to typical parameters. The suffix may consist of one or more letters.

For example: 1N4148 – silicon diode; 1N4001-1N4007 - silicon rectifier diode up to 1A; 2N2222A – transistor; 4N25 – optocoupler.

JIS (Japan, Asia)

<digit> <S> <letter> <serial number><letter>[suffix]

- The first element is a digit representing the number of p-n junctions in the element (0 - photodiodes; 1 - diodes, 2 - BJT or FET transistors, 3 - dual gate FET transistors).
- The second element is the letter "S" denoting semiconductor elements
- The third element is a letter denoting the type of semiconductor element:
  - A - PNP HF (High frequency) transistors;
  - B - PNP AF (Audio frequency) transistors;
  - C - NPN HF transistors
  - D - NPN AF transistors
  - E – Diodes;
  - F - Thyristors (SCR);
  - G - Gunn diodes, tunnel diodes;
  - H - UJT (Unijunction) transistors;
  - J - JFET / MOSFET transistors with P-channel;
  - K - JFET / MOSFET transistors with N-channel
  - M - Triac
  - Q - LED diodes
  - R - Rectifier diodes
  - S - Signal diodes
  - T - Avalanche diodes
  - V - Varicap diodes
  - Z - Zener Diodes
- The fourth element is the serial number (registration number) of the component.
- Fifth element - component modification ("A" - first, "B" - second, etc.).
- The standard designation may be followed by an additional suffix ("N", "M", "S") to reflect some special component properties.

Even though there exist industry standards for generating names of semiconductor components, some manufacturers still have their own name coding systems:

- MJ – Motorola, power devices, metal package
- MJE – Motorola, power devices, plastic package
- MPS – Motorola, low-power devices, plastic package
- MRF - Motorola RF transistor
- TIP - Texas Instruments, power transistors, plastic package
- TIS - Texas Instruments, low power transistors, plastic package

1.6 E series of preferred numbers for resistance and capacitance values

The nominal values of most industrially manufactured electronic components (resistance of resistors, capacitance of capacitors, inductance of small inductor coils) are not arbitrary, but will follow the so-called number series, denoted as E6, E12, E24, E48, E96 and E192. The number next to the letter E denotes the number of variants of nominal values per one decade. In addition, each series corresponds to a specific tolerance in the rated values of components:

E6	20%	1.0	-	1.5	-	2.2	-	3.3	-	4.7	-	6.8	-
E12	10%	1.0	1.2	1.5	1.8	2.2	2.7	3.3	3.9	4.7	5.6	6.8	8.2
E24	5%	1.0	1.1	1.2	1.3	1.5	1.6	1.8	2.0	2.2	2.4	2.7	3.0
		3.3	3.6	3.9	4.3	4.7	5.1	5.6	6.2	6.8	7.5	8.2	9.6
E48	2%	1.00	1.05	1.10	1.15	1.21	1.27	1.33	1.40	1.47	1.54	1.62	1.69
		1.78	1.87	1.96	2.05	2.15	2.26	2.37	2.49	2.61	2.74	2.87	3.01
		3.16	3.32	3.48	3.65	3.83	4.02	4.22	4.42	4.64	4.87	5.11	5.36
		5.62	5.90	6.19	6.49	6.81	7.15	7.50	7.87	8.25	8.66	9.09	9.53
E96	1%	1.00	1.02	1.05	1.07	1.10	1.13	1.15	1.18	1.21	1.24	1.27	1.30
		1.33	1.37	1.40	1.43	1.47	1.50	1.54	1.58	1.62	1.65	1.69	1.74
		1.78	1.82	1.87	1.91	1.96	2.00	2.05	2.10	2.15	2.21	2.26	2.32
		2.37	2.43	2.49	2.55	2.61	2.67	2.74	2.80	2.87	2.94	3.01	3.09
		3.16	3.24	3.32	3.40	3.48	3.57	3.65	3.74	3.83	3.92	4.02	4.12
		4.22	4.32	4.42	4.53	4.64	4.75	4.87	4.99	5.11	5.23	5.36	5.49
		5.62	5.76	5.90	6.04	6.19	6.34	6.49	6.65	6.81	6.98	7.15	7.32
		7.50	7.68	7.87	8.06	8.25	8.45	8.66	8.87	9.09	9.31	9.53	9.76
E192	0,5% 0.25% 0.1%	1.00	1.01	1.02	1.04	1.05	1.06	1.07	1.09	1.10	1.11	1.13	1.14
		1.15	1.17	1.18	1.20	1.21	1.23	1.24	1.26	1.27	1.29	1.30	1.32
		1.33	1.35	1.37	1.38	1.40	1.42	1.43	1.45	1.47	1.49	1.50	1.52
		1.54	1.56	1.58	1.60	1.62	1.64	1.65	1.67	1.69	1.72	1.74	1.76
		1.78	1.80	1.82	1.84	1.87	1.89	1.91	1.93	1.96	1.98	2.00	2.03
		2.05	2.08	2.10	2.13	2.15	2.18	2.21	2.23	2.26	2.29	2.32	2.34
		2.37	2.40	2.43	2.46	2.49	2.52	2.55	2.58	2.61	2.64	2.67	2.71
		2.74	2.77	2.80	2.84	2.87	2.91	2.94	2.98	3.01	3.05	3.09	3.12
		3.16	3.20	3.24	3.28	3.32	3.36	3.40	3.44	3.48	3.52	3.57	3.61
		3.65	3.70	3.74	3.79	3.83	3.88	3.92	3.97	4.02	4.07	4.12	4.17
		4.22	4.27	4.32	4.37	4.42	4.48	4.53	4.59	4.64	4.70	4.75	4.81
		4.87	4.93	4.99	5.05	5.11	5.17	5.23	5.30	5.36	5.42	5.49	5.56
		5.62	5.69	5.76	5.83	5.90	5.97	6.04	6.12	6.19	6.26	6.34	6.42
		6.49	6.57	6.65	6.73	6.81	6.90	6.98	7.06	7.15	7.23	7.32	7.41
		7.50	7.59	7.68	7.77	7.87	7.96	8.06	8.16	8.25	8.35	8.45	8.56
		8.66	8.76	8.87	8.98	9.09	9.20	9.31	9.42	9.53	9.65	9.76	9.88

For example, a resistor with the fourth value (1.8) in the E12 series may have one of the following ratings:

1.8Ω	18Ω	180Ω	18kΩ	18kΩ	180kΩ	18MΩ	18MΩ	180MΩ	…

In practice, there occur situations when in the documentation for an electronic component (in the schematics or in the BOM) one can find, for example, a resistor with a resistance of 50Ω, which differs from the standard values according to the E series. Most often the reason for this is an error at the stage of creating the documentation, in the case of which, during the preparation of the device for production, selecting a substitute with a standard maximum being maximally approximate to that given in the documentation will be required. In this case, the substitute could theoretically be a 49.9Ω (E96) or 51Ω (E24) resistor.
Either way, the selection of a substitute must be based on the knowledge of the requirements for each specific element of the scheme. Sometimes a slight difference in parameters is acceptable and sometimes it can be critical to the functioning of the entire system. In our case, if a resistor is, for example, a simple current limiter for a LED, then the substitute can be a resistor with any given value (in theory, 51Ω will be more available from most suppliers), while in the case of signal lines, the best option is to use a 49.9Ω resistor (maximally approximate to the standard impedance of transmission lines).

Of course, in the offer of some suppliers, a non-standard 50Ω resistor may be found, but it will be much more expensive and often limited in its availability compared to other standard components. Summing up, the E series of rated values can be helpful in selecting substitutes for passive components, yet substitutes should be selected very carefully, based on good knowledge about the functioning of the systems in which they are applied.

1.7 Standards and requirements of the automotive industry

For the needs of the automotive industry, which uses more and more electronics to produce cars, several leading manufacturers in this industry (Ford, General Motors, Chrysler) created the AEC (Automotive Electronic Council), which sets standards and requirements for electronic components in terms of their quality and reliability. The components that meet these standards can be used in the demanding conditions of the automotive industry.

General increased requirements for such components:

- resistance to mechanical shock and vibration
- moisture resistance
- operation over a wide range of higher temperatures
- operation with unstable power supply
- stability of operation in the conditions of spark interferences
- longer service life

The most common standards for automotive electronics are:

- **AEC-Q100** *(Stress Test Qualification for Integrated Circuits)* – standard for integrated circuits
- **AEC-Q101** *(Stress Test Qualification for Automotive Grade Discrete Semiconductors)* – a similar standard to discrete semiconductors (diodes, transistors, etc.)
- **AEC-Q200** *(Stress Test Qualification for Passive Components)* – a standard for passive components (resistors, capacitors, inductors, etc.)

As part of the AEC-Qxx standards, automotive component manufacturers are introducing numerous tests (in addition to standard ones) in extended temperature ranges to qualify them into different classes:

Class	Temperature range, ^0C	Common application
0	-50...+150	in any place of the car
1	-40...+125	under the hood in most cases
2	-40...+105	warmest places in the passenger compartment
3	-40...+85	in most cases inside the passenger compartment
4	0…+70	not qualified for the automotive industry

2. Passive components

2.1 Resistors

The resistor is the basic element of electrical circuits. The main task of the resistor is to resist the flow of current and induce a voltage drop. This results from the fact that the resistor is an element with a sufficiently weak conductivity. Resistors usually have two (or three) non-polar leads for connection to an electrical circuit.

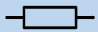
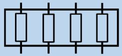
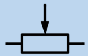
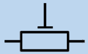
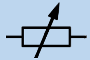
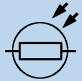
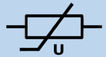
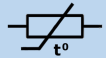
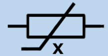
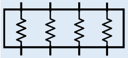
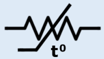
The main parameters of resistors are:

- **Resistance** (it is the main parameter) – the resistance value of a component under normal operating conditions;
- **Power rating** – the value of the allowable dissipation power on the component. It can be indicated in units of power (Watt), or as the maximum allowable voltage of the resistor (voltage squared to resistance ratio). Usually, the resistor power rating is selected with a margin of about 25% to the maximum possible power (based on calculations) when working in the electrical system. Replacing a resistor having higher power rating with a resistor having lower power rating is not allowed, because when the permissible power parameters are exceeded, the resistor undergoes irreversible damage;
- **Tolerance** (deviation from the rated value, error) – relative (percentage) or absolute (in ohms) value of the resistance by which the specified resistor value can change. Typically, resistors have a symmetrical error, e.g., ± 5%;
- **Temperature coefficient of resistance (α or TCR)** - a value that shows how much the resistance of a resistor can change as its temperature changes. Usually it is shown in PPM (parts per million), i.e., by how many fractions with a denominator of one million the value will change when the temperature changes per unit;
- **Maximum operating voltage** - voltage that can be applied to the resistor without causing its damage or malfunctioning;
- **Operating temperature** - temperature range in which the resistor maintains the values of its main parameters while working in an electrical system

In some electrical circuits, additional characteristics of resistors such as parasitic capacitance, parasitic inductance, intrinsic noise level can be significant, but in practice, the need of selecting resistors for such parameters is rather rare.

2.2 Types of resistors

In the table below one can see the classification of resistors according to types and production technology. We will look at the most common types of resistors.

Resistors classification									
	Fixed resistance resistors		Variable resistance resistors			Resistors with dependent resistance			
Type	Standard resistor	Resistor array	Potentiometer	Trimmer	Rheostat	Photoresistor	Varistor	PTC / NTC thermistor	Magneto resistor
IEC symbol									
ANSI symbol									
Type of material / technology									
Carbon film	•	•	•	•					
Metal film	•	•	•	•	•				
Metal oxide film	•						•		
Wirewound	•		•	•	•				
Conductive plastic			•		•				
Carbon composite	•				•		•		
Metal composite							•	•	•
Semiconductor						•		•	•

2.2.1 Fixed value resistors can be divided into the following groups:

- **Carbon film resistors**

They are available in **Axial** and **MELF** packaging.

A thin layer of pure carbon is deposited on an insulating cylindrical core. A spiral cut is made in the carbon layer to increase the resistance path.

Carbon film resistors have a power rating of 0.125 W to 5 W. Available resistances range from 1 Ohm to 10 Megaohm. The operating temperature range is from -55°C to +155°C. They have a maximum operating voltage range from 200 to 600 volts.

In terms of tolerance and stability of parameters, they are slightly inferior to metal and metal-oxide film resistors, which are more popular.

Typical tolerances are 2%, 5%, 10%, 20%. The temperature coefficient of resistance typically ranges from 200 to 1500 ppm/°C.

- **Metal film resistors**

They are available in **Axial** and **MELF** packaging.

Metal film resistors are structurally the same as carbon film resistors, but the main difference is that instead of a carbon layer, a metal layer (or a mixture of metal oxides, e.g., nickel and chromium or a mixture of metals and glass, which is called metal glaze) are used. As with the carbon film, the resistance value is regulated by cutting spiral grooves.

Metal film resistors are currently the most commonly used form of axial feed-through resistors. This type of resistor offers good performance at a lower cost and therefore has been practically universally adopted, except for some specific applications.

Its stability, temperature coefficient of resistance and tolerance are better than in the case of carbon film resistors. Typical tolerances range from 0.1% to 2%, the temperature coefficient of resistance reaches from 50 to 100 ppm/°C. The operating temperature range is from -55°C to +175°C.

- **Metal oxide film resistors**

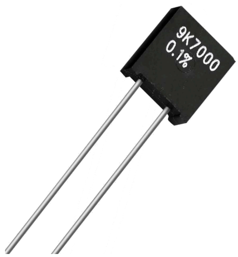
They are available in **Axial** type packaging.

They are similar to metal film resistors with such difference that the resistive material is a metal oxide layer (e.g., tin oxide). These durable resistors are characterised by greater reliability and stability than metal film resistors. Moreover, the operating temperature is higher. Therefore, they are more preferred in applications requiring high endurance.

Typical tolerances go from 1% to 10%, the temperature coefficient of resistance is on average 300 ppm/°C. Operating temperature range is typically from -55 °C to +205°C.

- **Foil resistors**

They are available in **Radial** and **SMD Chip** types of packaging.



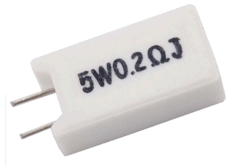
The foil resistor was invented in the 1960s. To this day, they have been the most accurate and stable type. The resistive element is a thin bulk metal foil (usually Nichrome with additives) which is cemented on a ceramic substrate. The thickness of the foil is several micrometres. Inherently associated with mechanical design, they are characterised by a very low temperature coefficient of resistance. They are used in applications with high precision requirements.

Film resistors are characterised by a low temperature coefficient of resistance, good long-term stability, low noise level, low capacitance, fast thermal stabilization and lack of inductance.

Typical tolerances start from 0.001%, the temperature coefficient of resistance ranges from 0.1 ppm/°C upwards. The operating temperature range is from -55°C to +125°C.

- **Wirewound resistors**

They are available in **Axial** and **Radial** types of packaging.



The resistive element is an insulated metal wire (usually nickel-chromium as called nichrome) which is wound around a ceramic, plastic or fiberglass core. They can be manufactured very accurately and have excellent properties for low resistance values and high-power ratings.

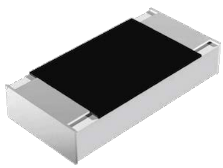
A typical tolerances range is from 1% to 10%, while for precision series the tolerances can start from 0.005%. The temperature coefficient of resistance in the low resistance range may be from 20 to 50 ppm/°C.

The second advantage of wirewound resistors is the rated power, which can reach even 1000W (then the resistor packaging is made in the form of a heat sink). Some series of wire wound resistors have an extended operating temperature range (up to 450°C).

Since wirewound resistors are essentially coils, they have a greater undesirable inductance than other types of resistors, though winding the wire into sections with alternating reverse directions may minimize the inductance. Other techniques use bifilar winding.

- **Thick film resistors**

They are available in **SMD Chip** and **Axial** types of packaging.



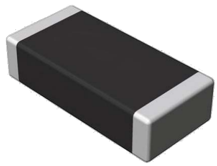
The resistive material is a special paste based on ruthenium, iridium or rhenium oxides (this is also referred to as Cermet (ceramic-metal composite)). The resistive layer is printed onto an aluminium oxide ceramic substrate at a temperature of 850°C. After the firing of the paste on the carrier, the film becomes a glaze, which makes it well protected against moisture.

Cermet based resistors have similar properties to metal film resistors and are typically used in the production of SMD resistors (including resistor arrays) and resistors for high-frequency ranges. Thick film resistors have a good temperature coefficient of resistance, low self-noise and good voltage ratings.

Today, they are by far the most widely used resistors in electronic devices and boast the lowest cost compared to any other technology.

The temperature coefficient of resistance is usually from 50 to 200 ppm/°C, the tolerances are on average from 0.5% to 5%.

- **Thin film resistors**



They are available in **SMD Chip** and **Axial** types of packaging.

The resistive layer (chrome-nickel or based on cermet, tantalum nitride, ruthenium oxide, lead oxide or others) is vacuum deposited on a dielectric substrate (aluminium oxide, silicon or glass). This creates a uniform metal film of around 0.1 µm thickness. Photo etching or laser trimming are used to create patterns in the film to increase the resistive path and calibrate the resistance value.

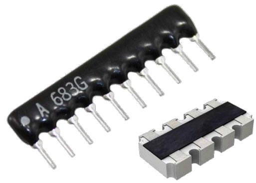
Thin film resistors are typically used for precision applications. They are characterised by relatively high tolerances, low temperature coefficients and low level of self-noise. Moreover, for high frequency applications, they perform better than thick film because they have much lower capacitance and parasitic inductance.

The temperature coefficient of resistance usually reaches values from 25 to 50 ppm/°C; the tolerance is on average from 0.1% to 1%.

The improved performance of thin film resistors comes at a cost that can be many times higher than that of thick film resistors.

Typical application examples for thin film resistors include medical equipment, audio installations, precision control devices and measuring devices.

- **Resistor networks or arrays**



They are available in **SMD Chip** and **SIP types of packaging.**

Resistor networks include several resistors (usually 4+) placed in one package while the resistors themselves may have separate leads or be connected into this or another circuit.

Typical advantages of using resistor arrays are:

- Lower part count which, as a result, speeds up assembly.
- Better matching of individual resistors' value drift owing to their being in the same packaging.
- Saving PCB board space: not always, but in complex layouts definitely possible.
- BOM cost - not always, but for higher quantities of resistors, almost certainly.

Why are they not always used:

- Availability - they are not as common as single resistors.
- Short-circuiting between resistors, posing a risk especially in small packages.
- BOM cost - with smaller quantities, they can be more expensive than single resistors.

Typically, resistor arrays are manufactured using the thick-film technology in the case of SMD components or in the technology of metal film resistors for feed-through components.

The most commonly encountered resistors come from manufacturers such as Panasonic, Vishay, Royal Ohm, Yageo, Walsin, KOA Speer Electronics, Ohmite, Stackpole Electronics, ROHM

Anti-Sulphur resistors

Silver is the most common material used on the internal contacts (leads) of chip resistors. However, when silver is exposed to sulphur in a polluted environment, it turns into silver sulphide and forms an open circuit at the point of contacts. In high-reliability products which are exposed to the influence of the environment, so-called anti-sulphide resistors, made of materials resistant to the emergence of this effect, should be used.

Sulphur contamination in chip resistors was primarily a problem for the automotive industry, but it has spread into other industries in the last few years, with many manufacturers now offering anti-sulphide resistors. Please keep this in mind when selecting and purchasing components for applications where high reliability of electronic systems is required.

2.2.2 Variable resistance resistors

The **variable resistance resistor** is a resistor whose electric resistance value can be adjusted. Typically, the adjustment of the resistance is accomplished through applying an external force to shift a slider which constitutes the centre lead and contacts the resistor with the two end leads.

Variable resistance resistors include:

- **Potentiometers**

They are mainly available in **THT** versions.

The potentiometer is a resistive device which has three leads and acts as a voltage divider. It produces a stepless voltage output signal that is proportional to the physical position of the slide along the resistance element.

The following materials may appear as the resistance element in potentiometers:

Carbon composite: the material used here is a mixture of filler material and carbon, deposited on a phenolic resin substrate. Carbon composite potentiometers are the most commonly used type of variable resistors. They are characterised by low cost and reasonable noise and wear characteristics.

Cermet: as the name suggests, it is a composite material consisting of ceramics and metal. It is especially used where high temperatures may occur. They also ensure a lower noise level than those offered by carbon-composite potentiometers. They have a stable and low temperature coefficient of resistance. On the other hand, they are quite expensive and often feature a limited number of adjustment cycles.

Conductive plastic: potentiometers made of conductive plastic have a very smooth, stepless adjustment range and good resolution, being often able to perform millions of adjustment cycles. Their limitations include fairly low power and quite a high cost. They are often used in high-end (audio) equipment where high resolution and low noise are important.

Wirewound: wirewound potentiometers are the most expensive type. As the name suggests, they are manufactured by winding a "coil" of resistance wire onto a dielectric core. These potentiometers are often used as high power or low resistance circuits.

Practically all potentiometers can be divided into two categories in terms of the dependence of resistance on the wiper movement:

Linear potentiometers: for this type of potentiometer, there is a linear dependence between the resistance and the wiper shift along the resistance path, i.e., for each successive level of rotation or step of wiper shift the resistance will differ by the same amount.

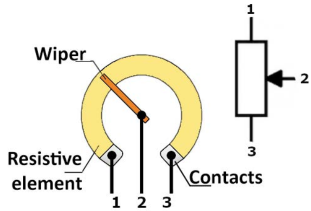
Logarithmic potentiometers: the dependence between the resistance and the shift of the wiper along the resistance path is logarithmic. In this case, potentiometers have a relatively small change in resistance in the first part of the wiper shift, which the farther the wiper moves, the faster it changes. The reason for this is that the audible perception characteristic of the human ear is logarithmic, and the use of potentiometers with the same characteristics allows for performing volume control which will be perceived fairly evenly by ear.

Some manufacturers offer both potentiometers with reverse logarithmic and anti-logarithmic characteristics, although they are not as common as standard logarithmic potentiometers.

In terms of design, potentiometers are divided into rotary and linear ones.

Rotary potentiometers

The most common type of potentiometer in which the wiper moves along a circular resistance path.



Type	Description	Application
Single-turn pot	Single rotation of approximately 270 degrees or 3/4 of a full turn	For application in circuits where a single turn provides sufficient control resolution.
Multi-turn pot	Multiple rotation (most often 5, 10 or 20) for increased adjustment precision. They are designed either with a wiper which follows a spiral path, or by using a worm-gear.	Systems where high precision and resolution is required.
Dual-gang pot	Two potentiometers (or more) are connected on the same shaft, enabling the parallel setting of two channels. They most often appear in the form of single-turn potentiometers with the same resistance.	They are used for volume control in stereo audio systems or other systems where 2 or more channels must be adjusted in parallel.
Concentric pot	A dual potentiometer where the two potentiometers are individually adjusted by means of concentric shafts. This allows for the use of two control elements designed for manufacture in one module.	For example, in audio systems where the volume and tone controls are combined into a single module.
Servo-connected pot	A motorised potentiometer which can be automatically adjusted by a servo motor.	It finds application where manual and automatic adjustment is required. It is often found in audio systems, where the remote-control can turn the volume control knob.

Slider potentiometers

A potentiometer in which the slider moves along the resistance path in a straight line.

Type	Description	Application
Single pot	Single linear slider potentiometer.	For single channel control or measurement of distance. They are often made of conductive plastic.
Double-slide pot	Double slide potentiometer where a single slider controls two potentiometers in parallel.	Often used for stereo control in professional audio systems or other applications where dual parallel channels are controlled.
Multi-turn slide pot	It consists of a spindle which actuates a linear potentiometer slider. Multiturn spindle (most often 5, 10 or 20) for increased precision.	It is used where high precision and resolution are required.
Servo-connected pot	It is a slide potentiometer which can be automatically adjusted by a servo motor.	It finds application where manual and automatic adjustment is required. For example, in studio mixers where slide potentiometers can be automatically set to a saved configuration.

- **Trimpots**

They are available in **SMD** and **THT** versions

A trimpot is a small potentiometer which is used for adjustment, tuning and calibration in electronic circuits. Carbon composite or cermet is the most commonly used material for the resistance element. The resistance characteristics of trimpots are practically always linear.

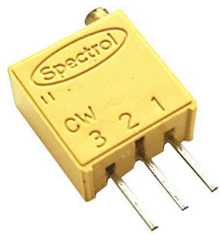
Trimmers are usually mounted directly on printed circuit boards (they are available in through-hole (THT) and surface mount (SMT) technology) and are adjusted with a screwdriver.

Trimmers can achieve a high resolution of resistance adjustment, but they are characterised by a relatively short lifespan, on average up to 200 cycles. The idea of using trimmers is such that they are used for initial adjustment at the stage of starting an electric circuit, they are not adjusted later.

According to the precision of resistance adjustment, trimmers can be divided into:

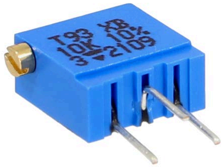
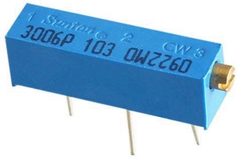
Single-turn pot

Single-turn trimmers are very common and used where the resolution of one turn is sufficient.

Open trimmers (without packaging) made of carbon composite	Cermet trimmers in package	Trimmer in SMD package
		

Multi-turn trimmers

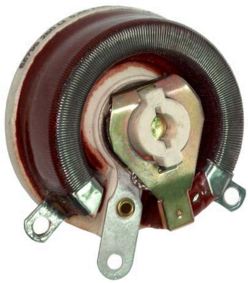
For higher adjustment resolutions, multi-turn trimmers are used. The number of rotations is on average 5-25. They are structurally based on worm-gears or lead screws. Because of their more complex design, they are more expensive, and in terms of the sustained electrical power, they are better.

Worm-gear, top adjust trimmer	Worm-gear, side adjust trimmer	Lead screw, side adjust trimmer
		

- **Rheostats**

They are available only in **THT** versions.

A rheostat is a variable resistor which is used for controlling the current. The design is very similar to potentiometers, the difference is such that a rheostat has two leads as the slide contact is connected to one of the end contacts. Unlike potentiometers, rheostats must conduct a considerable current, so in most cases the resistance element is a wound wire.



There are several types of rheostats:

Rotary rheostat	Linear rheostat	Adjustable rheostat
		

Typical values of resistors with variable resistance

Since potentiometers and trimmers are variable resistors, most of these components have typical values within the following multiplicity range:

Typical values of potentiometers (multiples)					
10	20	22	25	47	50

By far the most frequently used value for potentiometers is 10kΩ, but other, also very popular values are 1kΩ, 5kΩ, 50kΩ and 100kΩ.

The most common variable resistors come from manufacturers such as Bourns, Vishay, TT Electronics/BI

2.2.3 Resistors with dependent resistance

Resistors with dependent resistance include:

- **Photoresistors**

They are mainly available in **THT** versions.

Photoresistors, also known as Light Dependent Resistors (LDR), are light-sensitive components most frequently used to indicate the presence or absence of light, or to measure the intensity of light. In the dark, their resistance is very high, sometimes up to 1 MΩ, but when a LDR is exposed to light, the resistance drops drastically down to a few ohms, depending on the intensity of the light. LDRs have sensitivity which is dependent on the wavelength of light and are non-linear devices.

Modern photoresistors are made of lead sulphide, lead selenide, indium antimonide, and most often cadmium sulphide and cadmium selenide. Common types of cadmium sulphide are often labelled as CdS photoresistors. It should be noted that equipment containing lead or cadmium is not RoHS compliant and is prohibited for use in countries that comply with these regulations.

Technical parameters of photoresistors:

- **Maximum power** - this is the maximum power, which the device is able to dissipate in a given temperature range.
- **Maximum operating voltage** - As the device is semiconductor based, the maximum operating voltage must be adhered to. Usually, the value is given for 0 lux (i.e., in darkness).
- **Wavelength (peak)** - This specification of the photoresistor determines the maximum sensitivity wavelength. In some cases, general dependency curves will be given. The wavelength is specified in nm.
- **Resistance under exposure** - resistance during light exposure is the key parameter for any photoresistor. Often, due to some discrepancy, a minimum and maximum resistance may be quoted under certain lighting conditions, often 10 lux. A "fully on" status may also be given under extreme lighting conditions, such as 100 lux.
- **Dark resistance** - resistance in complete darkness. It is always determined after some time from switching from exposure to dark, because their slow response time.

- **Varistors**

They are available in **SMD** and **THT** versions

Varistors are a Voltage Dependent Resistors (VDR), with the dependence of resistance on voltage having a non-linear characteristic. The resistance of varistors decreases with the increase of voltage. In the case of excessive voltage increase, the resistance of a varistor drops drastically. This behaviour makes them suitable for protecting circuits during power surges.

Varistors are useful for short term protection in the case of high transient voltages (on the order of 1-1000 microseconds). However, they are not suitable for coping with sustained surges. If the pulse energy, measured in Joules (J), significantly exceeds the absolute maximum strength values of the varistor, it will cause damage to it.

The most important types of varistors are:

Metal Oxide Varistors (MOV) – These are the most common type of varistors. MOV varistors consist of a sintered matrix of zinc oxide (ZnO) or bismuth oxide (Bi_2O_3) grains.

Silicon Carbide Varistors - Varistors made of Silicon Carbide (SiC) were quite commonly used before MOV varistors were introduced to the market. Today, silicon carbide varistors are used in high power and high voltage applications.

Some of the more important parameters of varistors are summarized below:

- **Varistor voltage (Max)** or **Clamping voltage:** This is the voltage at which the varistor begins to show significant conductivity.
- **Rated voltage AC/DC** or **Maximum Operating AC/DC voltage:** This voltage, given as AC or DC, is the maximum voltage at which the device can be used. Normally there should be a good margin maintained between the rated voltage and the actual voltage at which the varistor will be used for an extended period of time, although this will need to be balanced in terms of the clamping voltage and the protection level required. Some manufacturers provide these values with the considerations for the varistor's safety margin already made.
- **Peak surge current:** The maximum pulse current of a specified waveform and a specified duration that can be applied without causing device failure. Although the varistor can handle this overvoltage, most manufacturers consider the surge current to be a one-time event after which the varistor needs to be replaced.
- **Maximum Pulse Energy**: This is the maximum energy, expressed in Joules, which a device can dissipate.
- **Capacitance:** MOV varistors have a relatively high capacity. For low frequency applications this may not be a complication, but it may be a problem when varistors are used with data lines etc. Therefore, it is necessary to check the capacitance value of the varistor in the case it is planned to be used in high frequency systems. Typical MOV varistors can have capacitance values between 100 and 1000 pF, although low-capacitance versions are also available.

- **Thermistors**

They are available in **SMD** and **THT** versions.

A thermistor is a resistor whose resistance is quite clearly temperature dependent. Unlike most other resistors, thermistors usually have a negative temperature coefficient of resistance, meaning that the resistance decreases with increasing temperature. These types are called NTC (Negative Temperature Coefficient) thermistors. Thermistors with a positive temperature coefficient of resistance are called PTC (Positive Temperature Coefficient) thermistors. NTC thermistors are often made of metal oxide powders which are compressed and sintered at a high temperature. The materials used include Mn_2O_3, NiO, Cr_2O_3, CuO, Fe_2O_3, TiO_2, etc. They can also be made of semiconductors with different levels of doping.

NTC thermistors

NTC thermistors are used when a change in resistance is required over a wide temperature range. They are often used as temperature sensors ranging from -55 °C to +200 °C, although they can be manufactured to measure much lower or higher temperatures. Their popularity is due to their quick response, reliability, and low price.

PTC thermistors

There are two types of PTC thermistors which have very different characteristics, one showing a linear increase while the other one showing a sudden change in resistance.

Switching thermistors: PTC type switching thermistors have a highly non-linear curve. The resistance initially decreases slightly with increasing temperature, and then at a critical temperature (called switch, transition, or Curie temperature) the resistance increases sharply, thus acting practically as a switch. The most common switching temperatures are between 60 °C and 120 °C. This makes it ideal for use in a wide range of security devices. Switching thermistors are usually made of polycrystalline materials including barium carbonate or titanium oxide with the addition of materials such as tantalum, silica, or manganese etc. They are often used for self-regulating heating elements and self-resetting overcurrent protection.

Silistors: PTC thermistors based on a semiconductor as a base material and characterised by a linear resistance-temperature dependence, making them suitable for temperature sensors. They are usually made of doped silicon.

Some of the more important thermistor parameters are summarised below:

- **Thermistor type** - The first decision to make when selecting a thermistor is to make sure you have selected the correct type. You must consider not only the division into NTC or PTC types, but also additional types - switching ones and silistors.
- **Resistance** - it is naturally one of the key parameters. Thermistors can be manufactured with various resistance values from Ω to kΩ.
- **Tolerance**-- As with any resistor, there is a tolerance to the standard resistance. It is adopted as the value at the temperature for which the resistance was specified. Values of ± 2%, ± 3% and ± 5% are common.
- **The material constant B** - also known as the β value, is a parameter given in Kelvin degrees and characterizes the dependence of resistance on temperature. Based on this parameter, the characteristic curve of this dependency can be approximated.
- **Time constant, τ** - reaction to temperature changes takes time, and the main parameter measuring this response is the thermistor's time constant.
- **Heat dissipation factor δ** – it is an important characteristic of a thermistor because some current flows through the thermistor during operation in the circuit, which causes the thermistor to heat itself up. This specification defines the correlation between the applied power and the thermistor self-heating.
- **Operating temperature range** - it is the temperature range for which a thermistor is intended. To ensure reliability and precision, a thermistor should not be operated outside the specified temperature range.
- **Rated power** - For sensing applications, power dissipation is kept low to prevent self-heating, but in some circumstances, there may be reasons for more power to dissipate. The rated power value should not be exceeded. In order to attain the best reliability, a thermistor should only operate at 50-66% of its nominal power.

- **Magneto Resistors**

They are mainly available in **THT** versions.

Magnetic Dependent Resistors (MDR) have a variable resistance which is dependent on the strength of the magnetic field. Magneto resistors are often made of long thin layers of permalloy (an alloy consisting of 81% nickel and 19% iron).

Magneto resistors can be used to measure the presence, strength and direction of a magnetic field. Their applications as magnetic field sensing devices include:

- Electronic compass
- Magnetometry (measuring the intensity and direction of a magnetic field)
- Position sensors (angular, rotary, linear)
- Detection of ferrous metals
- Vehicle and traffic detection

2.3 Details of resistors' application and selection of substitutes

In practice, the need to select chip resistors most often arises, because they are present in almost every electronic circuit, and their number, on average, accounts for 20 to 40% of all components in the BOM.

If our task is to purchase electronic components according to the BOM, it may turn out that instead of specific Part Numbers we have only basic resistor values, or a resistor with a specific Part Number is not available. In this case, we need to know what to pay attention to when selecting resistors.

First, we need to establish the basic parameters of each resistor, i.e., resistance value, tolerance and type of packaging. In most cases, this will be enough information for the selection of resistors. For some projects, we will have to consider a few more parameters. The requirement to ensure these parameters may stipulate, among other things, that the BOM contains information directly pointing to it or the Part Number that we want to replace indicates a component with additional parameters than standard chip resistors.

These additional extended parameters can be related to a larger range of operating voltages, temperature range, slightly higher power (resistors with the same packaging may have different power ratings), temperature coefficient of resistance, technology and materials from which the resistor is made.

We must keep in mind whether the device for which we select the components will be used in rigorous operating conditions and whether it is necessary to use resistors meeting the requirements of the automotive industry AEC-Q200 (see chapter 1.7) or resistant to sulphur compounds, the so-called anti-sulfur (see chapter 2.2.1).

Now that we have all the necessary information, you can start searching for resistors on the websites of manufacturers or suppliers of electronic components.

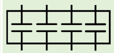
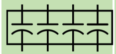
2.4 Capacitors

The main parameters of capacitors that should be considered when selecting and purchasing include:

- **Capacitance** - The nominal capacitance is probably the most important parameter of a capacitor. The basic unit of capacitance is Farad, while in most electronic circuits, the most commonly found capacitors are ones with capacitances given in picofarads (pF), nanofarads (nF) and microfarads (µF). Sometimes capacitors can be labelled in two ways. For example, 100nF is the same as 0.1 µF.
- **Tolerance** - the tolerance value is the range within which the actual value of a capacitor can deviate from the stated or rated value and is often expressed as a percentage, although for values of a few picofarads it can be expressed as an actual value i.e., 22pF ±1pF, etc.
- **Maximum operating voltage** - The maximum continuous voltage that can be applied to the capacitor. Usually, it refers to the highest DC voltage that can be used. For capacitors intended to operate in AC circuits, the maximum AC voltage will be listed, but it should be borne in mind that this refers to the RMS voltage and not the peak value, which is √2 or 1.414 times greater. Often, design guidelines envisage that a capacitor should not operate above 50% of the operating voltage.
- **Operating temperature range** - All capacitors have a limited operating temperature range, whether they are ceramic, electrolytic, tantalum, or any other type. On the other hand, the operating temperature is especially important for electrolytic capacitors because their life expectancy drops sharply with increasing temperature.
- **Dielectric type** - depends on the insulating material used in the capacitor. This is one of the main parameters of the capacitor, as it determines its temperature characteristics, that is, the deviation of the capacitance from the nominal value depending on the temperature change. The dielectric type has its own coding system: the first symbol is the lower limit of the operating temperature range, the

second symbol is the upper limit of the operating temperature range, the third symbol denotes the tolerance. Example: the X7R dielectric has an operating temperature range of -55 ... +125 ^{0}C, with capacitance tolerance of ±15%.

- **ESR (Equivalent Series Resistance)** - this is the total resistance of the capacitors (consists of the AC current resistance at higher frequencies and the DC current in the leads and plates). It mainly affects electrolytic capacitors (it can be as high as a few ohms) and deteriorates over time.
- **The resonant frequency of the capacitor** - this is the frequency at which the capacitance and inductance of the leads and the plates form a series resonance circuit. Usually, it is given for capacitors intended for high-frequency circuits. In most cases they are ceramic capacitors.
- **Leakage current / Leakage resistance** - These parameters indicate the amount of current flowing through the capacitor. Leakage current arises because capacitors are not perfect insulators. Supercapacitors and aluminium electrolytic capacitors usually have leakage current values given, but for ceramic or foil capacitors where the leakage current is minimal, resistance values are usually given. Leakage current and resistance can have a severe effect, e.g., in a high voltage circuit, where even small levels of leakage current can cause appreciable amounts of heat dissipation.
- **Ripple current** - this is the current flowing through the capacitor when its load changes periodically. Such a current causes a high level of heat dissipated in the capacitor; therefore, the maximum importance of the ripple current is an important parameter that must be considered when selecting capacitors operating in systems with high current values.
- **Service life** - the manufacturer's specified time of the continuous operation of the capacitor under specific conditions (temperature, current loads), as a result of which the capacitor loses no more than 20% of the value of its main parameters (rated capacitance, ESR and others).

Classification of capacitors														
	Fixed capacitance capacitors									Variable capacitance capacitors			Other types of capacitors	
Polarization	polar				non-polar					non-polar		polar	nonpolar	polar
Type	Aluminium	Tantalum	Niobium	Hybrid	Ceramic	Foil	Paper	Mica	Resistor networks or arrays	Adjustable capacitors	Trimmers	Varicaps	Feed-through capacitors	Supercapacitors
IEC symbol														
ANSI symbol														
Type of electrical / technology														
Barium titanate					●				●		●		●	
Aluminum trioxide	●													
Tantalum Oxide		●												
Niobium oxide			●											
Polymers PE, PP, pet						●								
Paper							●							
Mica								●						
Metal film	●									●			●	
Conductive polymer				●									●	●
Semiconductor												●		
Electrolyte, activated charcoal														●
Lithium ion														●

2.5 Types of capacitors

In the table above, you can see the classification of capacitors by types and production technology. Next, we will consider the most common types of capacitors.

2.6.1 Standard fixed capacitance capacitors

- **Aluminum electrolytic capacitors**

They are available in **SMD** and **THT** versions.

Aluminum electrolytic capacitors use the chemical property of aluminium, which, on contact with a specific electrolyte, forms a very thin layer of insulating oxide which acts as a dielectric.

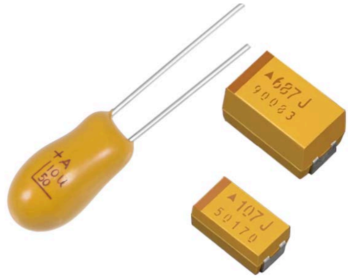
These capacitors have a large capacitance (from 1 µF upwards) but have poor properties in the higher frequency ranges and are not usually used in circuits above 100KHz. In addition, the shortcomings include high leakage currents, lower tolerance, and limited service life. As standard, the ESR resistance is quite high, while the manufacturers' offer includes a special type of aluminium capacitors marked as Low ESR – i.e., with low ESR resistance.

The service life of an electrolytic capacitor is given in hours at maximum operating temperature. For every 10°C drop in operating temperature, the capacitor life doubles, so for a 2000-hour capacitor at 105 ° C, it can be four-fold extended at the operating temperature of 85°C.

It is worth mentioning that aluminium electrolytic capacitors usually have a limited shelf life (from several months to two years depending on the materials and technologies used). The unused oxide layer deteriorates and must be rebuilt in a process called capacitor reforming. This can be done by connecting a capacitor to a voltage source through a resistor and slowly increasing the voltage until the oxide layer is completely rebuilt. Therefore, if a capacitor remains unpolarised for a long time, it must be reformed before use.

- **Tantalum electrolytic capacitors**

They are available in **SMD** and **THT** versions.



Tantalum capacitors are made of tantalum, which is the anode material covered with an oxide layer (Ta_2O_5 - acts as a dielectric) surrounded by a conductive cathode (it could be manganese oxide - MnO_2 or a hardened polymer). The use of tantalum allows for a very thin dielectric layer. This results in a higher capacitance value per volume, superior frequency characteristics compared to many other types of capacitors and excellent stability over time.

The main difference between tantalum and aluminium capacitors (apart from the cover materials) is the electrolyte. The electrolyte comes with a solid material in a tantalum capacitor and a liquid in an aluminium capacitor.

Due to the solid electrolyte, tantalum capacitors are very stable over time and their capacity does not change significantly with age, especially when compared to aluminium electrolytic capacitors. They are very reliable when handled properly and their shelf life is virtually unlimited.

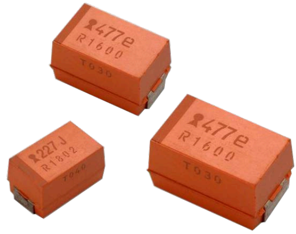
The downside to using tantalum capacitors is their unfavourable failure mode (leading to a short circuit), which may cause a sudden increase in component temperature, which may trigger ignition or a small explosion.

Tantalum capacitors do not have high operating voltages, 35V is usually the maximum voltage, and some capacitors have voltage values as low as around a few volts.

It should be noted that tantalum capacitors usually have a positive terminal labelled on the package, unlike aluminium electrolytic capacitors which have a negative terminal labelled.

- **Niobium electrolytic capacitors**

They are available in **SMD** and **THT** versions.



Niobium capacitors are similar to tantalum capacitors (using niobium oxide instead of tantalum oxide creates the difference). They are mainly used in systems where safety is the priority because they have a safe failure mode - unlike tantalum capacitors, niobium capacitors form an open circuit, i.e., a circuit with high impedance, during failure. They are usually used in digital circuits where operating voltages do not exceed 10V.

- **Hybrid electrolytic capacitors**

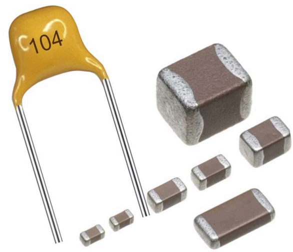
They are available in **SMD** and **THT** versions.

Similarly, to traditional electrolytic aluminium capacitors, hybrid capacitors come with a wound structure of aluminium foil and paper in a metal can. The innovation is an electrolyte which combines conventional liquids and a modern conductive polymer. A polymer significantly lowers the ESR series resistance, while the wet electrolyte maximizes the contact area and increases the voltage tolerance.

Hybrid capacitors have emerged as highly promising components for automotive applications as they primarily ensure a very capability in terms of high ripple currents. This helps reducing both the number of components required and the size of printed circuit boards intended for the automotive industry, resulting with more efficient automotive design.

- **Ceramic capacitors**

They are available in **SMD** and **THT versions.**



Ceramic capacitors are the most common type of capacitors that can be found in almost any electronic device. This group of capacitors includes through-hole, single-layer and multi-layer chip capacitors.

Through-hole ceramic capacitors form a component in the shape of disc, "droplet" or otherwise shaped component (it can be highly diverse and non-standard depending on the manufacturer) with wired leads. The characteristic features of through-hole capacitors include high values of the maximum operating voltage, but relatively low capacitance values.

Single layer ceramic capacitors usually come in the form of disks. They have relatively high capacitance with small size, which ranges from 1 pF to 220 nF. The maximum operating voltage usually reaches no more than 50 V. These capacitors have a small leakage current and low inductance; they can operate at high frequency and also have high capacitance stability with increasing temperature. These capacitors can be used in DC, AC and pulsed current circuits.

Multilayer Ceramic Capacitors (MLCC) are the fastest growing market compared to other types of capacitors. MLCCs are used in all fields of electronics: consumer, automotive, military, medical, industrial, etc.

MLCCs boast valuable properties, including a wide range of nominal capacities, wide range of operating voltages, standard sizes that allow for easy use of substitutes from various manufacturers, they have played the key role in surface mount technology since the very beginning.

The dielectric type of ceramic capacitors determines the temperature characteristics of the capacitor, that is, the deviation of the capacitance from the nominal value depending on the temperature change. The dielectric type has its own coding system: the first symbol is the lower limit of the operating temperature range, the second symbol is the upper limit of the operating temperature range, the third symbol denotes the tolerance. Example: the X7R dielectric has an operating temperature range of -55 ... +125 ^{0}C, with capacitance tolerance of ±15%.

Depending on the type of dielectric, ceramic capacitors can be divided into several classes:

- Class I - ceramic capacitors in this class offer high stability and low losses in circuits using the effect of frequency resonance.
- Class II – capacitors with a very good ratio of capacitance to geometric dimensions. They are typically used as buffer, blocking or coupling capacitors.
- Class III - other capacitors, not classified in the two previous classes.

In class I, the most common dielectrics are NP0/C0G. In class II - X8R, X7R, X6R, X5R, X7S, Z5U, Y5V.

The table below shows the dielectric coding system for class II:

Symbol for the lower limit of the operating temperature range	Number for the upper limit of the operating temperature range	Symbol for capacitance tolerance
X = −55 °C	4 = +65 °C	P = ±10%
Y = −30 °C	5 = +85 °C	R = ±15%
Z = +10 °C	6 = +105 °C	L = ±15% or +15/-40% above 125 °C
	7 = +125 °C	S = ±22%
	8 = +150 °C	T = +22/−33%
	9 = +200 °C	U = +22/−56%
		V = +22/−82%

The most common MLCC manufacturers represented on the EU market are: Kemet, Vishay, Yageo, Samsung, Murata, Walsin.

- **Film capacitors**

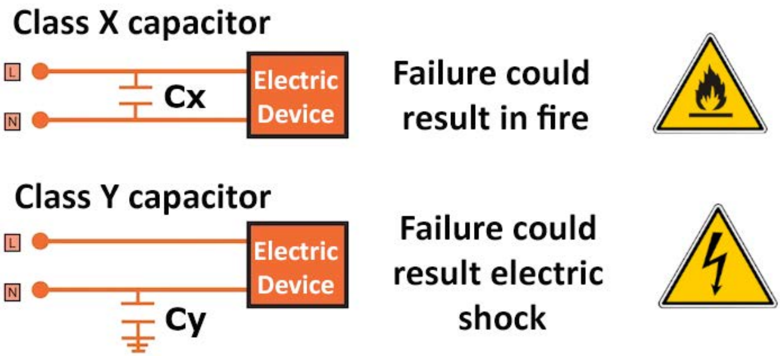
Available in **THT** versions.

Film capacitors are ones that use an extremely thin plastic film as a dielectric. There are many types of film capacitors, including polyester film, polypropylene, polystyrene, PTFE film.

Film capacitors have good stability and service life; they are very reliable, with a very low average failure rate. They have low ESR resistance, low self-inductance and, as a result of that, very low electrical energy dissipation factors. They can be made to withstand voltages in the kilovolt range and can withstand very high surge current pulses.

The so-called Class X and Class Y capacitors create a special group of film capacitors. Class X and Class Y capacitors help to minimize EMI/RFI generation and negative effects associated with EMI/RFI interference received by various electronic devices.

The name of the classes comes from the way these capacitors are connected in electrical circuits (please see the figure below).

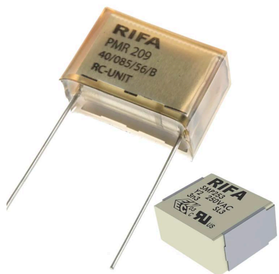


Depending on the values of the maximum operating voltages, the capacitors of classes X and Y are additionally classified (in accordance with IEC 60384-14) as:

- Sub-class X3 – peak pulse voltage lower than or equal to 1.2 kV
- Sub-class X2 – peak pulse voltage lower than or equal to 2.5 kV
- Sub-class X1 – peak pulse voltage from 2.5 kV to lower than or equal to 4.0 kV
- Subclass Y4 – voltage rated up to 150VAC
- Subclass Y3 – voltage rated to less than or equal to 150VAC to 250VAC
- Subclass Y2 – voltage rated to less than or equal to 150VAC to 300VAC
- Subclass Y1 – voltage rated to less than or equal to 500VAC

While the capacitors X2 and Y2 are suitable for home appliance applications, the safety capacitors X1 and Y1 are used in industrial settings.

- **Paper capacitors**



They are available in **SMD** and **THT** versions.

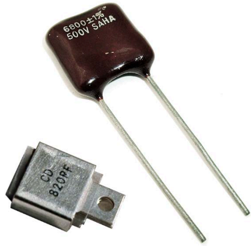
In metallised paper capacitors, the dielectric paper is coated with a thin layer of zinc or aluminium and rolled into a cylinder. The entire cylinder is covered with wax to protect it from the environment.

Paper capacitors have the following characteristics:

- Wide capacitance range and high working voltage.
- Low production costs and simple technology.
- The working temperature is generally between 85°C and 100°C.
- Lack of chemical and thermal stability, due to which they are prone to aging.
- There occur considerable dielectric losses.
- Paper capacitors are typically used in low frequency circuits and DC circuits.

Paper capacitors are not polarised; however, the capacitor body is usually marked with a stripe at one end. The stripe indicates the terminal which is connected to the outer cover of the capacitor. This terminal should be connected to the lower potential part of the circuit (as a precautionary measure in high voltage systems).

- **Mica capacitors**



They are available in **SMD** and **THT** versions.

Mica capacitors are made by coating mica plates with silver and stacking them to achieve the required capacitance.

Mica capacitors have a relatively small value of capacitance: usually from a few pF to a few nF. Operating voltages can reach 1000 V or more for special applications.

Mica capacitors are very stable and very accurate. The average temperature coefficient of capacity is about 50 ppm/°C.

They find primary application in high voltage or high-power RF systems where stability is of paramount importance.

- **Capacitor Arrays**

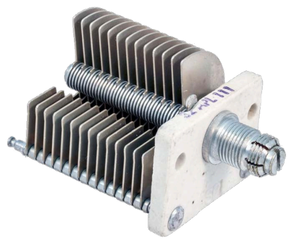
Mainly available in **SMD** versions.

Capacitor arrays come with several capacitors (usually 4+) placed in one package. The most common are arrays of MLCC capacitors in the SMD version.

Similarly, to resistor arrays (see chapter 2.2.1), capacitor arrays are used to save space on PCBs as well as to reduce the costs of assembly and purchase of components for large quantities of manufactured circuits.

2.6.2 Variable capacitance capacitors

- **Variable (adjustable) capacitors**



Available in **THT** versions.

Variable capacitor - a capacitor whose electrical capacitance can be changed mechanically.

Variable capacitors are used in oscillatory and other frequency-dependent circuits to change their resonant frequency - for example, in frequency response correction circuits of amplifiers, generators, antenna devices.

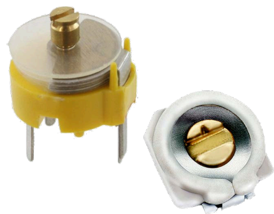
Variable capacitors can be divided into three types with regard to their design:

- with air dielectric
- with a solid dielectric
- vacuum

The capacitance of mechanically changing capacitance variable capacitors is usually shown in the range from units to tens or hundreds of picofarads.

- **Trimmer capacitors**

They are available in **SMD** and **THT** versions.



Trimmer capacitors are variable capacitors which are used for the initial calibration of equipment during manufacturing or servicing. They are not intended for interaction with the end-user. Trimmer capacitors are almost always mounted directly on the PCB, so that the user does not have access to them, and they are set during initial tuning of the circuit with a small screwdriver.

There are two types of trimmer capacitors: air dielectric and ceramic dielectric. Both types use rotating action to change the capacitance values. The design of the trim capacitors is like that of their larger variant, the variable capacitor.

Ceramic dielectric based trim capacitors are small, inexpensive, and readily available on tape or reel for use in automatic assembly. These capacitors can be specified with a capacity range down to about 120 pF and are well suited for applications requiring a small size and low cost.

These elements are available with a nominal temperature capacitance factor of 0 to 750 ppm /°C. The capacitance drift is typically about ± 1% to ± 5%, while the maximum operating voltages are about 200 VDC or less.

2.6.3 Other capacitors

- **Supercapacitors**

They are available in **SMD** and **THT** versions.

A supercapacitor is a specialised form of electrolytic capacitor which offers an extremely high level of capacitance - sometimes even up to multiple farads.

Like traditional capacitors, supercapacitors have two metal plates. These plates are coated with activated carbon, which is a porous, sponge-like material. The plates are immersed in an electrolyte which contains positive and negative ions. As they are charged, the carbon electrodes have two layers of charge covering their surfaces. The distance between the two charge layers on the electrodes is extremely small, which means that very high levels of capacitance are achievable.

It is worth looking at the comparison of a typical supercapacitor with the current high-capacity lithium-ion battery technology:

Parameter	Supercapacitor	Lithium-ion battery
Single cell voltage	2.3 - 2.7V	3.6V
Charge time	1 - 10 seconds	10 - 60 minutes
Charge/discharge cycles	~ 1 million	500 - 3000
Self-discharge	~ 50%/month	~ 5%/month
Energy density (W*h/kg)	~5	100 - 200
Stability of the output voltage	poor	good
Safety during operation	Relatively safe	Less safe; they can explode on rare occasions when misused
Cost per W*h	~ 20 unit.	~ 1 unit.
Service life	~ 10 years	~ 5 years
Operating temperature range	~ -40 to +65°C	~ 0 to +40°C

- **Feed-through capacitors**

Available in **THT** versions.

A feed-through capacitor is a three-terminal capacitor which is used to reduce the influence of high frequencies on electronic circuits.

Special design of the feed-through capacitor ensures low parallel inductance and offers excellent ability to reduce noise in digital circuits up to 5 GHz.

These capacitors are perfect choice for EMI suppression, wideband I/O filtering or Vcc power supply lines.

2.7 Details of application and selection of substitutes for various types of capacitors

In practice, the most commonly it is necessary to select MLCC chip capacitors, as they are present in almost every electronic circuit, and their number is on average from 10 to 25% of all components in the BOMs.

If our task is to purchase electronic components according to the BOM, it may turn out that instead of specific Part Numbers we only have the basic values of capacitors, or the capacitor with a given Part Number is not available. In this case, we need to know what to look up to when selecting capacitors.

First, we need to determine the basic parameters of the capacitor being searched for, i.e., capacity, tolerance, operating voltage, type of dielectric and type of packaging. In most cases, this will be enough information for selecting capacitors.

We must keep in mind whether the device for which we select the components will be used in rigorous operating conditions and whether it is necessary to use capacitors that meet the requirements of the automotive industry AEC-Q200 (see section 1.7).

Now that we have all the necessary information, you can start searching for specific capacitors on the websites of manufacturers or suppliers of electronic components.