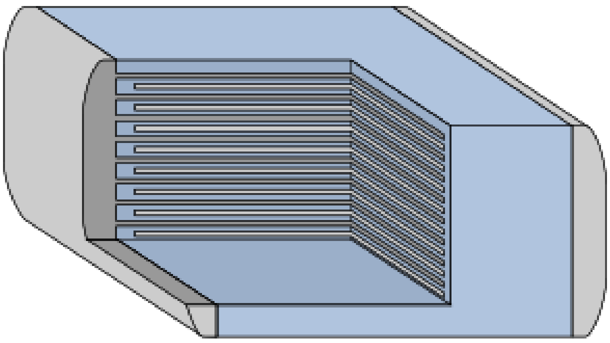
Types of capacitor

Practical capacitors are often classified according to the material used as the dielectric, with the dielectrics divided into two broad categories: bulk insulators and metal-oxide films (so-called *electrolytic capacitors*).

Capacitor construction



Structure of a surface mount (SMT) film capacitor.

Capacitors have thin conducting plates (usually made of metal), separated by a layer of dielectric, then stacked or rolled to form a compact device.

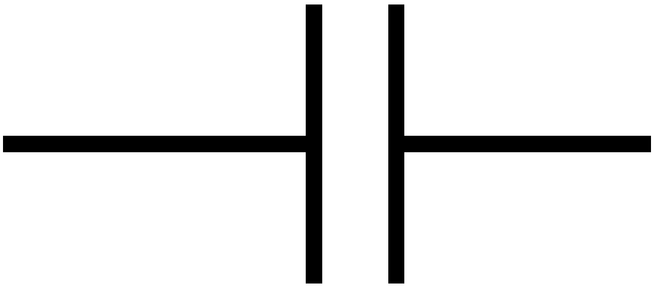
Many types of capacitors are available commercially, with capacitance ranging from the picofarad, microfarad range to more than a farad, and voltage ratings up to hundreds of kilovolts. In general, the higher the capacitance and voltage rating, the larger the physical size of the capacitor and the higher the cost. Tolerances in capacitance value for discrete capacitors are usually specified as a percentage of the nominal value. Tolerances ranging from 50% (electrolytic types) to less than 1% are commonly available.

Another figure of merit for capacitors is stability with respect to time and temperature, sometimes called *drift*. Variable capacitors are generally less stable than fixed types.

The electrodes need round edges to avoid field electron emission. Air has a low breakdown voltage, so any air inside a capacitor - especially at plate edges - will reduce the voltage rating. Even closed air bubbles in the insulator or between the insulator and the electrode lead to gas discharge, particularly in AC or high frequency applications. Groups of identically constructed capacitor elements are often connected in series for operation at higher voltage. High voltage capacitors need large, smooth, and round terminals to prevent corona discharge.

Types of dielectric

- : air-gap capacitors have a low dielectric loss. Large-valued, tunable capacitors that can be used for resonating HF antennas can be made this way.
- : the main differences between ceramic dielectric types are the temperature coefficient of capacitance, and the dielectric loss. C0G and NP0 (negative-positive-zero, i.e. ±0) dielectrics have the lowest losses, and are used in filters, as timing elements, and for balancing crystal oscillators. Ceramic capacitors tend to have low inductance because of their small size. NP0 refers to the shape of the capacitor's temperature coefficient graph (how much the capacitance changes with temperature). NP0 means that the graph is flat and the device is not affected by temperature changes.
  - or NP0: typically 1 pF to 0.1 µF, 5%. High tolerance and good temperature performance. Larger and more expensive.
  - : typically 100 pF to 22 µF, 10%. Good for non-critical coupling, timing applications. Subject to microphonics.
  - or 2E6: typically 1 nF to 10 µF, 20%. Good for bypass, coupling applications. Low price and small size. Subject to microphonics.
  - : 1% accurate, values up to about 1 µF, typically made from Lead zirconate titanate (PZT) ferroelectric ceramic
- : these capacitors are made by twisting together 2 pieces of insulated wire. Values usually range from 3 pF to 15 pF. Usually used in homemade VHF circuits for oscillation feedback.
- : these capacitors have a rotating plate (which can be rotated to change the capacitance) separated from a fixed plate by a dielectric medium. Typically values range from 5 pF to 60 pF.
- : used to form extremely stable, reliable capacitors.
- : common in antique radio equipment, paper dielectric and aluminum foil layers rolled into a cylinder and sealed with wax. Low values up to a few µF, working voltage up to several hundred volts, oil-impregnated bathtub types to 5 kV used for motor starting and high-voltage power supplies, and up to 25 kV for large oil-impregnated energy discharge types.
- : good for filters, low temperature coefficient, good aging, expensive.
- , (PET film): (from about 1 nF to 10 µF) signal capacitors, integrators.



Capacitor

Polarized Capacitor

Capacitor symbols

- : (usually in the picofarad range) stable signal capacitors.
- : low-loss, high voltage, resistant to breakdown, signal capacitors.
- Teflon: high performing and more expensive than other plastic dielectrics.
- Silver mica: These are fast and stable for HF and low VHF RF circuits, but expensive.
- have a larger capacitance per unit volume than other types, making them valuable in relatively high-current and low-frequency electrical circuits, e.g. in power-supply filters or as coupling capacitors in audio amplifiers. High-capacity electrolytics, also known as supercapacitors or ultracapacitors, have applications similar to those of rechargeable batteries, e.g. in electrically powered vehicles.
- : metal conductive areas in different layers of a multi-layer printed circuit board can act as a highly stable capacitor. It is common industry practice to fill unused areas of one PCB layer with the ground conductor and another layer with the power conductor, forming a large distributed capacitor between the layers, or to make power traces broader than signal traces.
- In , small capacitors can be formed through appropriate patterns of metallization on an isolating substrate.
- vacuum variable capacitors are generally expensive, housed in a glass or ceramic body, typically rated for 5-30 kV. Typically used in high power RF transmitters because the dielectric has virtually no loss and is self-healing. May be fixed or adjustable.

Fixed capacitor comparisons

A 12 pF, 20 kV fixed vacuum capacitor

Two 8 μF, 525 V paper electrolytic capacitors in a 1930s radio.[1]

- Images of different types of capacitors

Variable capacitors

Main article: Variable capacitor

Variable capacitors may have their capacitance intentionally and repeatedly changed over the life of the device. They include capacitors that use a mechanical construction to change the distance between the plates, or the amount of plate surface area which overlaps, and variable capacitance diodes that change their capacitance as a function of the applied reverse bias voltage.

Variable capacitance is also used in sensors for physical quantities, including microphones, pressure and hygro sensors.

Non-ideal properties of practical capacitors

Breakdown voltage

Main article: Breakdown voltage

The breakdown voltage of the dielectric limits the power density of capacitors. For a particular dielectric, the breakdown voltage is proportional to the thickness of the dielectric.

If a manufacturer makes a new capacitor with the same dielectric as some old capacitor, but with half the thickness of the dielectric, the new capacitor has half the breakdown voltage of the old capacitor.

Because the plates are closer together, the manufacturer can put twice the parallel-plate area inside the new capacitor and still fit it in the same volume (capacitor size) as the old capacitor. Since the capacitance of a parallel-plate capacitor is given by:

$$C \approx \frac{\varepsilon A}{d}$$

this new capacitor has 4 times the capacitance as the old capacitor.

Since the energy stored in a capacitor is given by:

$$E_{\text{stored}} = \frac{1}{2}CV^2,$$

this new capacitor has the same maximum energy density as the old capacitor.

The energy density depends only on the dielectric. Making a few thick layers of dielectric (which can support a high voltage, but results in a low capacitance), or making many very thin layers of dielectric (which results in a low breakdown voltage, but a higher capacitance) has no effect on the energy density.

Q factor, dissipation and *tan-delta*

Capacitors have *Q* (quality) factor (and the inverse, *dissipation factor* , *D* or *tan-delta*) which relates capacitance at a certain frequency to the combined losses due to dielectric leakage and series internal resistance (also known as *ESR*) dissipation factor (dielectric loss). The lower the *Q*, the lossier the capacitor. Aluminum electrolytic types have typically low *Q* factors. High *Q* capacitors tend to exhibit low DC leakage currents. Tan-delta is the tangent of the phase angle between voltage and current in the capacitor. This angle is sometimes called the loss angle. It is related to the power factor which is zero for an ideal capacitor.

Equivalent series resistance (ESR)

This is an effective resistance that is used to describe the resistive parts of the impedance of certain electronic components. The theoretical treatment of devices such as capacitors and inductors tends to assume they are ideal or "perfect" devices, contributing only capacitance or inductance to the circuit. However, all physical devices are constructed of materials with finite electrical resistance, which means that all real-world components

Capacitor type	Dielectric used	Features/applications	Disadvantages
Paper Capacitors	Paper or oil-impregnated paper	Impregnated paper was extensively used for older capacitors, using wax, oil, or epoxy as an impregnant. Oil-Kraft paper capacitors are still used in certain high voltage applications. Has mostly been replaced by plastic film capacitors.	Large size. Also, paper is highly hygroscopic, absorbing moisture from the atmosphere despite plastic enclosures and impregnates. Absorbed moisture degrades performance by increasing dielectric losses (power factor) and decreasing insulation resistance.
Metalized Paper Capacitors	Paper	Comparatively smaller in size than paper-foil capacitors	Suitable only for lower current applications. Has been largely superseded by metalized film capacitors
PET film Capacitor	Polyester film	Smaller in size when compared to paper or polypropylene capacitors of comparable specifications. May use plates of foil, metalized film, or a combination. PET film capacitors have almost completely replaced paper capacitors for most DC electronic applications. Operating voltages up to 60,000 V DC and operating temperatures up to 125 °C. Low moisture absorption.	Temperature stability is poorer than paper capacitors. Usable at low (AC power) frequencies, but inappropriate for RF applications due to excessive dielectric heating.
Kapton Capacitor	Kapton polyimide film	Similar to PET film, but significantly higher operating temperature (up to 250 °C).	Higher cost than PET. Temperature stability is poorer than paper capacitors. Usable at low (AC power) frequencies, but inappropriate for RF applications due to excessive dielectric heating.
Polystyrene Capacitor	Polystyrene	Excellent general purpose plastic film capacitor. Excellent stability, low moisture pick-up and a slightly negative temperature coefficient that can be used to match the positive temperature co-efficient of other components. Ideal for low power RF and precision analog applications	Maximum operating temperature is limited to about +85 °C. Comparatively bigger in size.
Polycarbonate Plastic Film Capacitor	Polycarbonate	Superior insulation resistance, dissipation factor, and dielectric absorption versus polystyrene capacitors. Moisture pick-up is less, with about ±80 ppm temperature coefficient. Can use full operating voltage across entire temperature range (−55 °C to 125 °C)	Maximum operating temperature limited to about 125 °C.

Polypropylene Plastic Film Capacitors	Polypropylene	Has become the most popular capacitor dielectric. Extremely low dissipation factor, higher dielectric strength than polycarbonate and polyester films, low moisture absorption, and high insulation resistance. May use plates of foil, metalized film, or a combination. Film is compatible with self-healing technology to improve reliability. Usable in high frequency applications due to very low dielectric losses. Larger value and higher voltage types from 1 to 100 μF at up to 440 V AC are used as run capacitors in some types of single phase electric motors.	More susceptible to damage from transient over-voltages or voltage reversals than oil-impregnated Kraft paper for pulsed power energy discharge applications.
Polysulphone Plastic Film Capacitors	Polysulfone	Similar to polycarbonate. Can withstand full voltage at comparatively higher temperatures. Moisture pick-up is typically 0.2%, limiting its stability.	Very limited availability and higher cost
PTFE Fluorocarbon (TEFLON) Film Capacitors	Polytetra- fluoroethylene	Lowest loss solid dielectric. Operating temperatures up to 250 °C, extremely high insulation resistance, and good stability. Used in stringent, mission-critical applications	Large size (due to low dielectric constant), and higher cost than other film capacitors.
Polyamide Plastic Film Capacitors	Polyamide	Operating temperatures of up to 200 °C. High insulation resistance, good stability and low dissipation factor.	Large size and high cost.
Metalized Plastic Film Capacitors	Polyester or Polycarbonate	Reliable and significantly smaller in size. Thin metalization can be used to advantage by making capacitors "self healing".	Thin plates limit maximum current carrying capability.
Stacked Plate Mica Capacitors	Mica	Advantages of mica capacitors arise from the fact that the dielectric material (mica) is inert. It does not change physically or chemically with age and it has good temperature stability. Very resistant to corona damage	Unless properly sealed, susceptible to moisture pick-up which will increase the power factor and decrease insulation resistance. Higher cost due to scarcity of high grade dielectric material and manually-intensive assembly.
Metalized Mica or Silver Mica Capacitors	Mica	Silver mica capacitors have the above mentioned advantages. In addition, they have much reduced moisture infiltration.	Higher cost
Glass Capacitors	Glass	Similar to Mica Capacitors. Stability and frequency characteristics are better than silver mica capacitors. Ultra-reliable, ultra-stable, and resistant to nuclear radiation.	High cost.
Class-I Temperature Compensating Type Ceramic Capacitors	Mixture of complex Titanate compounds	Low cost and small size, excellent high frequency characteristics and good reliability. Predictable linear capacitance change with operating temperature. Available in voltages up to 15,000 volts	Capacitance changes with change in applied voltage, with frequency and with aging effects.

Class-II High dielectric strength Type Ceramic Capacitors	Barium titanate based dielectrics	Smaller than Class-I type due to higher dielectric strength of ceramics used. Available in voltages up to 50,000 volts.	Not as stable as Class-I type with respect to temperature, and capacitance changes significantly with applied voltage.
Aluminum Electrolytic Capacitors	Aluminum oxide	Very large capacitance to volume ratio, inexpensive, polarized. Primary applications are as smoothing and reservoir capacitors in power supplies.	Dielectric leakage is high, large internal resistance and inductance limits high frequency performance, poor low temperature stability and loose tolerances. May vent or burst open when overloaded and/or overheated. Limited to about 500 volts.
Lithium Ion Capacitors	Lithium ion	The lithium ion capacitors have a higher power density as compared to batteries and LIC's are safer in use than LIB's in which thermal runaway reactions may occur. Compared to electric double layer capacitor (EDLC), the LIC has a higher output voltage. They both have similar power densities, but energy density of an LIC is much higher.	New technology.
Tantalum Electrolytic Capacitors	Tantalum oxide	Large capacitance to volume ratio, smaller size, good stability, wide operating temperature range, long reliable operating life. Extensively used in miniaturized equipment and computers. Available in both polarized and unpolarized varieties. Solid tantalum capacitors have much better characteristics than their wet counterparts.	Higher cost than aluminum electrolytic capacitors. Voltage limited to about 50 volts. Explodes quite violently when voltage rating, current rating, or slew rates are exceeded, or when a polarized version is subjected to reverse voltage.
Electrolytic double-layer capacitors (EDLC) Supercapacitors	Thin Electrolyte layer and Activated Carbon	Extremely large capacitance to volume ratio, small size, low ESR. Available in hundreds, or thousands, of farads. A relatively new capacitor technology. Often used to temporarily provide power to equipment during battery replacement. Can rapidly absorb and deliver larger currents than batteries during charging and discharging, making them valuable for hybrid vehicles. Polarized, low operating voltage (volts per capacitor cell). Groups of cells are stacked to provide higher overall operating voltage.	Relatively high cost.
Alternating current oil-filled Capacitors	Oil-impregnated paper	Usually PET or polypropylene film dielectric. Primarily designed to provide very large capacitance for industrial AC applications to withstand large currents and high peak voltages at power	Limited to low frequency applications due to high dielectric

		line frequencies. The applications include AC motor starting and running, phase splitting, power factor correction, voltage regulation, control equipment, etc..	losses at higher frequencies.
Direct current oil-filled capacitors	Paper or Paper-polyester film combination	Primarily designed for DC applications such as filtering, bypassing, coupling, arc suppression, voltage doubling, etc...	Operating voltage rating must be derated as per the curve supplied by the manufacturer if the DC contains ripple. Physically larger than polymer dielectric counterparts.
Energy Storage Capacitors	Kraft capacitor paper impregnated with electrical grade castor oil or similar high dielectric constant fluid, with extended foil plates	Designed specifically for intermittent duty, high current discharge applications. More tolerant of voltage reversal than many polymer dielectrics. Typical applications include pulsed power, electromagnetic forming, pulsed lasers, Marx generators, and pulsed welders.	Physically large and heavy. Significantly lower energy density than polymer dielectric systems. Not self-healing. Device may fail catastrophically due to high stored energy.
Vacuum Capacitors	Vacuum capacitors use highly evacuated glass or ceramic chamber with concentric cylindrical electrodes.	Extremely low loss. Used for high voltage high power RF applications, such as transmitters and induction heating where even a small amount of dielectric loss would cause excessive heating. Can be self-healing if arc-over current is limited.	Very high cost, fragile, physically large, and relatively low capacitance.

contain some resistance in addition to their other properties. A low ESR capacitor typically has an ESR of 0.01 Ω. Low values are preferred for high-current, pulse applications. Low ESR capacitors have the capability to deliver huge currents into short circuits, which can be dangerous.

For capacitors, ESR takes into account the internal lead and plate resistances and other factors. An easy way to deal with these inherent resistances in circuit analysis is to express each real capacitor as a combination of an ideal component and a small resistor in series, the resistor having a value equal to the resistance of the physical device.

Equivalent series inductance (ESL)

ESL in signal capacitors is mainly caused by the leads used to connect the plates to the outside world and the series interconnects used to join sets of plates together internally. For any real-world capacitor, there is a frequency above DC at which it ceases to behave as a pure capacitance. This is called the (first) resonant frequency. This is critically important with decoupling high-speed logic circuits from the power supply. The decoupling capacitor supplies transient current to the chip. Without decouplers, the IC demands current faster than the connection to the power supply can supply it, as parts of the circuit rapidly switch on and off. Large capacitors tend to have much higher ESL than small ones. As a result, electronics will frequently use multiple bypass capacitors—a small 0.1 µF rated for high frequencies and a large electrolytic rated for lower frequencies, and occasionally, an intermediate value capacitor.

Maximum voltage and current

Important properties of capacitors are the maximum working voltage (potential, measured in volts) and the amount of energy lost in the dielectric. For high-power or high-speed capacitors, the maximum ripple current, peak current, fault current, and percent voltage reversal are further considerations. Typically the voltage is 66% of the rated voltage. A voltage higher than that, usually reduces the life expectancy depending on manufacturer. The time for a voltage to discharge is 6 time constants.

Temperature dependence

Another major non-ideality is temperature coefficient (change in capacitance with temperature) which is usually quoted in parts per million (ppm) per degree Celsius.

Aging

When refurbishing old (especially audio) equipment, it is a good idea to replace all of the electrolyte-based capacit-

Series	Values										
E3	1.0				2.2				4.7			
E6	1.0		1.5		2.2		3.3		4.7		6.8	
E12	1.0	1.2	1.5	1.8	2.2	2.7	3.3	3.9	4.7	5.6	6.8	8.2

ors. After long storage, the electrolyte and dielectric layer within electrolytic capacitors may deteriorate; before powering up equipment with old electrolytics, it may be useful to apply low voltage to allow the capacitors to reform before applying full voltage. Deteriorating capacitors are a frequent cause of hum in aging audio equipment.

Non-polarised capacitors also suffer from aging, changing their values slightly over long periods of time.

In high voltage DC applications, accumulated capacitor stress due to in-rush currents at circuit power-up can be minimized with a pre-charge circuit.

Dielectric absorption (soakage)

Some types of dielectrics, when they have been holding a high voltage for a long time, maintain a "memory" of that voltage. After they have been quickly discharged to zero volts, if they are then left disconnected, the voltage across the capacitor will slowly recover some fixed percentage—up to 10%–of the "remembered" voltage. This percentage is a measure of the dielectric absorption, and depends on the type of dielectric.

In the construction of long-time-constant integrators, it is important that the capacitor will not retain a residual charge when shorted. This phenomenon of unwanted charge storage is called *dielectric absorption* or *soakage*, and it effectively creates a memory effect in the capacitor. This is a non-linear phenomenon, and is also important when building very low distortion filters. This is also why, for safety, high voltage capacitors are stored with their terminals short circuited.

For long-time-constant integrators and sample-and-hold systems, good designers pick capacitors that have almost no dielectric absorption hysteresis–capacitors such as those employing polystyrene, polypropylene, NPO ceramic, and Teflon dielectrics. [2][3]

Voltage non-linearities

Capacitors may also change capacitance with applied voltage. This effect is more prevalent in high *k* ceramic and some high voltage capacitors. This can be another small source of non-linearity when building low distortion filters.

Leakage

Capacitors also have some level of parasitic resistance across the terminals which is called 'leakage'. This fundamentally limits how long capacitors can store charge. Historically, this was a major source of problems in some types of applications (long RC timers, sample-and-holds, etc.)

Component values and identification

Capacitor markings

Most capacitors have numbers printed on their bodies to indicate their electrical characteristics.

Some are indicated with XYZ J/K/M VOLTS V where XYZ represents the capacitance (calculated as $XY \times 10^{Z}$), the letters J, K or M indicate the tolerance (±5%, ±10% and ±20% respectively) and VOLTS V represents the working voltage.

Example:

A capacitor with the following text on its body:

105 K 330 V

has a capacitance of 10×10^5 pF = 1 μF (±10%) with a working voltage of 330 V.

A capacitor with the following text:

473 M 100 V

has a capacitance of 47×10^3 pF = 47 nF (±20%) with a working voltage of 100 V.

Standard values

In the early days of electronics, components were often made to fit a specific need, the values of early capacitors were of arbitrary (usually integer) base numbers. The more common values included 1.0, 1.5, 2.0, 3.0, 5.0, 6.0, and 8.0 as base numbers, but they were not necessarily limited to these values. Values were generally in microfarads (μF) and could be multiplied by any power of ten; picofarads were often called micro-microfarads (μμF) then.

In the late 1960s, a standardized set of geometrically increasing base values was introduced. According to the number of values per decade, these were called the E3, E6 or E12 series:

The same series are used for resistors, where E24/E48/E96 series are additionally used for even lower-tolerance components. These number series are known as preferred values.

Since most electrolytic capacitors have a tolerance range of ±20%, meaning that the manufacturer is stating that the actual value of the capacitor lies within ±20% of its nominal value, they are normally available in E6 (or even just E3) series values only (e.g. 2200 μF, 3300 μF,

preferred	in pF	in nF	in μF
1pF	1	0.001	0.000,001
10pF	10	0.01	0.000,01
100pF	100	0.1	0.000,1
1nF	1000	1	0.001
10nF	10,000	10	0.01
100nF	100,000	100	0.1
1μF	1,000,000	1000	1

Color	Significant digits	Multiplier	Capacitance tolerance	Characteristic	DC working voltage	Operating temperature	EIA/vibration
Black	0	1	±20%	—	—	−55 °C to +70 °C	10 to 55 Hz
Brown	1	10	±1%	B	100	—	—
Red	2	100	±2%	C	—	−55 °C to +85 °C	—
Orange	3	1,000	—	D	300	—	—
Yellow	4	10,000	—	E	—	−55 °C to +125°C	10 to 2000 Hz
Green	5	—	±5%	F	500	—	—
Blue	6	—	—	—	—	−55 °C to +150 °C	—
Violet	7	—	—	—	—	—	—
Grey	8	—	—	—	—	—	—
White	9	—	—	—	—	—	EIA
Gold	—	—	±0.5%*	—	1000	—	—
Silver	—	—	±10%	—	—	—	—

4700 μF) – the tolerance ranges overlap the intermediate values from the next higher series anyway.

Other types of capacitors, e.g. ceramic, can be manufactured to tighter tolerances and are available in E12 values (e.g. 47 pF, 56 pF, 68 pF).

Capacitors were once specified by their values in either microfarads or picofarads, which meant that both very small (such as 0.01 μF) and very large (such as 10,000 pF) numbers were in common use. Nowadays, it is considered preferable to use the nanofarad as well, and specify all values in the numeric range 1–999 only. Above 999 μF, the practice is not yet in common use; capacitors are not usually specified in millifarads (mF), probably because it would be too easily confused with microfarads (for which mF was once an acceptable abbreviation).

A table giving translations of previous commonly used multiples is as follows:

Colour coding

*Or ±0.5 pF, whichever is greater.

See also

- Capacitor plague (premature failure of some electrolytic capacitors)
- Supercapacitor
- Electronic devices and circuits
- Electronic color code
- Inductor

Notes

[1] The abbreviation "MF" was used to indicate microfarads at the time; "MMF" was common for micro-microfarad = 10^{-12} F or picofarads.

[2] "Understand Capacitor Soakage to Optimize Analog Systems" by Bob Pease 1982 http://www.national.com/rap/Application/0,1570,28,00.html

[3] "Modeling Dielectric Absorption in Capacitors" by Ken Kundert http://www.designers-guide.org/Modeling/da.pdf

References

- Tre Clifford *Super Charged: A Tiny South Korean Company is Out to Make Capacitors Powerful enough to Propel the Next Generation of Hybrid-Electric Cars*, IEEE Spectrum, January, 2005 Vol 42, No. 1, North American Edition.
- *The ARRL Handbook for Radio Amateurs, 68th ed*, The Amateur Radio Relay League, Newington CT USA, 1991
- *Basic Circuit Theory with Digital Computations*, Lawrence P. Huelsman, Prentice-Hall, 1972
- *Philosophical Transactions of the Royal Society LXXII*, Appendix 8, 1782 (Volta coins the word *condenser*)
- A. K. Maini *Electronic Projects for Beginners*, "Pustak Mahal", 2nd Edition: March, 1998 (INDIA)

External links

- Spark Museum (von Kleist and Musschenbroek)
- Biography of von Kleist
- Modeling Dielectric Absorption in Capacitors
- A different view of all this capacitor stuff