Dielectric Properties of Ceramics

MATR 4347

Dielectric

- An electrical insulator
- Electrical behaviour is properties associated with certain ceramics & polymer but not metal
- E.g : $BaTiO_3$
  - Structure- perovskites
  - Used in capacitor
  - It is polarized in the absence of applied electric field
  - Structure change create permanent electric dipole that cause the materials to become polarized
  - Polarization allows the materials to store charge

Polarization principles

ferroelectricity

- Polarized in the absence of an applied electric field
- Direction of polarization can be reversed
- Self polarizing
- Used in capacitor

pyroelectric

- Spontaneous polarization of dielectric depend strongly on temperature
- Dipole moments vary as the crystal expands or contracts
- E.g. intruder alarms, thermal imaging

piezoelectric

- Dimensions of dielectric may change when it is polarized
- Principle of converting energy by applying pressure to a crystal
- Application of external force produces on electric (polarization)
- E.g. MEMS , Sonar, medical ultrasound imaging

Ceramic capacitors

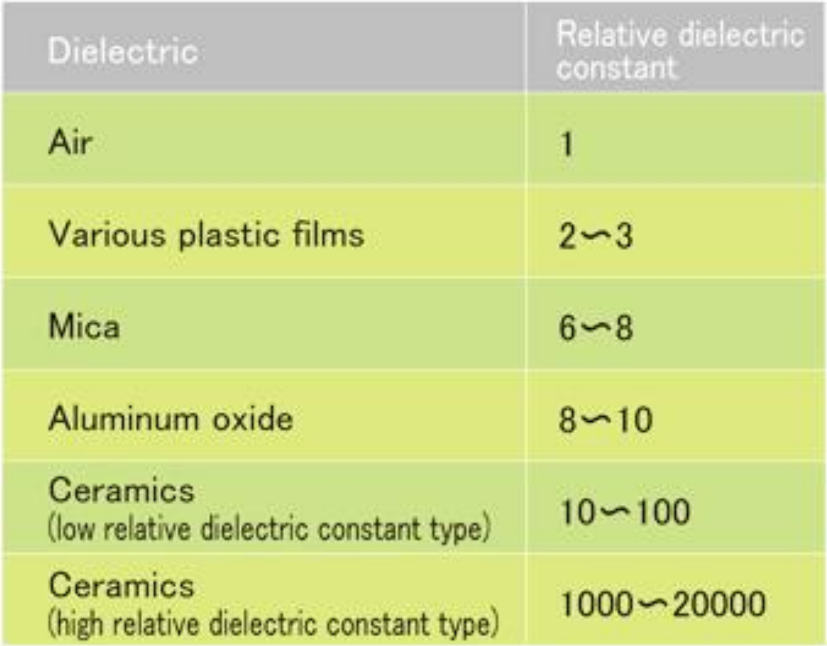
- Capacitance is defined as the total charge stored by the capacitor
- C=Q/V
- It depends on the
  - Dielectric between the conductor
  - Area of each conductor, A
  - Separation between them
- Example ceramic capacitor
  - Film capacitors using in memory devices
  - Single layer discrete capacitors (Disk capacitor)
  - Multilayer chip capacitor (MLCC)

Dielectric Constant

- The capacitance, C, of a capacitor formed by two parallel plates of area A spaced d apart with the area between the plates filled with dielectric material with a relative dielectric constant of ε

$$C = \frac{\varepsilon \varepsilon_0 A}{d}$$

☐Various dielectrics and their relative dielectric constant



Dielectric	Relative dielectric constant
Air	1
Various plastic films	2〜3
Mica	6〜8
Aluminum oxide	8〜10
Ceramics (low relative dielectric constant type)	10〜100
Ceramics (high relative dielectric constant type)	1000〜20000

Capacitors

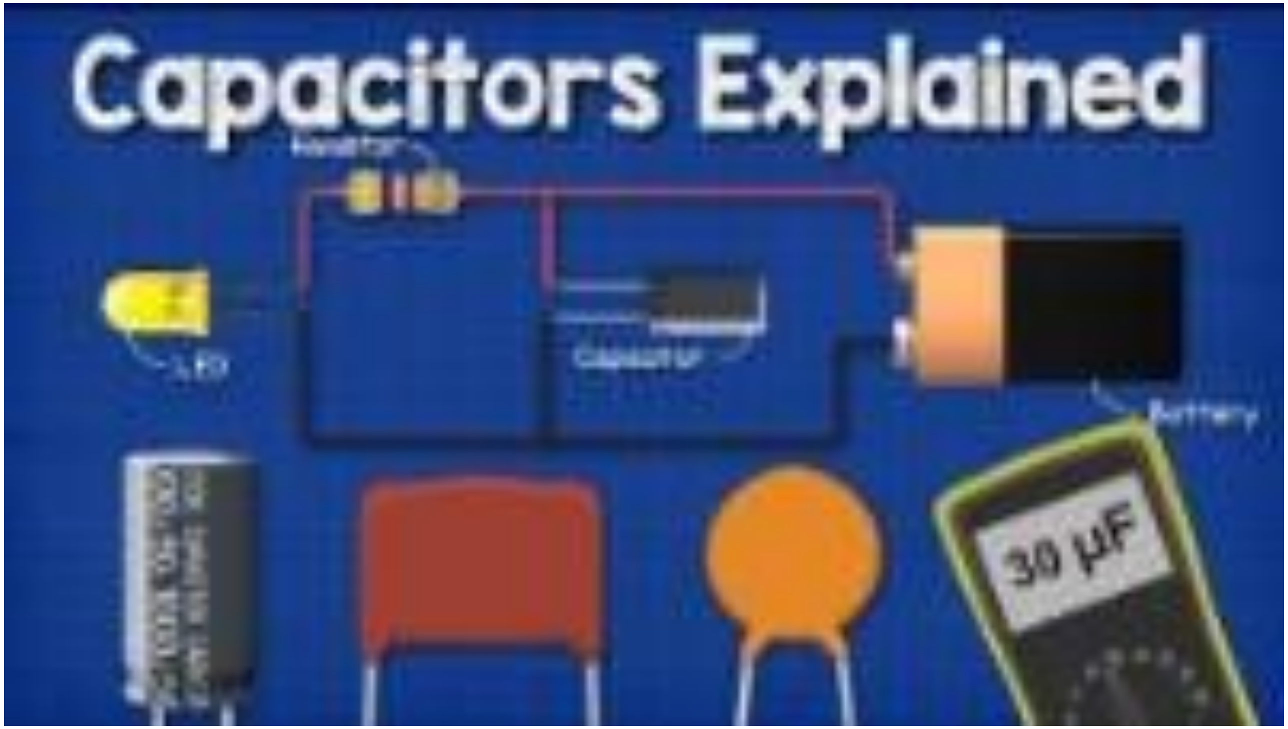
- The basic formula for the capacitance of a parallel-plate capacitor is:

$$C = \varepsilon_r \varepsilon_o \frac{A}{d}$$

- To increase *C*, one either increases ε, increases *A*, or decreases *d*.
- Early capacitors consisted of metal foils separated by wax (ε ~ 2.5), mica (ε ~ 3 - 6), steatite (ε ~ 5.5 - 7.5), or glass (ε ~ 5 - 10).
- The use of titania provided a significant increase (ε ~ 170), was followed by perovskite-based, such as $BaTiO_3$ (ε ~ 1000).

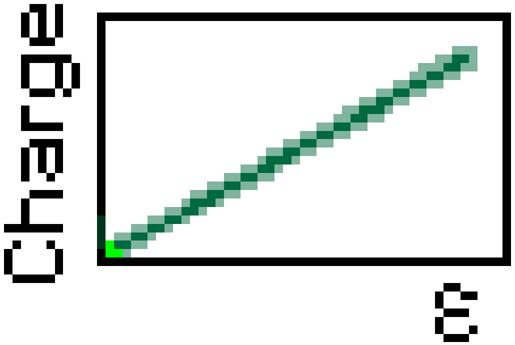
How capacitor works?

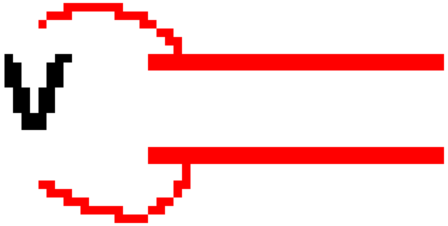
- https://www.youtube.com/watch?v=X4EUwTwZ110



$$C = \varepsilon_r \varepsilon_o \frac{A}{d}$$

$$Q = \varepsilon_r \varepsilon_o \frac{AV}{d}$$





$Q = CV$

Q: charge (Coulomb)

C: capacitance (Farad)

V: potential difference (Volt)

d: separation/thickness (meter)

ε_o: permitivity of vacuum =

8.854×10^{-12} C^2/m^2 or F/m

ε_r: dielectric constant

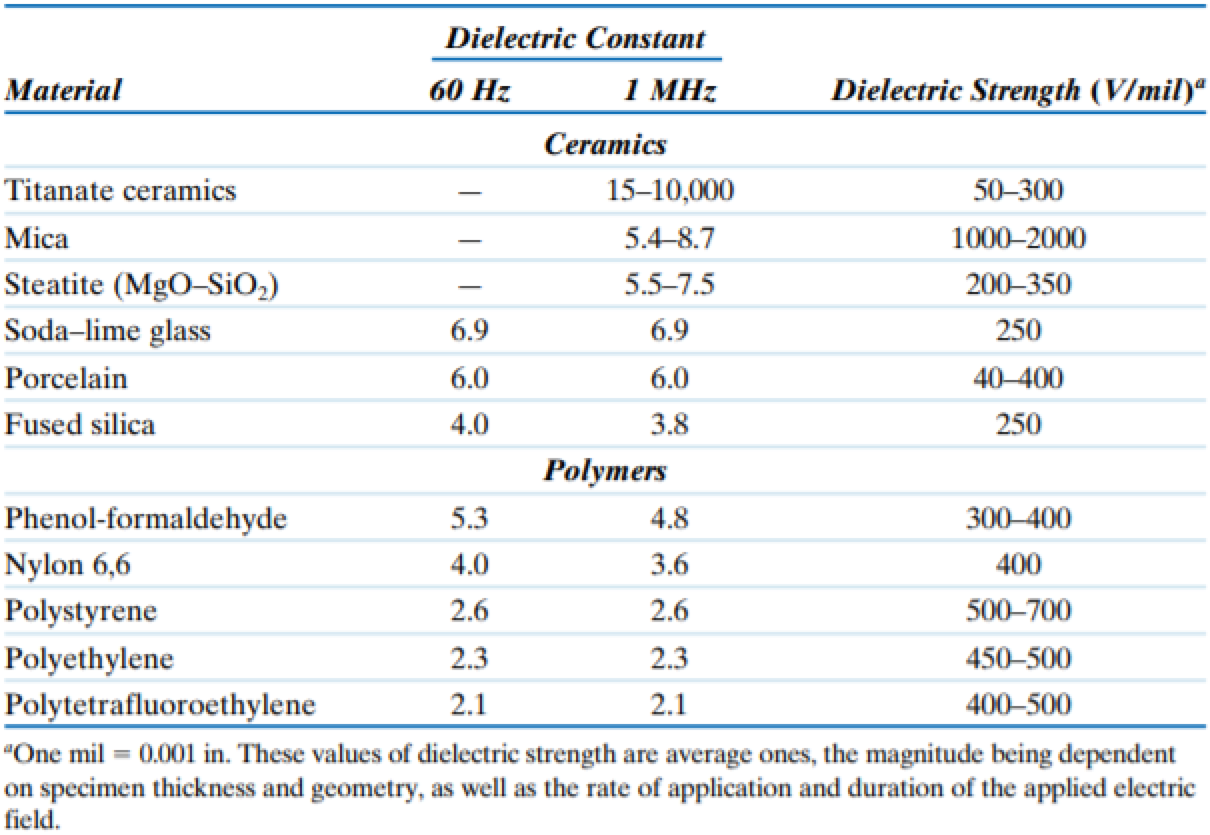
Example questions

- Consider a parallel-plate capacitor having an area of 6.45 10^{-4} m^2 and a plate separation of 2 x10^{-3} m across which a potential of 10 V is applied. If a material having a dielectric constant of 6.0 is positioned within the region between the plates, compute the following:
  (a) The capacitance
  (b) The magnitude of the charge stored on each plate

- Consider a parallel-plate capacitor having an area of 2800 mm^2 and a plate separation of 4 mm, and with a material of dielectric constant 4.0 positioned between the plates.
  (a) What is the capacitance of this capacitor?
  (b) Compute the electric field that must be applied for 8.0 x 10^{-9} C to be stored on each plate.

Example questions

- A parallel-plate capacitor with dimensions of 120 mm by 30 mm and a plate separation of 3 mm must have a minimum capacitance of 38 pF (3.8×10^{-11} F) when an AC potential of 500 V is applied at a frequency of 1 MHz. Which of those materials listed in Table 19.5 are possible candidates? Why?



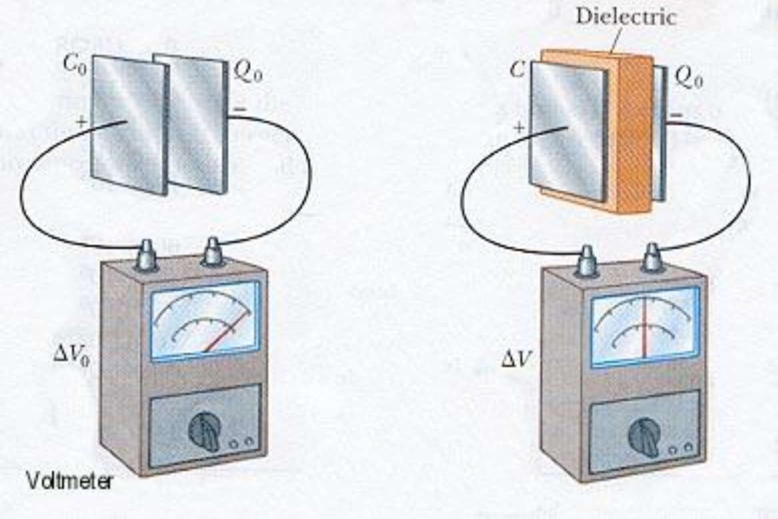
	Dielectric Constant		
Material	***60 Hz***	***1 MHz***	***Dielectric Strength (V/mil)[a]***
	Ceramics		
Titanate ceramics	—	15–10,000	50–300
Mica	—	5.4–8.7	1000–2000
Steatite ($MgO–SiO_2$)	—	5.5–7.5	200–350
Soda–lime glass	6.9	6.9	250
Porcelain	6.0	6.0	40–400
Fused silica	4.0	3.8	250
	Polymers		
Phenol-formaldehyde	5.3	4.8	300–400
Nylon 6,6	4.0	3.6	400
Polystyrene	2.6	2.6	500–700
Polyethylene	2.3	2.3	450–500
Polytetrafluoroethylene	2.1	2.1	400–500

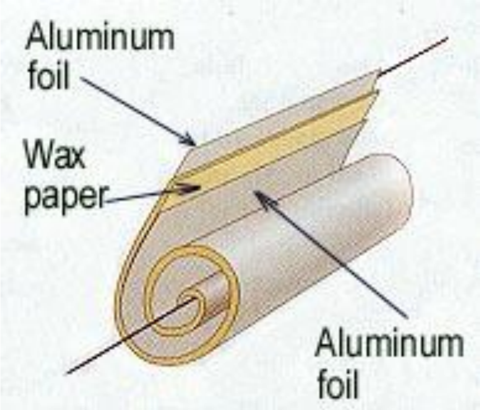
[a] One mil = 0.001 in. These values of dielectric strength are average ones, the magnitude being dependent on specimen thickness and geometry, as well as the rate of application and duration of the applied electric field.

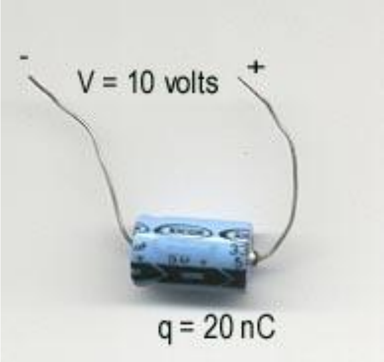
Example questions

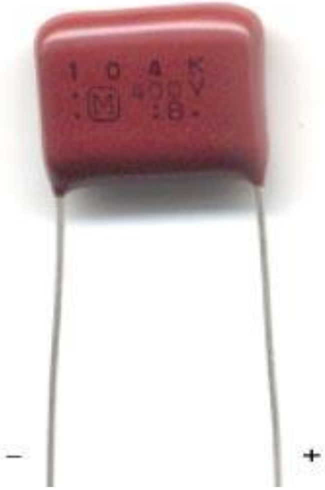
- A parallel plate capacitor consists of metal sheets with an area of 1.35 m and are separated by calcium titanate sheets with dielectric constant of 2800 and thickness of 0.002 mm. The maximum electric field across the calcium titanate is 60 x 106 V/m. Calculate the capacitance, maximum voltage and maximum energy that can be stored in the capacitor.

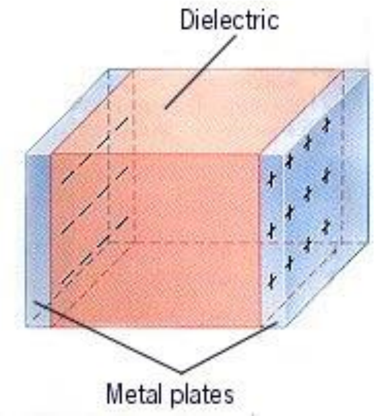
Capacitors

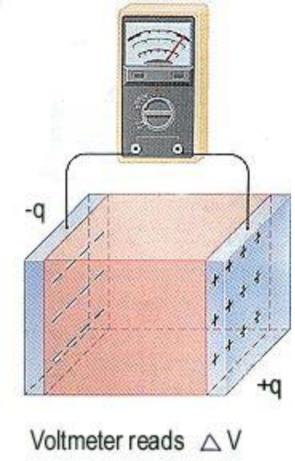






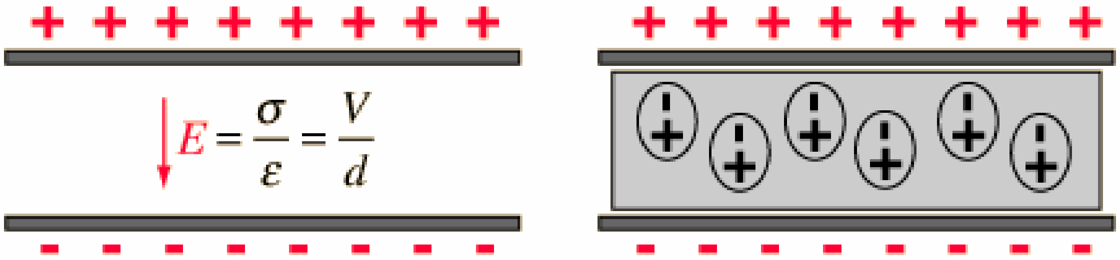






Tantalum capacitor

Capacitors



For air, $\varepsilon \approx \varepsilon_0$

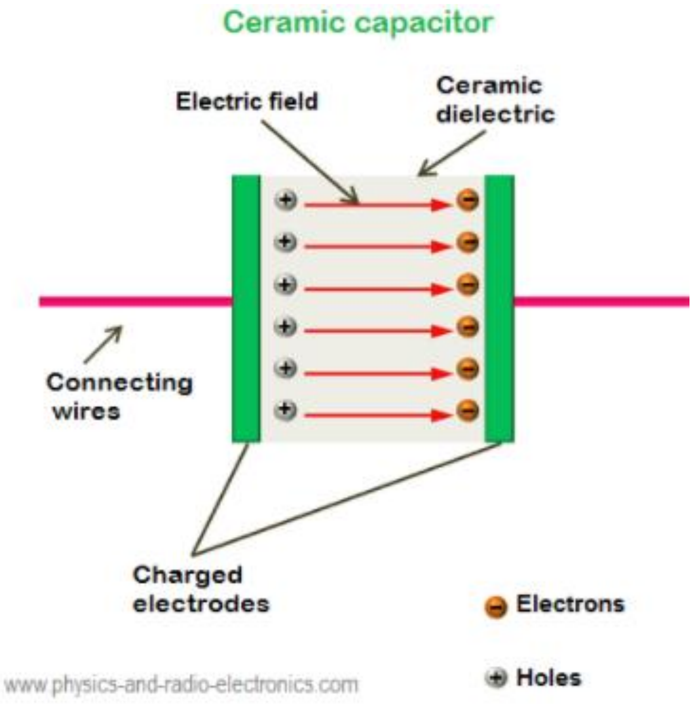
$$E_{\text{effective}} = E - E_{\text{polarization}} = \frac{\sigma}{\varepsilon\varepsilon_0}$$

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

The capacitance is increased by the factor ε

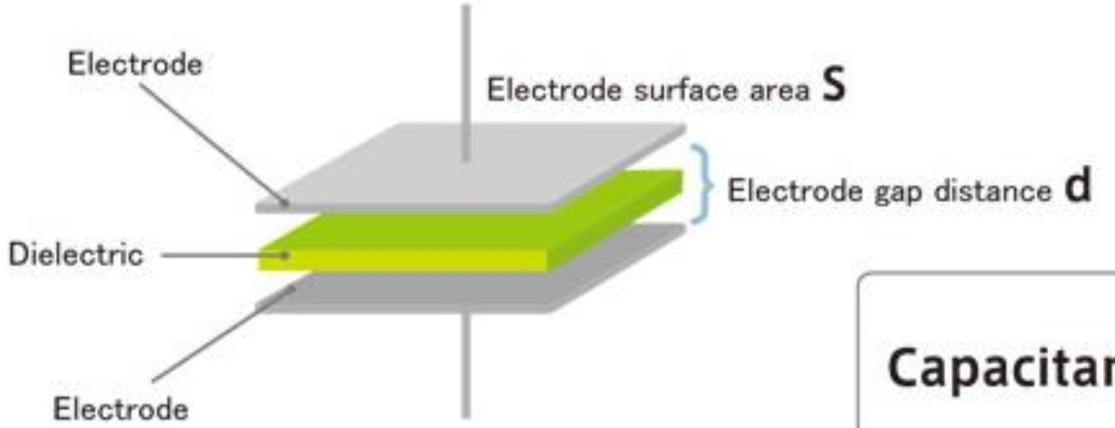
$$C = \frac{\varepsilon\varepsilon_0 A}{d}$$

$$E_{\text{stored}} = \frac{1}{2}CV^2 = \frac{1}{2}\frac{Q^2}{C} = \frac{1}{2}VQ$$



- Typical capacitor comprises 2 conductive plates & non-conductive dielectric material.
- The dielectric material separates 2 conductive metal electrode plates.
- Applying voltage to the electrode plates of a capacitor causes an electric field in the non-conductive dielectric material.
- This electric field stores energy.
- The dielectric constant, also commonly known as relative permittivity, is the measure of the ability of a material to store electrical energy & is one of the key properties of a dielectric material.
- Capacitance of a parallel plate capacitor is a function of distance between plates, plate area, & dielectric material constant.
- Increase in plate area & dielectric constant results in an increase in capacitance
- Increase in the separation distance between the plates results in a decrease in capacitance.
- Different dielectric materials have different dielectric constants.

□Basic capacitor construction and capacitance



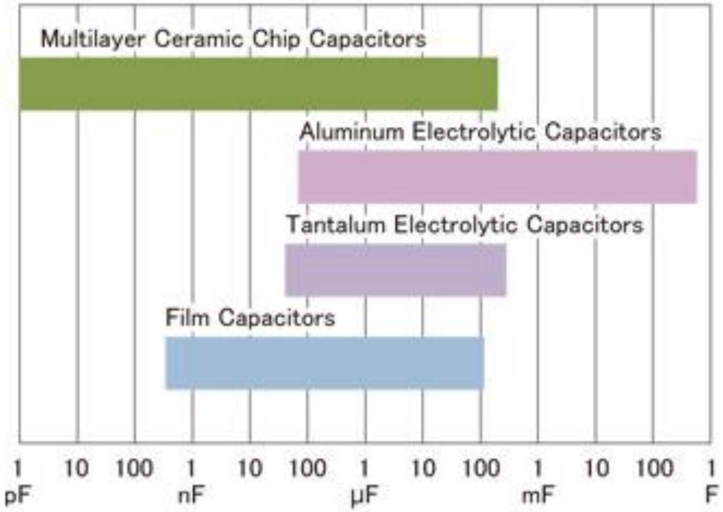
Capacitance $C = \varepsilon_0 \varepsilon_r \frac{S}{d}$

ε_0: Dielectric constant in vacuum (8.854×10^{-12} F/m)

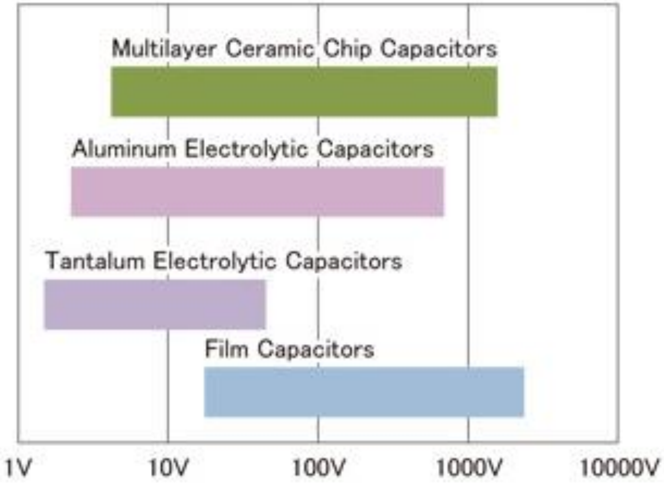
ε_r : Relative dielectric constant in a material

- Larger electrode surface area = larger capacitance
- Higher relative dielectric constant = larger capacitance
- Smaller electrode gap distance = larger capacitance

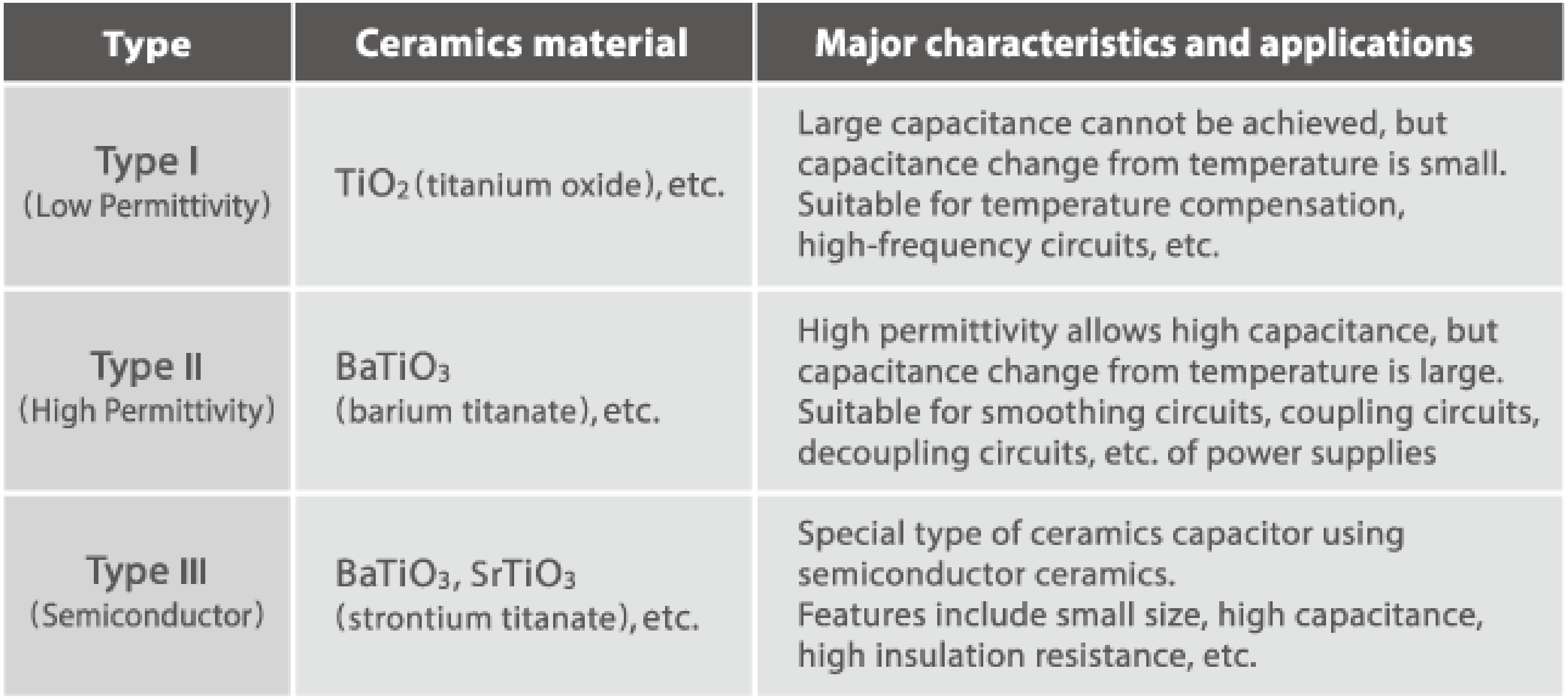
□Capacitance ranges of various capacitor types



□Rated voltage range of various capacitors.



Classification by dielectric ceramics



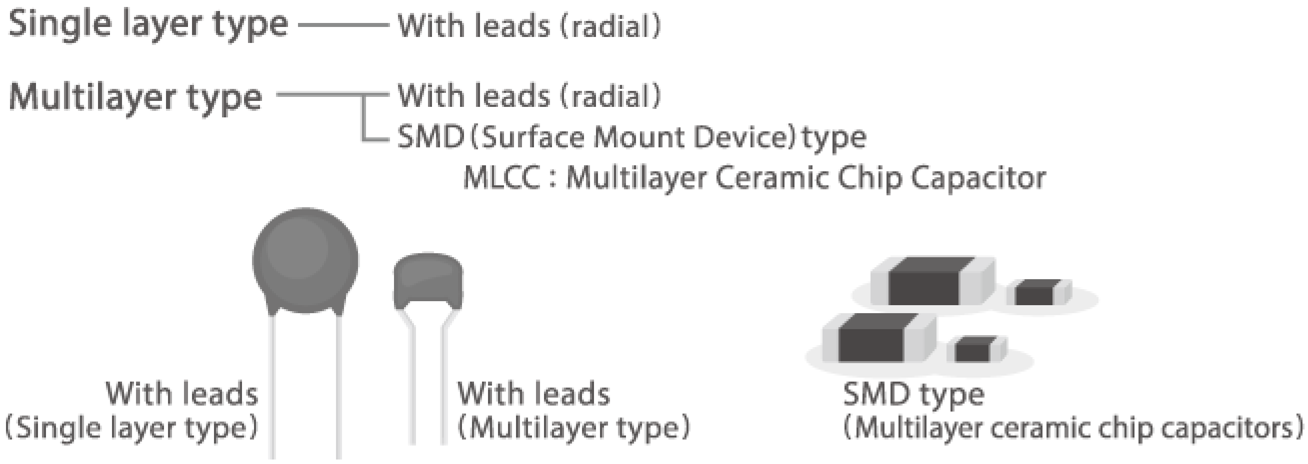
Type	Ceramics material	Major characteristics and applications
Type I (Low Permittivity)	TiO_2 (titanium oxide), etc.	Large capacitance cannot be achieved, but capacitance change from temperature is small. Suitable for temperature compensation, high-frequency circuits, etc.
Type II (High Permittivity)	$BaTiO_3$ (barium titanate), etc.	High permittivity allows high capacitance, but capacitance change from temperature is large. Suitable for smoothing circuits, coupling circuits, decoupling circuits, etc. of power supplies
Type III (Semiconductor)	$BaTiO_3$, $SrTiO_3$ (strontium titanate), etc.	Special type of ceramics capacitor using semiconductor ceramics. Features include small size, high capacitance, high insulation resistance, etc.

Ceramic Capacitor

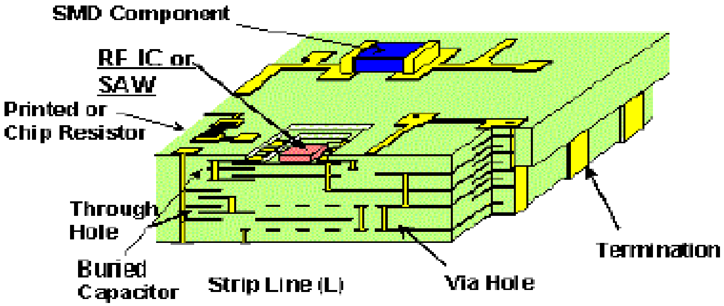
1- Film capacitors used in memory devices

2- Single layer discrete capacitors (disc capacitor)

3- Multilayer chip capacitors (MLCCs)



Capacitors



- DRAM chips currently utilize capacitors with Si_3N_4 or SiO_2 as dielectric materials.
- The electrodes are made of doped Si or poly-Si.
- Capacitors can be fabricated onto IC chips.
- They are commonly used in conjunction with transistors in DRAM.
- The capacitors help maintain the contents of memory.
- Because of their tiny physical size, these components have low capacitance.
- They must be recharged thousands of times per second or the DRAM will lose its data.

Multilayer Ceramic Capacitor

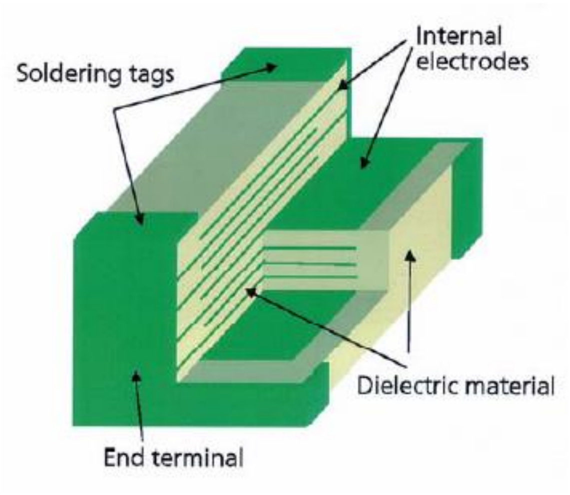
- The multilayer ceramic capacitor (MLCC):

$$C = \varepsilon_r \varepsilon_o \frac{A(N-1)}{d}$$

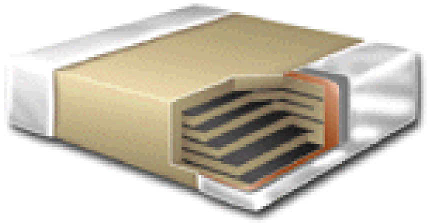
http://www.btu.com/images/smt_epp.jpg

- where *N* is the number of stacked plates.
- Ideally, the dielectric should have a low electrical conductivity so that the leakage current is not too large.

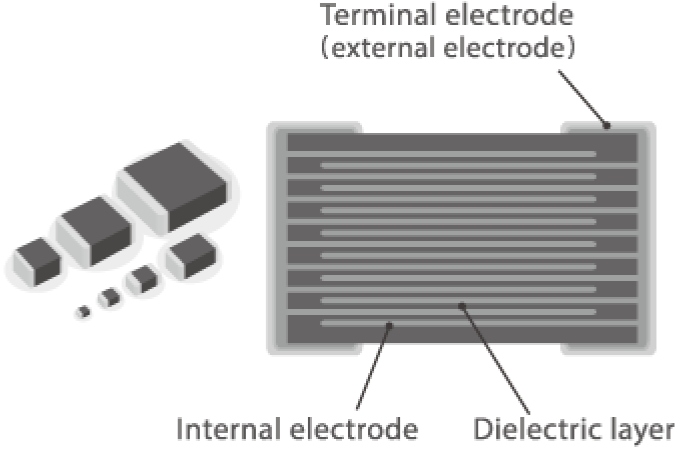
Multilayer Ceramic Capacitor



Ceramic surface-mount capacitors.



Cut-away view of multilayer ceramic capacitor.



- A multilayer ceramic chip capacitor incorporates multiple dielectric and internal electrode layers in a sandwiched configuration.
- Instead of using leads, terminal electrodes (external electrodes) are integrated in the SMD (surface mount device) itself, making the capacitor more compact.
- This saves space and enables high-density mounting on circuit boards.

$$C = \varepsilon_0 \varepsilon_r \frac{S}{d} N \quad [\mathrm{F}]$$

C : Capacitance [F]

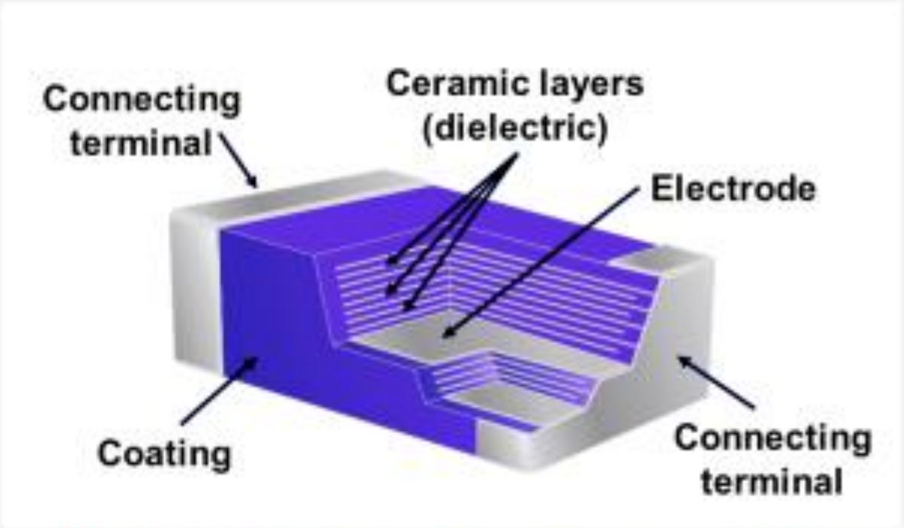
ε_0: Permittivity in a vacuum [F/m]

ε_r: Relative permittivity of dielectric

S : Electrode area [m^2]

d : Electrode gap distance [m]

N : Number of layers



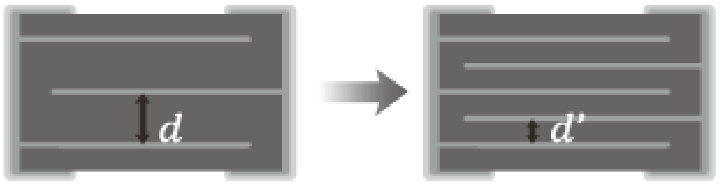
Circuit Functions Multilayer Ceramic Capacitor Model Detailing Standard Industry Capacitor Construction

Basic technologies for increasing capacitance of multilayer ceramic chip capacitors

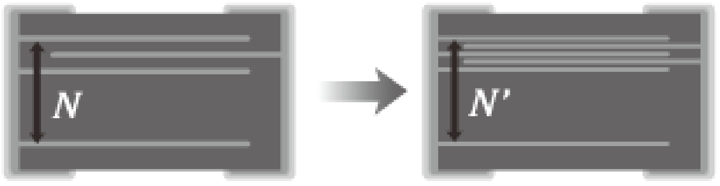
As can be deducted from the above equation, ways to increase the capacitance of multilayer ceramic chip capacitors are making:

1) the dielectric layer thinner,
2) reducing the distance between layers
3) increasing the number of layers to increase the total electrode area.

The basic technologies to achieve these aims are thin film technology and multilayering technology.



●Thin film technology
Making dielectric layers thinner and reducing the distance between electrodes



●Multilayering technology
Increasing the number of layers to increase the total electrode area

Ceramic Capacitor & Dielectric Materials

- Ceramic capacitor advantages - low cost, small size, transience resistance, and being non-polarized
- Weaknesses -having a large voltage coefficient and aging rate, which becomes increasingly problematic as industry standards move towards smaller and smaller capacitors.
- Large voltage coefficient causes a capacitor to be unstable over VDC, or Volts of Direct Current.
- Class of dielectric within a ceramic capacitor affects the capacitor's aging process.
- Ageing- negative logarithmic capacitance change that occurs in ceramic capacitors over time.
- The more stable the class of dielectric, the lower the aging rate.
- The aging rate/ aging constant - the %loss of capacitance due to the aging process of the dielectric which occurs during a decade of time. It is expressed as percent per logarithmic decade of hours.

Dielectric Strength

- Dielectric materials are insulators (conduction cannot generally occur).
- However, under certain conditions, dielectric materials can break down and conduct a significant current.
- Generally, the lattice of a dielectric has sufficient strength to absorb the energy from impacting electrons that are accelerated by the applied electric field.
- However, under a sufficiently large electric field, some electrons present in the dielectric will have sufficient kinetic energy to ionize the lattice atoms causing an avalanching effect.
- As a result, the dielectric will begin to conduct a significant amount of current.

Dielectric Strength

- This phenomenon is called dielectric breakdown and the corresponding field intensity is referred to as the dielectric breakdown strength.
- Dielectric strength may be defined as the maximum potential gradient to which a material can be subjected without insulating breakdown, that is

$$DS = \left(\frac{dV}{dx}\right)_{\max} = \frac{V_B}{d}$$

where *DS* is the dielectric strength in kV/mm,

V_B the breakdown voltage, and *d* the thickness.

Dielectric Strength

- Dielectric strength depends on
  - material homogeneity
  - specimen geometry
  - electrode shape and disposition
  - stress mode (ac, dc or pulsed)
  - ambient condition.