

Passive Components

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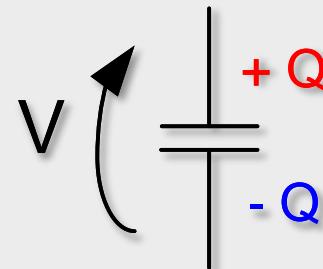
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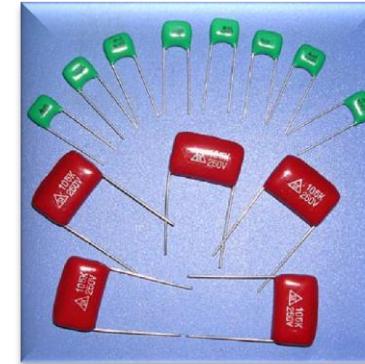


Capacitors

$$C = \frac{dQ}{dV}$$

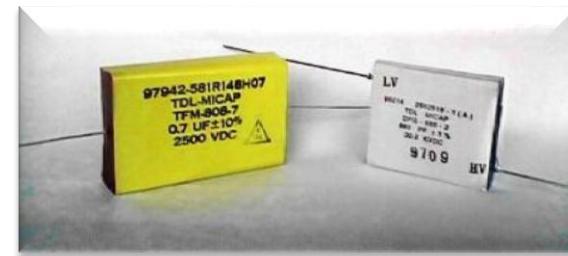


$$E_{stored} = \frac{1}{2} CV^2$$

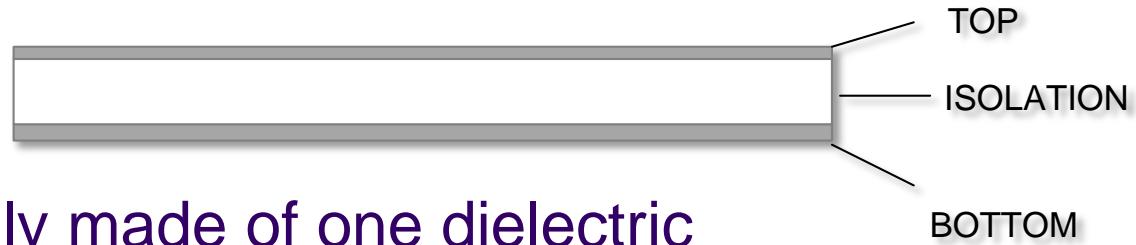


Applications:

- Supply filtering
- Interference suppression
- AC coupling



Capacitors



- A capacitor is usually made of one dielectric layer and two conducting layers
- Capacitance $C = \frac{dQ}{dV}$
 - Parallel plate capacitor $C = \epsilon \frac{S}{d}$
- Dielectric properties change with temperature:
 - Temperature coefficient $\alpha = \frac{1}{C} \frac{\partial C}{\partial T}$

Capacitors

- A capacitor is essentially an energy storage element:
- Energy stored $E_s = \frac{1}{2} CV^2$
- Only a limited amount of energy can be stored in a capacitor due the maximum voltage (max electric field E_R) that the oxide can withstand before breakdown

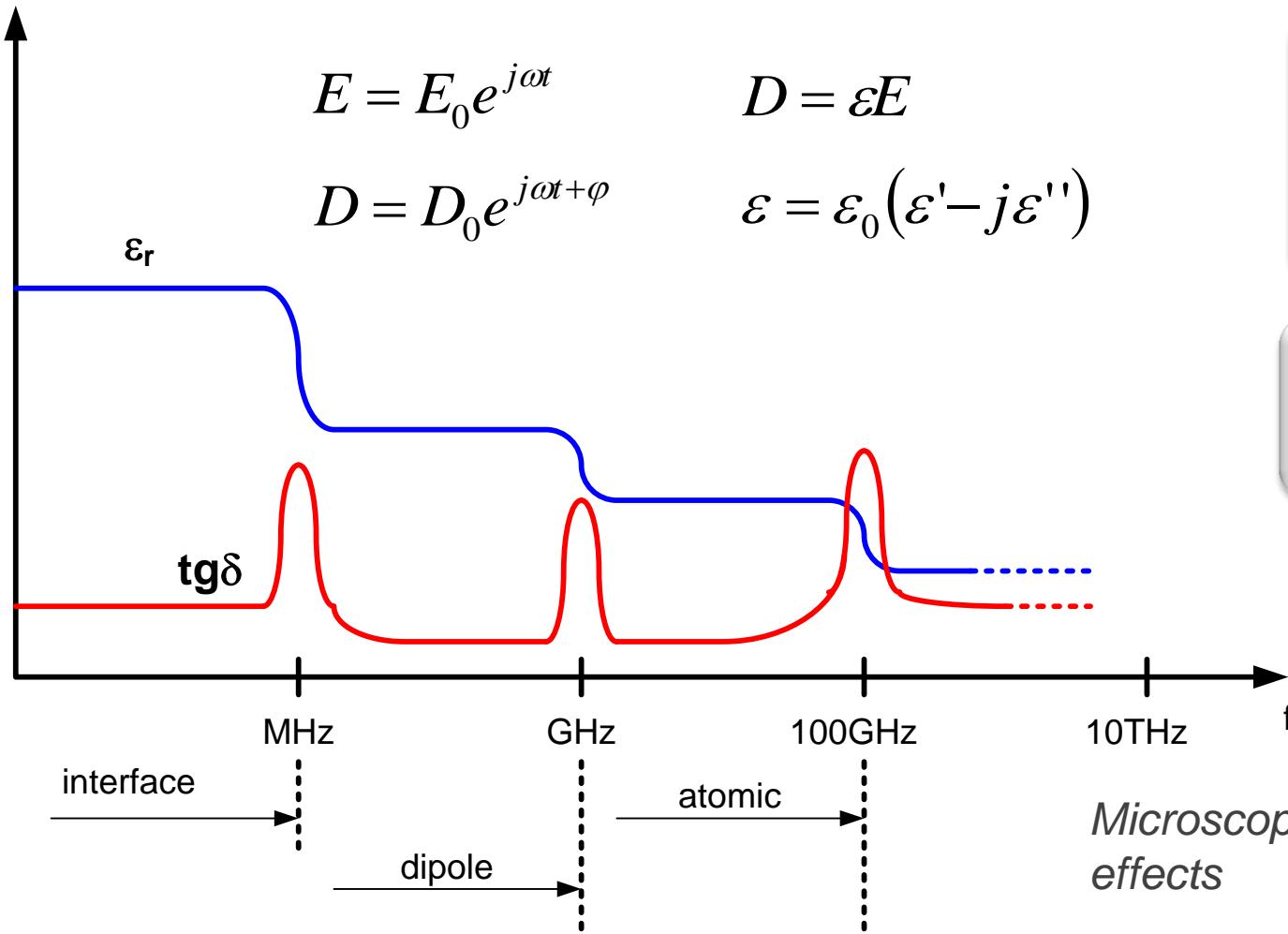
- Maximum energy density $E_v = \frac{E_s}{Vol} = \frac{1}{2} \epsilon E_R^2$

Maximum electric field

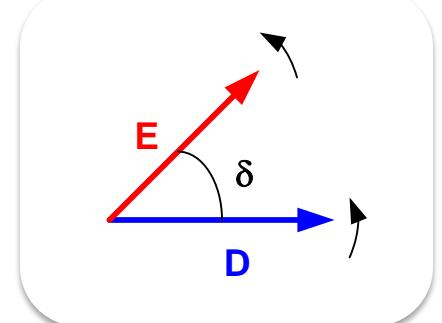
Electric permittivity

Dielectric Electrical Properties

Electric Permeability vs Frequency

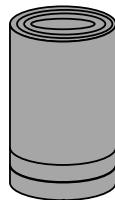


Loss tangent



$$\tan \delta = \frac{\epsilon''}{\epsilon'}$$

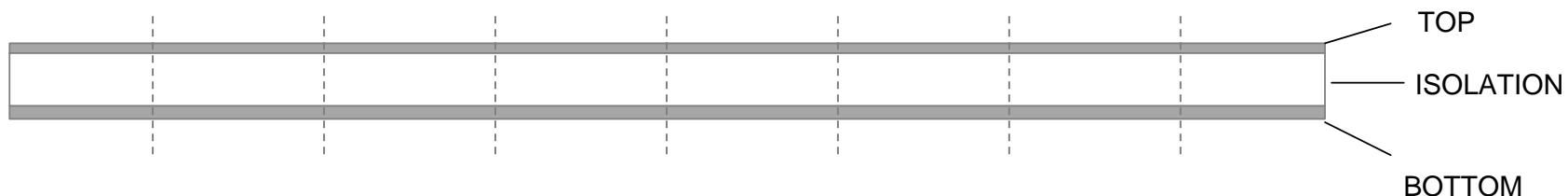
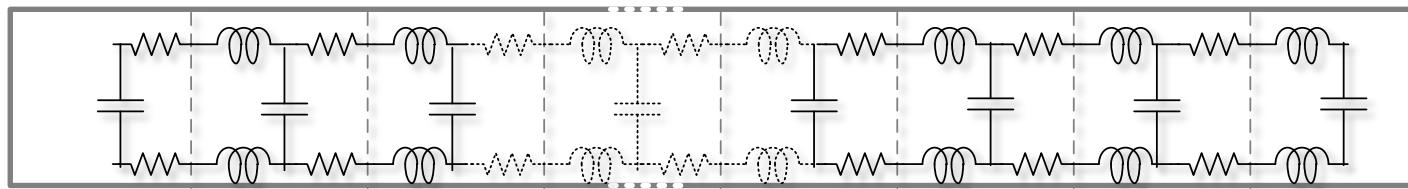
Capacitors: Distributed Effects



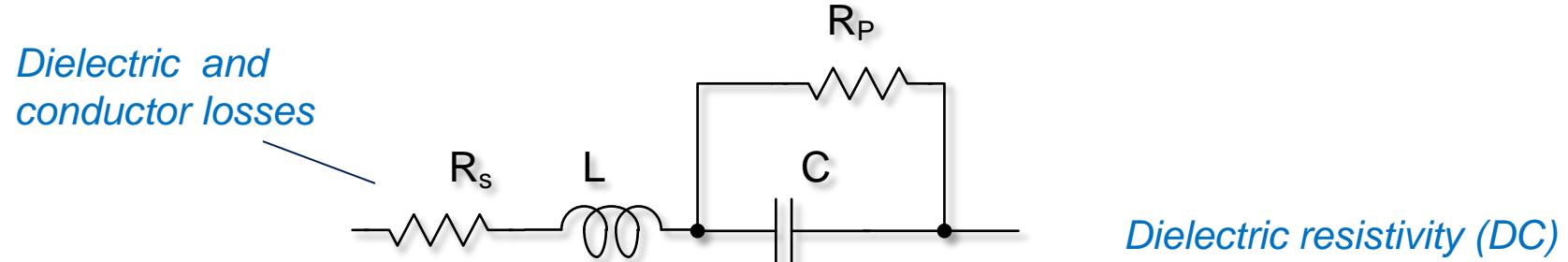
The capacitor can be divided into several sections in series:
Each section is modeled with an RLC equivalent circuit

- Very accurate but very complicated
- Can account for frequency-dependent effects

Equivalent Circuit



Simplified Equivalent Circuit



$$C = \epsilon_0 \epsilon_r \frac{S}{d}$$

$$Y = j\omega C + G$$

$$R_p = \rho \frac{d}{S}$$

- Loss tangent

$$\tan \delta = \frac{\text{Re}\{Y\}}{\text{Im}\{Y\}} = \frac{P_{diss}}{P_r} \quad \begin{aligned} &\frac{1}{2} G V^2 \\ &\frac{1}{2} \omega C' V^2 \end{aligned}$$

- Relaxation time constant

$$\tau = CR_p = \epsilon_0 \epsilon_r \rho$$

Dielectric Losses

If we ignore all other sources of loss (connectors, metal plates resistive losses, etc.), the capacitor loss tangent is given by the dielectric loss tangent ($\tan \delta$)

$$Y = j\omega C = j\omega\epsilon_0 (\epsilon' - j\epsilon'') \frac{S}{d}$$

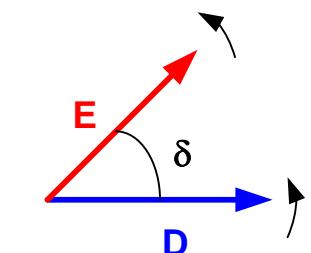
$$Y = j\omega C' + G \quad C' = \epsilon_0 \epsilon' \frac{S}{d} \quad G = \omega \epsilon_0 \epsilon'' \frac{S}{d}$$

$$P_{diss} = \frac{1}{2} G V^2$$

$$P_{diss,vol} = \frac{P_{diss}}{Sd} = \frac{1}{2} \omega \epsilon'' E^2$$

$$P_r = \frac{1}{2} \omega C' V^2$$

$$P_{r,vol} = \frac{P_r}{Sd} = \frac{1}{2} \omega \epsilon_0 \epsilon' E^2$$

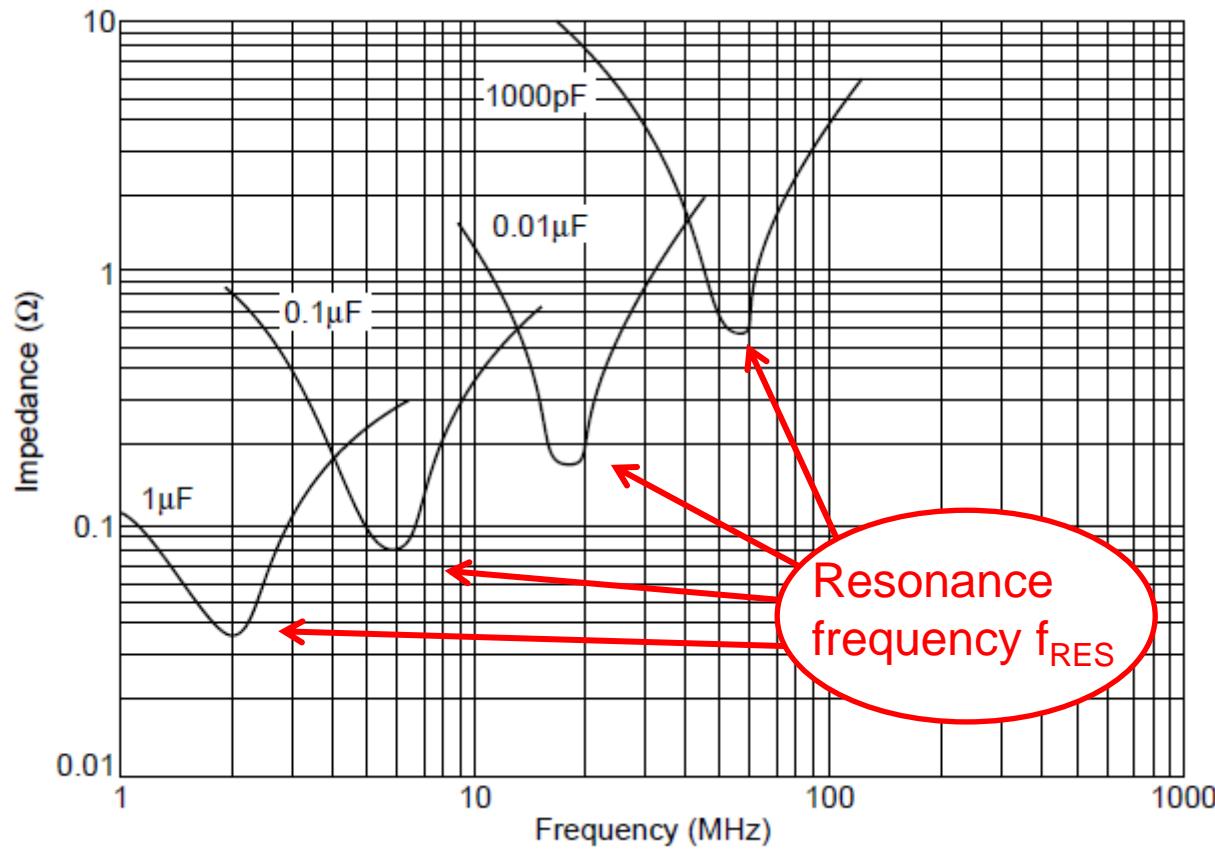


$$\tan \delta = \frac{\epsilon''}{\epsilon'}$$



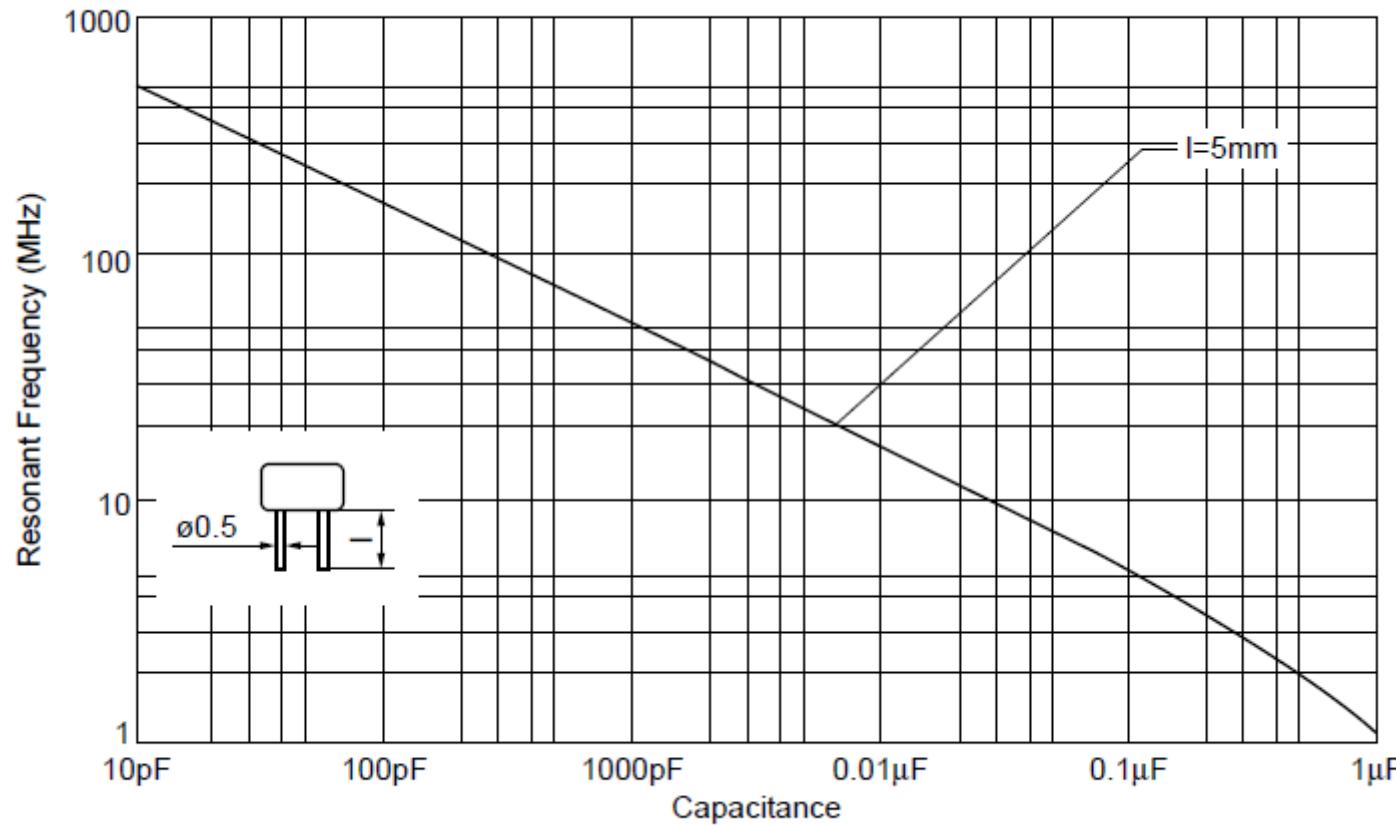
$$\tan \delta = \frac{P_{diss}}{P_r} = \frac{\epsilon''}{\epsilon'}$$

Capacitor Impedance vs Frequency



The impedance magnitude $|Z(\omega)|$ decreases as $\sim 1/\omega$ up to the resonant frequency f_{RES} .
Above f_{RES} the parasitic inductance dominates..

Resonance Freq. vs Cap. Value

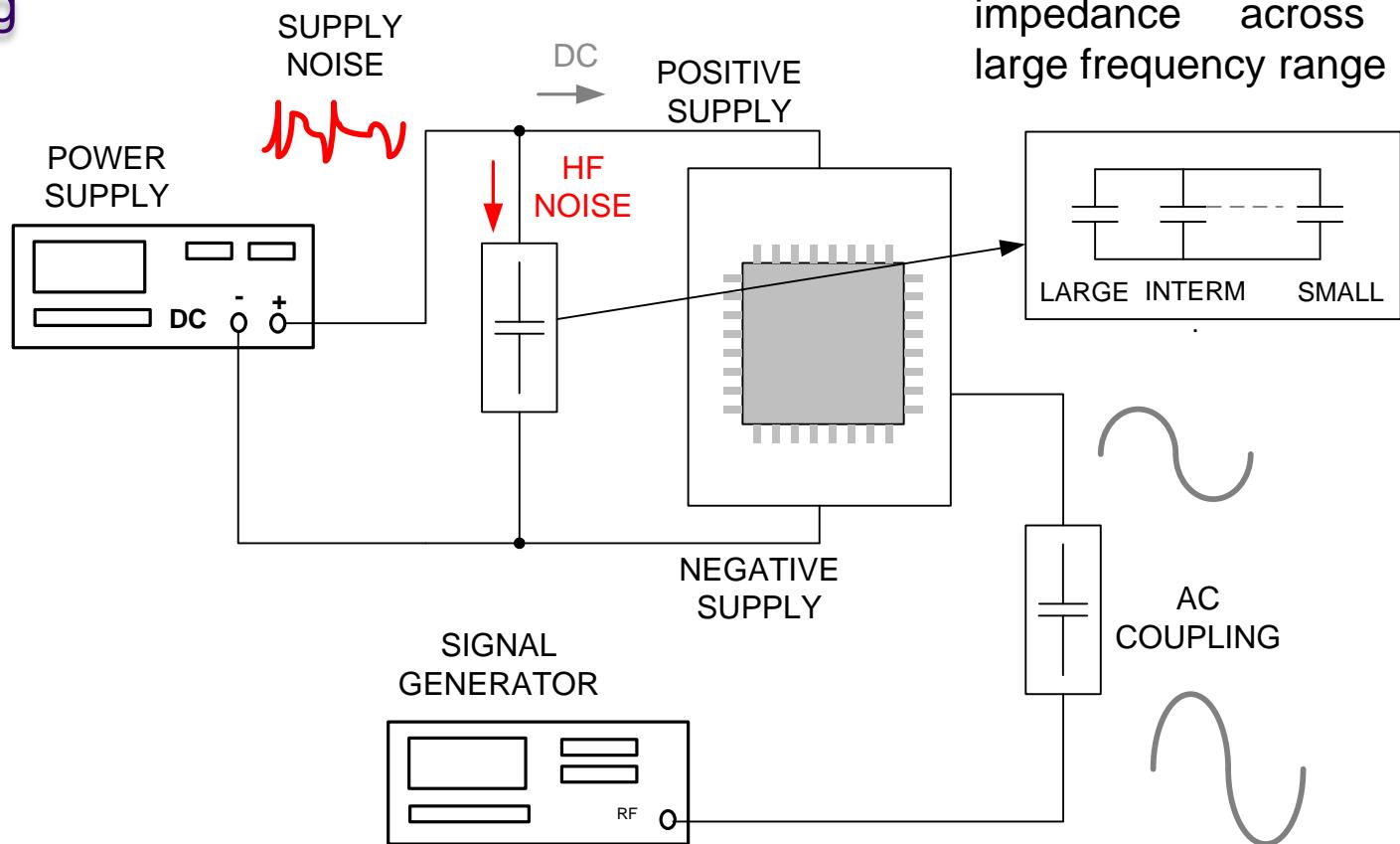


For a given capacitor type and package size, f_{RES} decreases for increasing capacitance

Applications

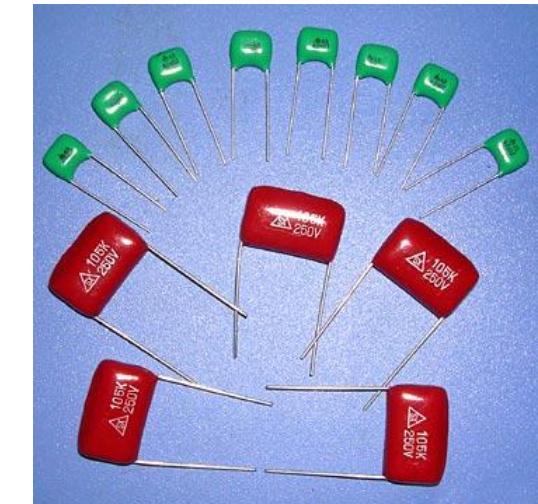
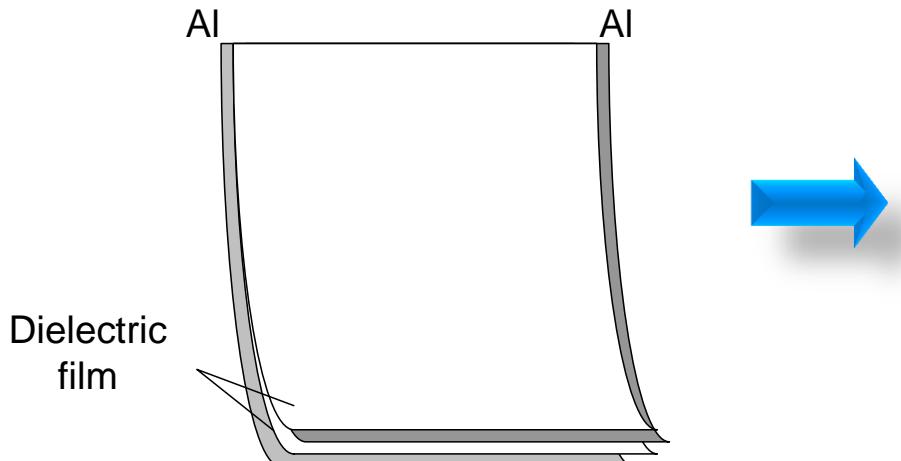
- Supply filtering
- Interference suppression
- AC coupling

Several capacitors in parallel provide a small impedance across a large frequency range



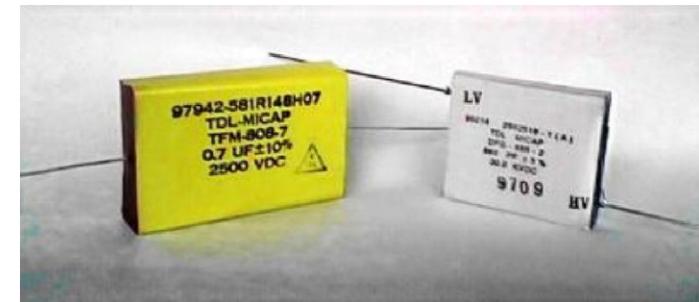
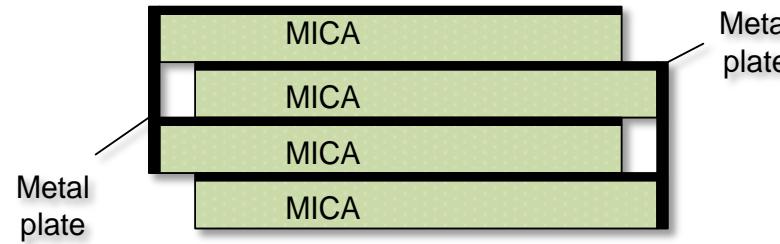
Film Capacitors

- Made from high quality polymer (polycarbonate, polystyrene, polypropylene, polyester) or paper film, and a thin (~50 μm) Al foil
- Down to 10 μm dielectric thickness
- Air and humidity removed to increase max voltage
- Conductive resin terminals
- Metallization of polymer sheet
 - increases energy per unit volume
 - Improved reliability
- Capacitance values: up to ~50 μF
- Frequency range: up to a few MHz



Mica Capacitors

- Muscovite mica is a natural crystal
 - Easy to obtain layers ($\sim 50 \mu\text{m}$ thickness)
 - $\epsilon_r \sim 5-7$
 - Low loss tangent (10^{-4} @ 1MHz)
 - Low temperature coefficient $\sim 100 \text{ ppm}/^\circ\text{C}$
 - High voltage applications
 - 1% accuracy: trimming done removing top-plate metallization
 - Moderate range of capacitance values: up to $\sim 100\text{nF}$

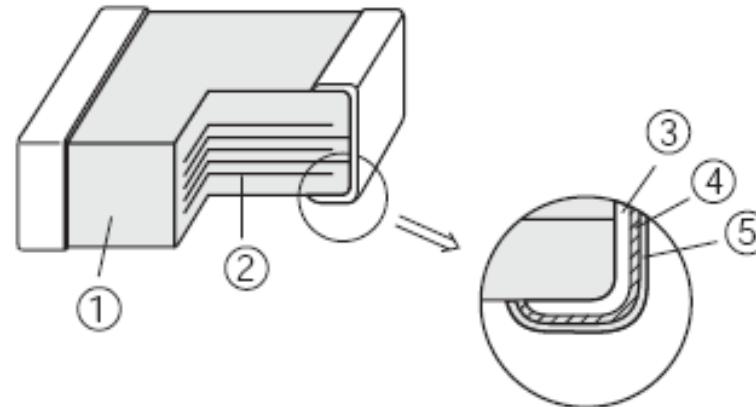


Ceramic Capacitors

- A ceramic capacitor is based on a ceramic dielectric with metal electrodes
- Parameters depend on the dielectric materials:
 - Stetatites $\epsilon_r=6$ $\tan\delta=5 \cdot 10^{-4}$
 - $(\text{TiO}_2)_x(\text{BaO})_{1-x}$ $\epsilon_r=37$ $\tan\delta=3 \cdot 10^{-4}$
 - TiBaO_3 $\epsilon_r \sim 1000$ $\tan\delta \sim 10^{-2}$
- Production steps:
 - Ceramic dielectric firing
 - Electrodes deposition and firing
 - Multi-layer ceramic capacitors: several layers are pressed and fired again together



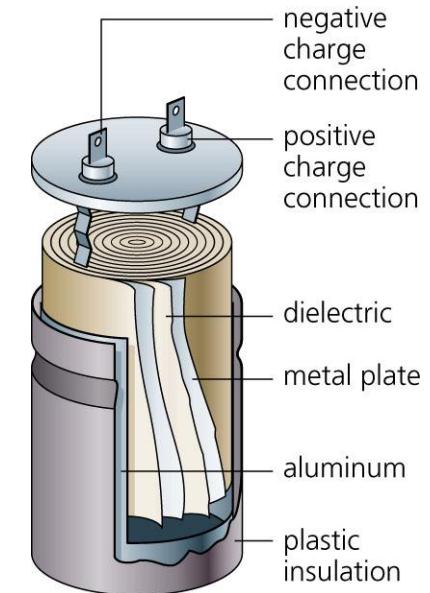
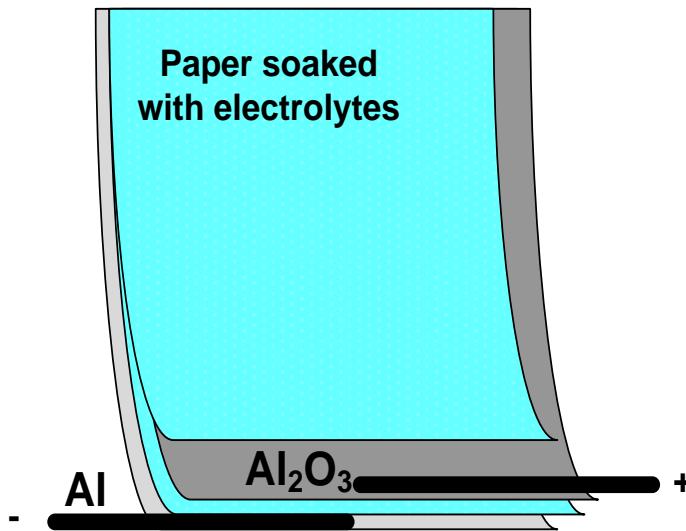
Multi-layer Ceramic Capacitors



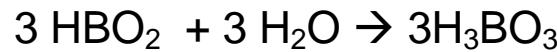
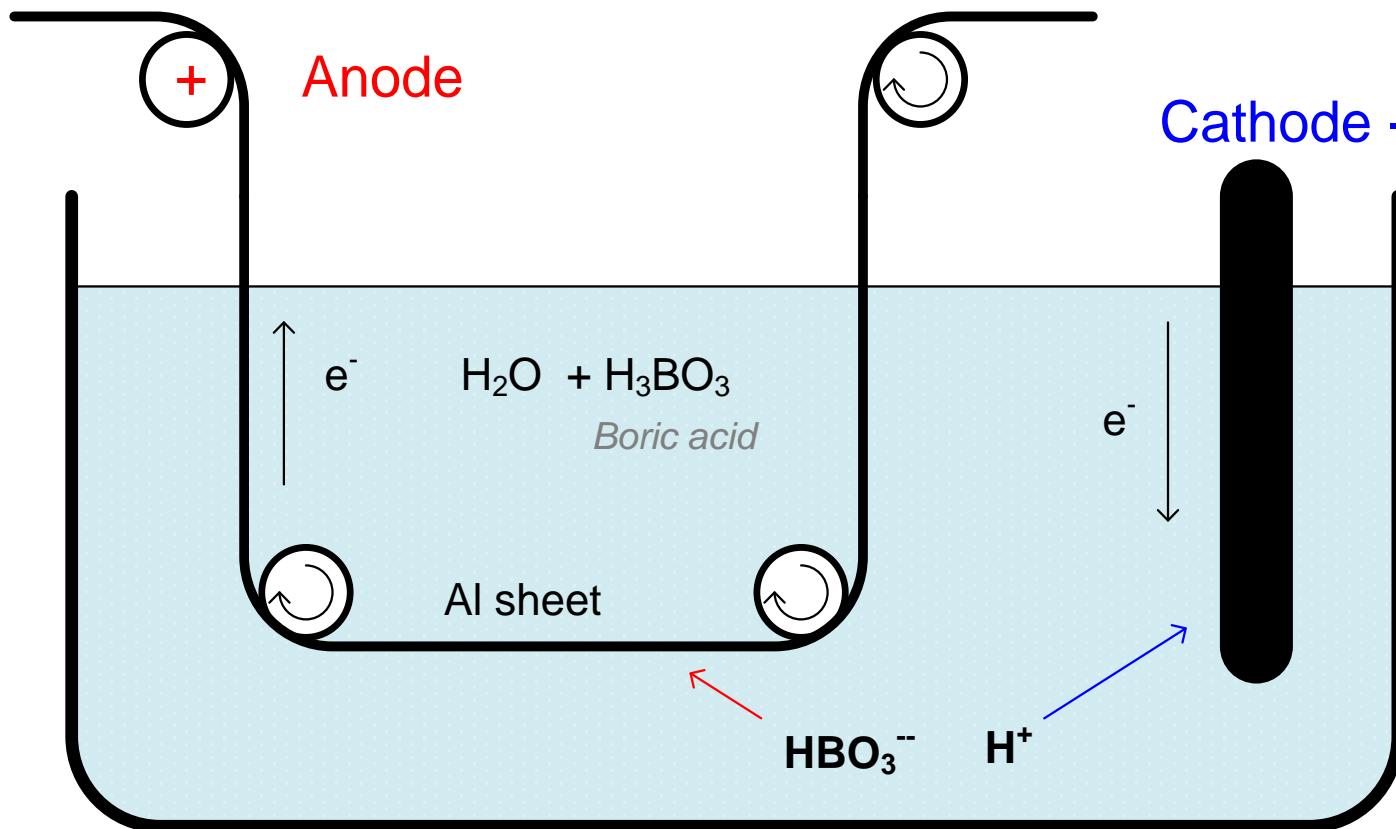
No	Name	
1	Ceramic dielectric	
2	Internal electrode	
3	Terminal electrode	Substrate electrode
4		Intermediate electrode
5		External electrode

Al - Electrolytic Capacitor

- The foil insulated by the oxide layer is the anode (+)
- The liquid electrolyte and the second foil act as cathode. (-)
- The layer of insulating aluminum oxide acts as the dielectric
 - thin Al_2O_3 dielectric → **high** capacitance (~mF) in a small volume
 - $E_r \sim 10^9 \text{ V/m}$ → high energy density
 - High series inductance → low frequency applications
 - **Applied voltage must have positive (V_a-V_c) polarity**



Electrolytic Capacitor

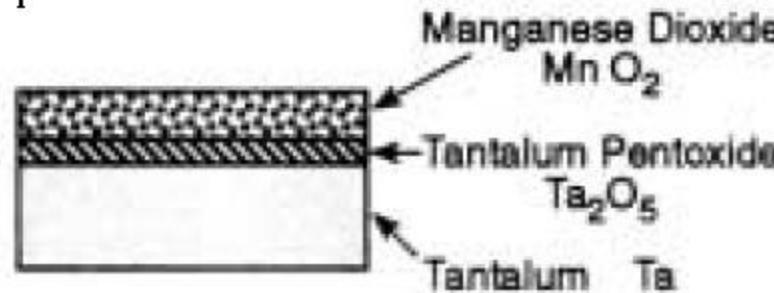


Oxide thickness:

$$S = \frac{V_{cell}}{E_R} \left(1 - e^{-t/\tau} \right)$$

Ta Electrolytic Capacitor

- Porous sintered Tantalum (Ta) is used as first electrode (cathode)
- Oxide Ta_2O_5 is formed during firing with $\text{Mn}(\text{NO}_3)_2$
- MnO_2 acts as electrolyte
- Second electrode (anode) is composed of graphite
- Reduced size and values (up to several $100\mu\text{F}$) compared with Al electrolytic capacitors



Capacitor Types

	<i>Polymer sheet</i>	<i>Mica</i>	<i>Ceramic</i>	<i>Electrolytic (Al)</i>
MAX Cap.	50 μ F	50nF	10nF	\sim mF
Accuracy	10%	2%	5%	20%
f _{MAX}	\sim MHz	\sim 10MHz	\sim 100MHz	\sim 100kHz
Tan δ	5·10 ⁻⁴ (10kHz)	10 ⁻⁴ (1MHz)	10 ⁻³ (1kHz)	10 ⁻² (100Hz)
α [ppm/ $^{\circ}$ C]	\pm 100	100	\pm 20	\pm 1000
E _V [J/cm ³]	100m	1m	1m	1
τ [MΩ· μ F]	10.000	1000	1000	50