Lecture 5 17-18 March 2025

Dielectric properties of crystalline materials - part III – applications & examples

- some applications of dielectrics

- examples, linear and non-linear dielectrics

- performance issues: temperature& frequency dependence, breakdown

Some « classic » applications of ceramics as insulators

- Insulators for high voltage lines
- Insulators for spark plugs
- Insulators for circuit switches

The most important characteristics of an insulator

High resistivity
•Low (high?) dielectric constant
•Low dielectric loss
•High breakdown resistance
•Low absorption of water
•High mechanical resistance
•Resistance to thermal shock

Insulators : porcelain

The porcelaine is made of a sintered mixture of:

- ~ 1/4 sand (SiO_2),
- ~ 1/4 feldspar (KSi_3AlO_8)
- ~ 1/2 clay ($Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$)

-The sand increases the mecahnical stability of porcelain

-The feldspar decreases the sintering temperature

-The clay gives plasticity need for shaping

Porcelain

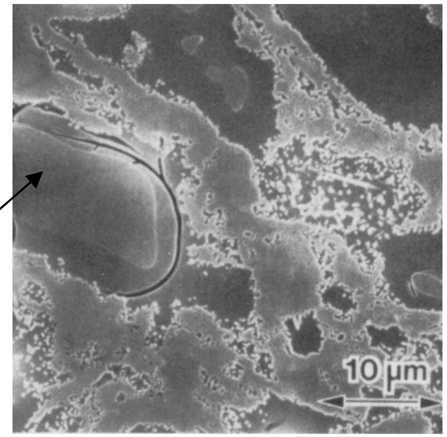
~ 1/4 sand (SiO_2),

~ 1/4 feldspath (**K**Si_3AlO_8)

~ 1/2 clay ($Al_2O_3 \cdot 2SiO_2 \cdot 2H_2O$)

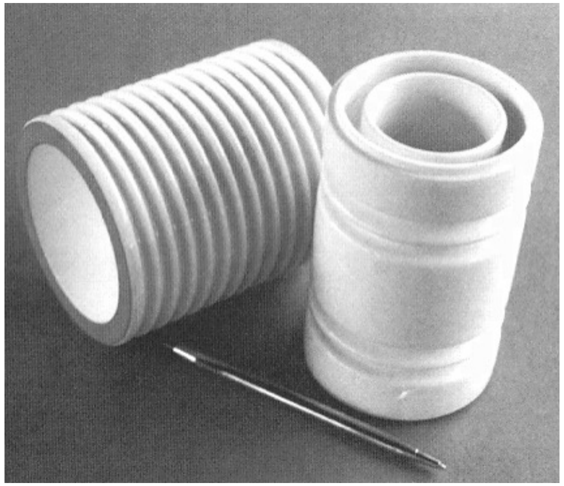
K^{+1} introduces ionic conductivity -->
The porcelains with a very high electrcal resistance have little feldspath, and a high content of alumino-silicates.

SiO_2



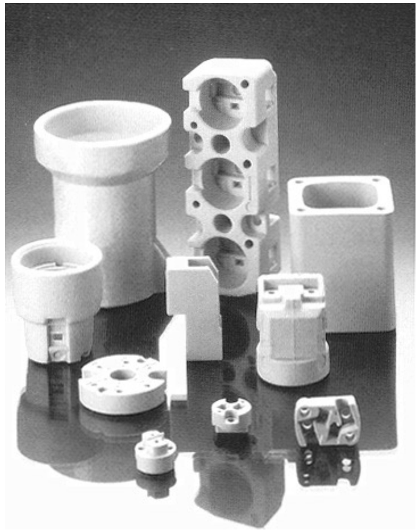
Ceramic insulators

An example:



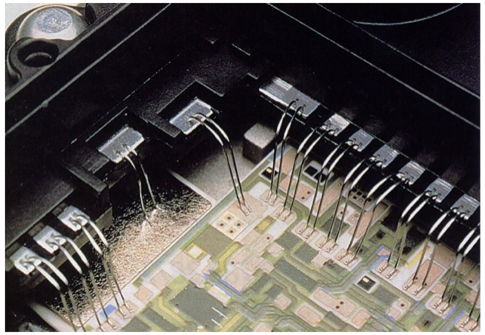
Porcelain:

- Typical properties:
  - **dielectric constant k' = 6-7**
  - **dielectric losses tanδ = 0.008 (60 Hz)**
  - **resistivity $\rho = 10^{13}$ (Ωcm)**
  - **Breakdown field ~10^{5} V/cm.**



- For applications in electronics, porcelain with a high content of alumina is preferable.
- .

The substrates for integrated circuits



Holder for the chips

Carry connections among different components

facilitates cooling of the components

Properties of a dielectric substrate for IC

- **Low dielectric constant**
- **Low dielectric losses**
- **High electrical resistance**
- **High thermal condution**
- **Thermal expansion close to that of Si**
- **High mechanical resistance**
- **Easy cutting and polishing**
- **Stable and nontoxic**
- **Smooth surface finish**
- **Compatibility with electrodes**

For applications where speed of the signal is important, the dielectric permittivity must be low because

$$V \propto \frac{1}{\sqrt{k}}$$

(v – speed of propagation of electrical signal)

Materials often used Al_2O_3 et AlN

Cheap, cheap, cheap…

Properties of materials for substrates

Material	Dielectric constant k	Thermal expansion (10^{-6}/C°)	Thermal conductivity (W/mK)
Alumina (Al_2O_3)	9.6	7.8	50
Mullite ($Al_6Si_2O_{13}$)	6.6	5.5	4
Glucine (BeO)	6.9	9.0	370
Aluminium Nitrate(AlN)	8.8	4.5	320
Silica (SiO_2)	3.8	0.6	2
Cordierit ($Mg_2Al_4Si_5O_{18}$)	5.5	1.5	2
Silicon nitrate (Si_3N_4)	6.0	3.0	33
Silicium carbide (SiC)	4.0	3.7	490
Diamond (C)	5.7	1.5	2000
Silicon (Si)	12	3.5	130
Polyimide ($nC_{23}H_{12}N_2O_4$)	3.5	35	0.2

Capacitors

Capacitors are used:

- •Block direct current (DC)
- •Separate direct and alternating currents (AC/DC)
- •High frequency filters
- •Store the energy

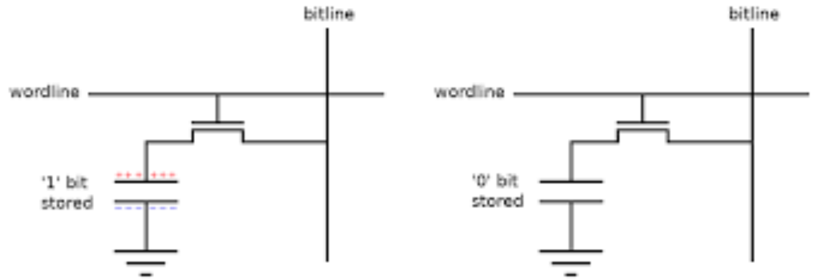
Important parameters : geometry of the component and the magnitude of the dielectric permittivity

Ceramic capacitors

The most important requirements for the ceramic are:

- •Low dielectric loss
- •High dielectric permittivity
- •Stability with temperature and frequency
- •Large breakdown field.

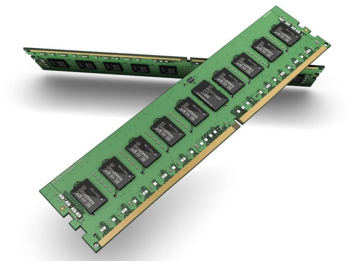
Giga-bit DRAM

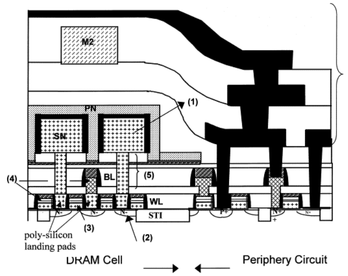


Dielectirc constant Surface of the capacitor

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

Thickness of the capacitor





Example: (Samsung, 2017, 21nm)

Density: 16GB

Cell area (μm^2) 0.0043 - 0.142 Gb/mm^2

To increase memory capacity :

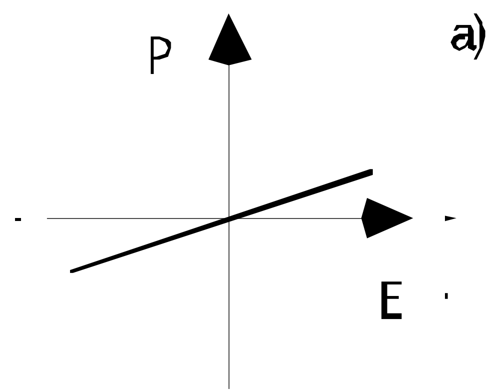
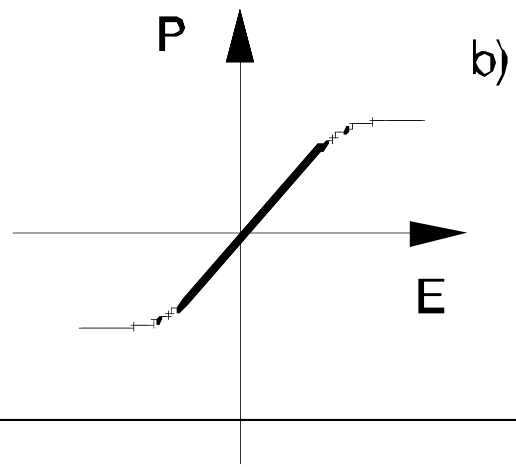
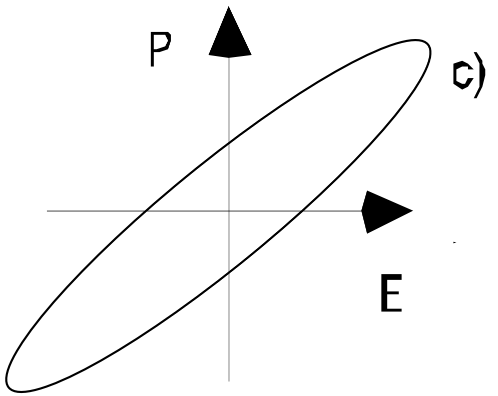
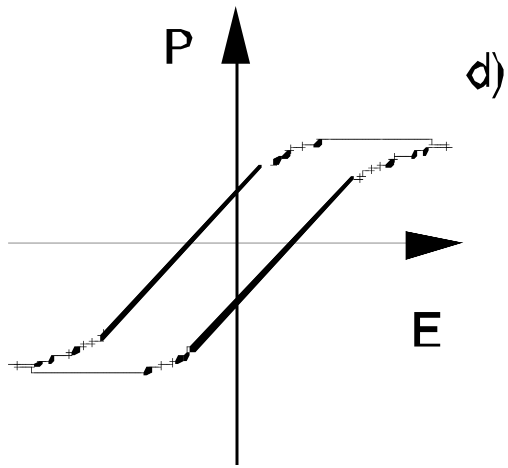
- **Increase number of elements**
- **Reduce surface of the elements**
- **Impossible to decrease d**
- **Increase K if want to keep the same C**

SiO_2/Si_3N_4	$K \approx 4...7$
Ta_2O_5	$K \approx 25$
$(Ba,Sr)TiO_3$	$K \approx 300...600$

Hi-K perovskites present a challenge for integration on CMOS

Linear and non-linear dielectrics

$P = \varepsilon_o (k-1) E$

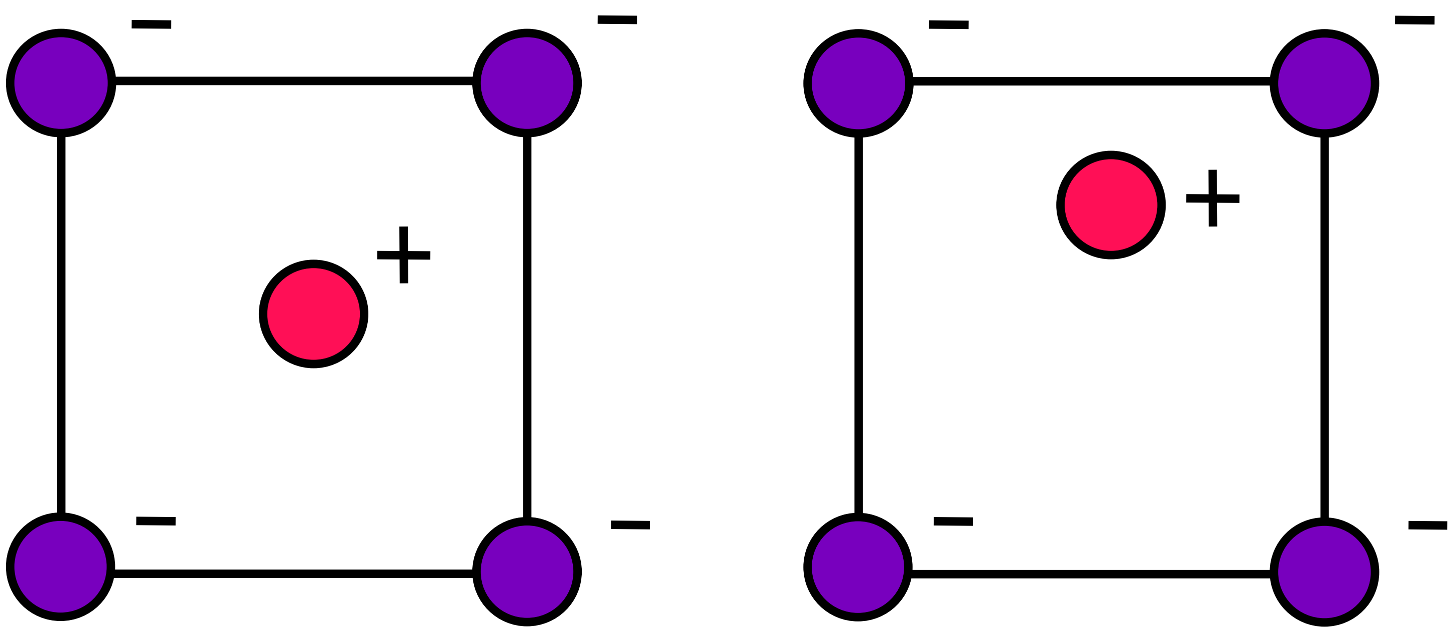
	linear	non-linear
Without losses		
With losses		

Polar materials

Polar materials **posses a permanent electrical dipole moment.**

NaCl is not polar.

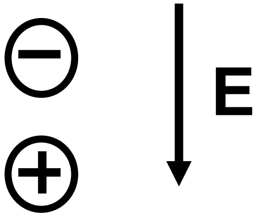
Molecules of water have a polar structure.



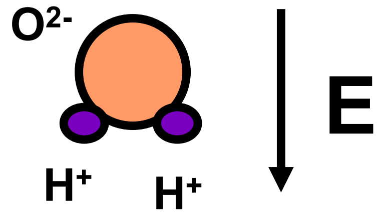
a) Nonpolar structure **b) polar structure**

Polar structures

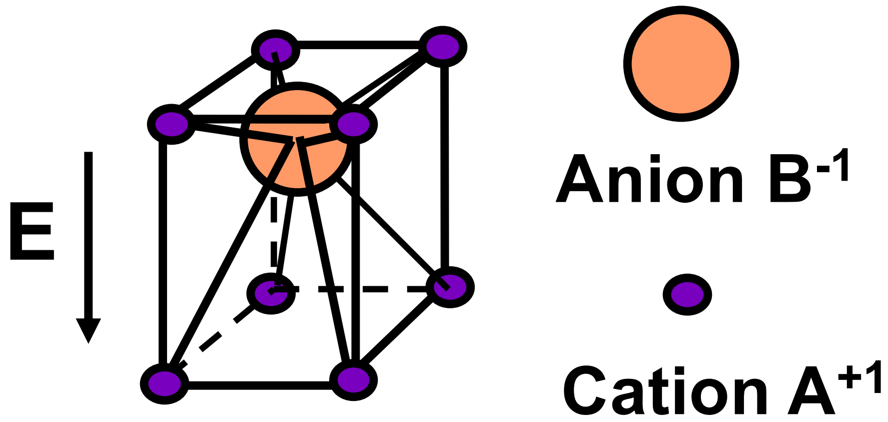
A dipole



A polar molecule

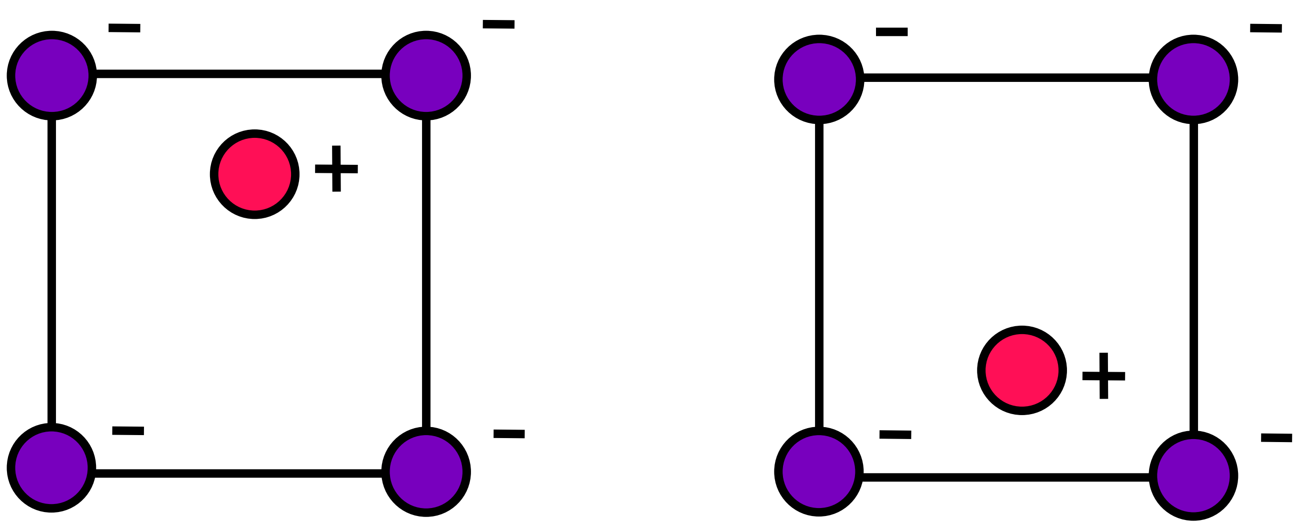


A polar crystal AB



Ferroelectrics

Ferroelectrics are materials with a permanent dipole moment, in which **direction of the spontaneous polarisation can be inversed** by an external field.



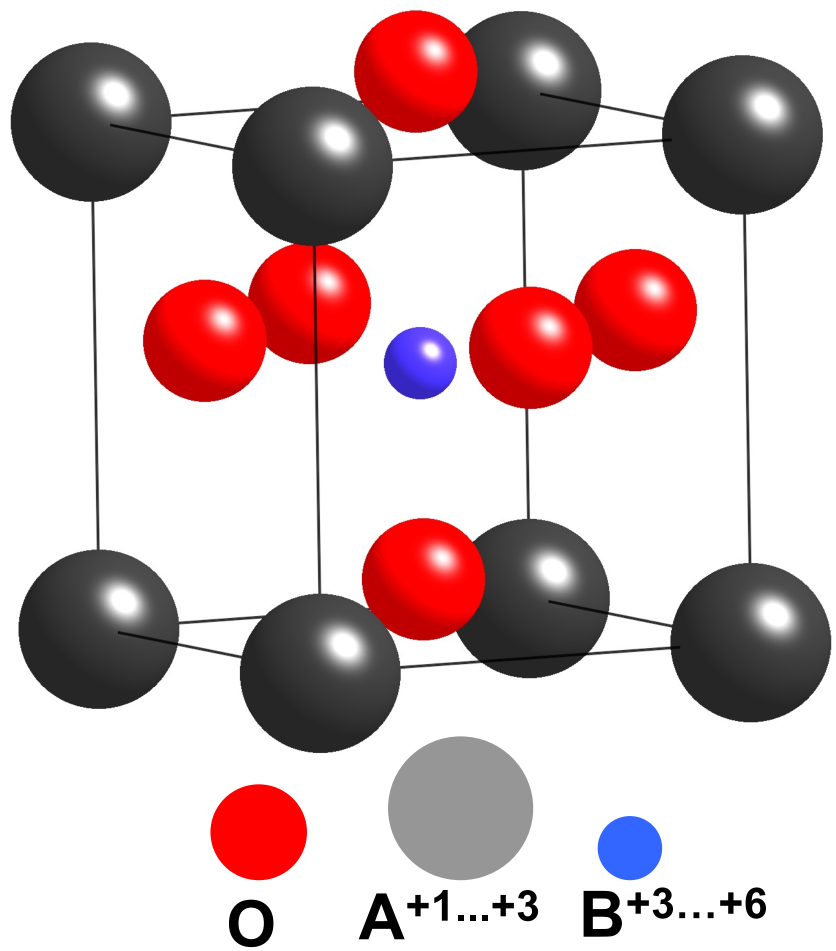
Ferroelectricity dissapears above a certain temperature, called Curie temperature, Tc

Structural origin of the ferroelectricity

- A $T > T_{Curie}$ (120-130° C) : cubic symmetry with cation Ti^{4+} in the centre.
- A $T < T_{Curie}$: Ti^{4+} occupies one of the positions off centre within the tetragonal cell (according to symmetry)

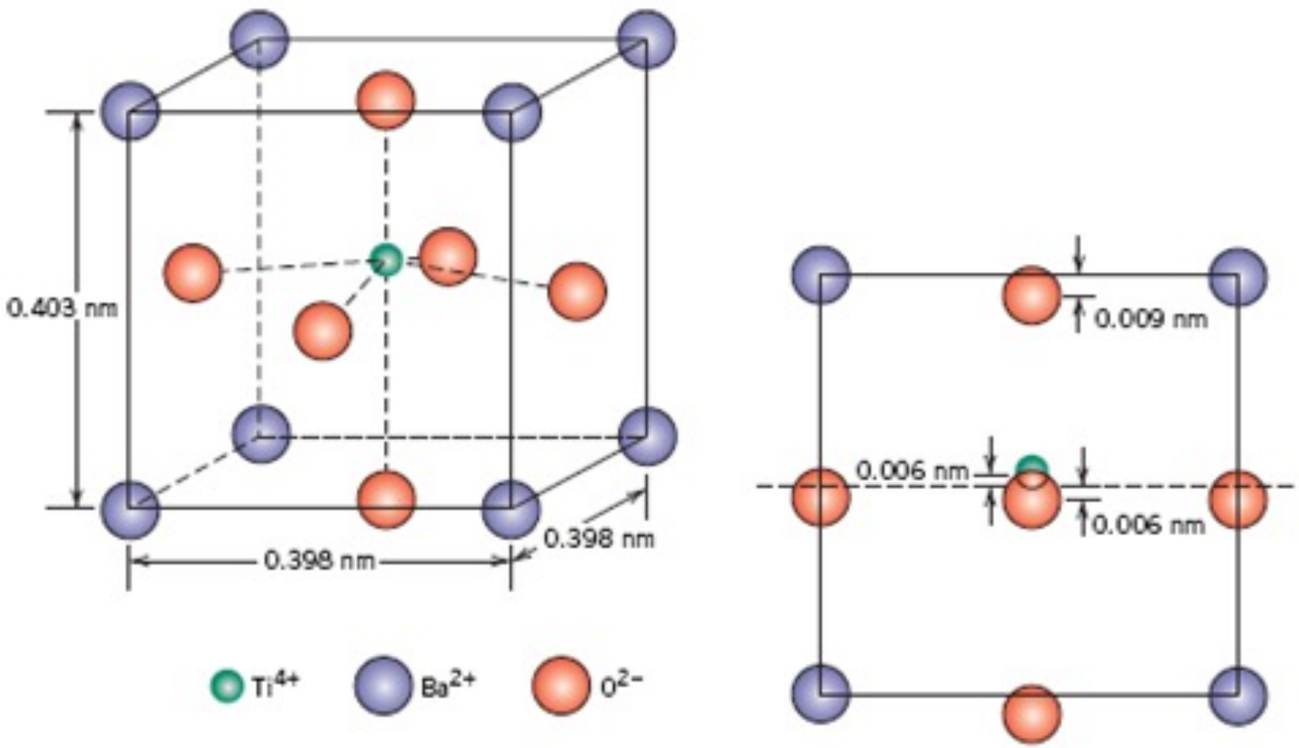
➪ Spontaneous polarization whose direction depends on the crystal structure

$BaTiO_3$ - perovskite



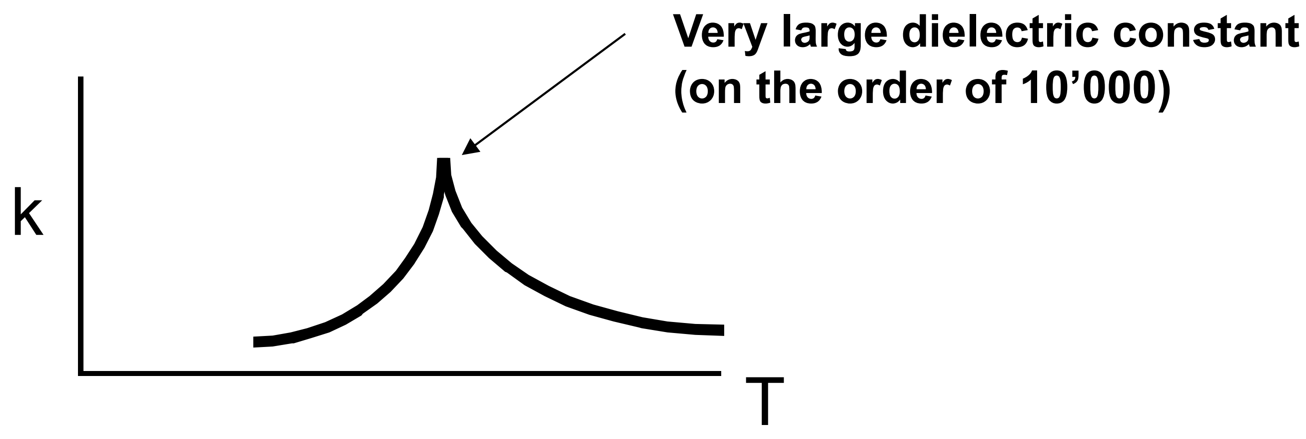
Barium titanate

- *$BaTiO_3$* **is a** *perovskite***.**
- **Above** *Curie* **temperature (around 130° C) the crystalline cell is cubic**
- **Below the** *Curie temperature* **the unit cell is tetragonal and cations are displaced with anion network**



(a) (b)

The ferroelectric phase transitions



- ferroelectric materials transform to a ferroélectric state from a *paraelectrc phase,*
- This phase **transition** is always accompanied by a change in the crystal structure

- The temperature of the paraelectric-ferroelectric phase trasnition is called Curie temperature, Tc.

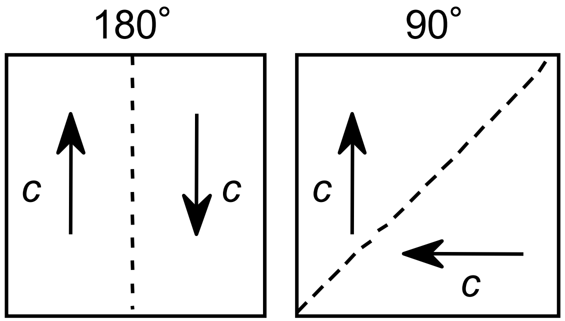
Examples of perovskite ferroelectrics

Material	*Curie temperature [K]	Structure at room temperature
Barium titanate, $BaTiO_3$	393	tetragonal
Lead titanate $PbTiO_3$	833	tetragonal
Potassium niobate $KNbO_3$	693	orthorhombic

Self-test: What are the permitted directions of polarization depending on the symmetry?

Ferroelectric domains

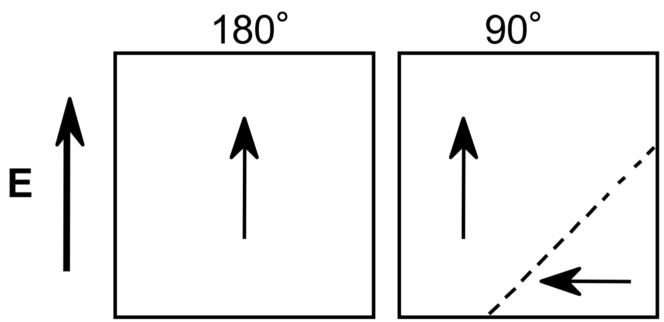
The regions of the material in which dipoles have the same orientation and direction are called ferroelectric domains



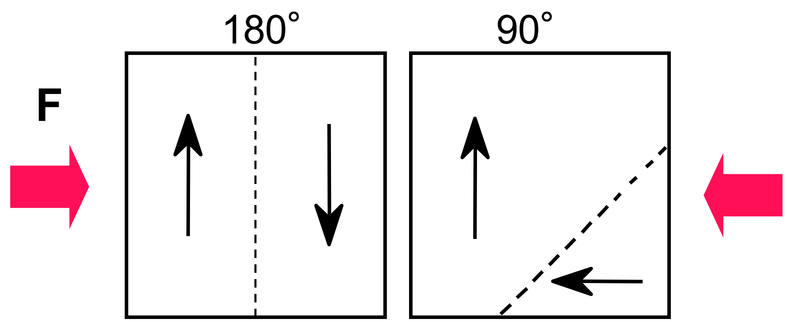
Initial casel

Tetragonal structure :
180° and 90° domains

The domains can be inverted by electric field (180° and non 180°) or by a mechnaical pressure (non-180°)

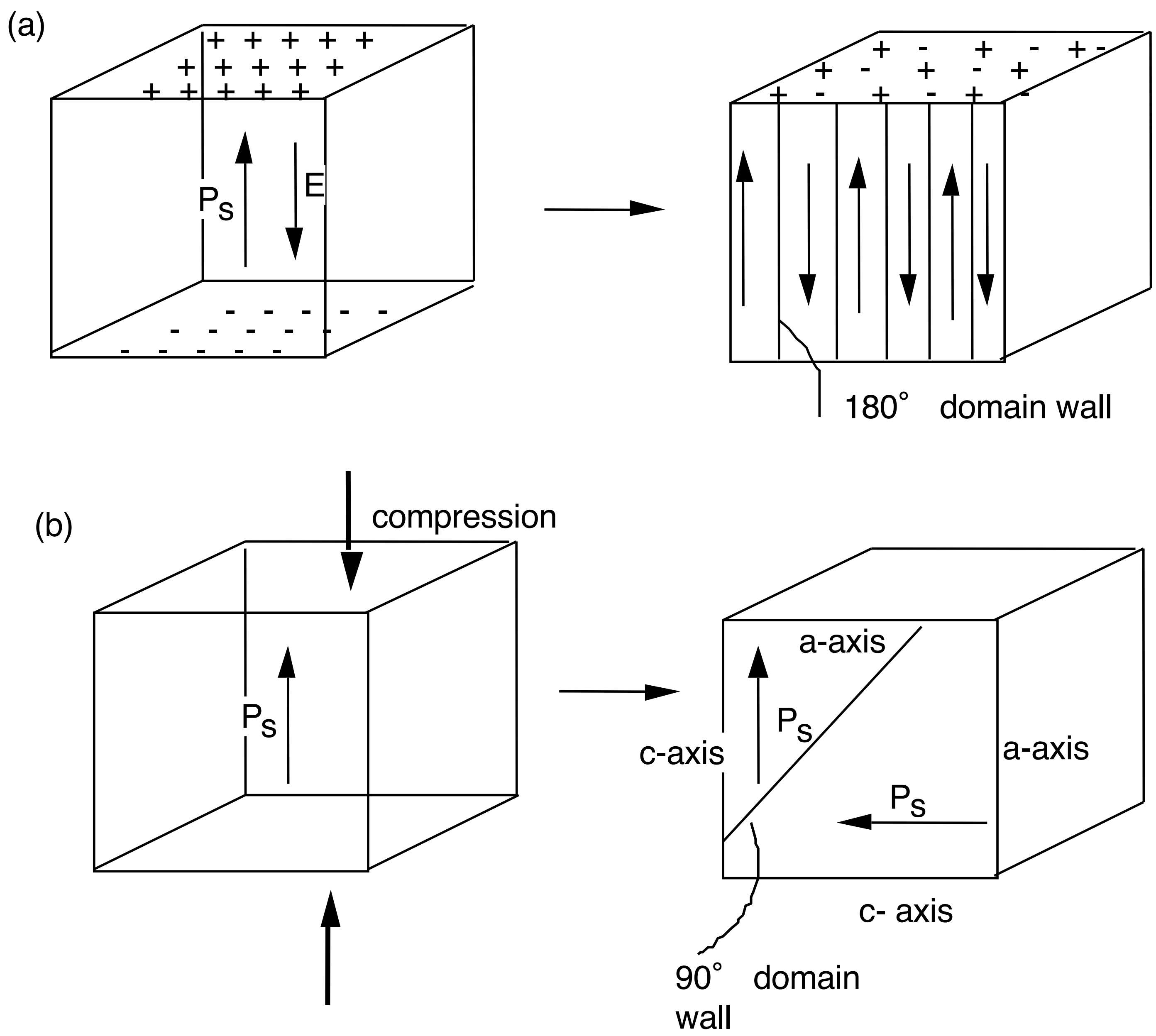


Application of electric field



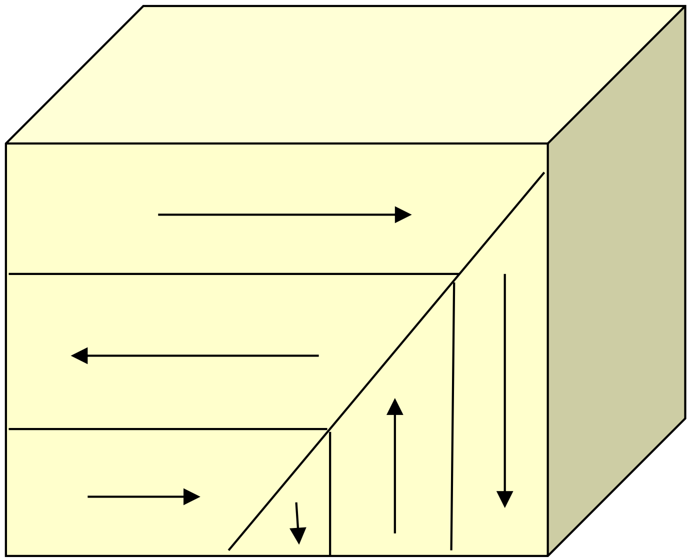
application
of mechanical pressure

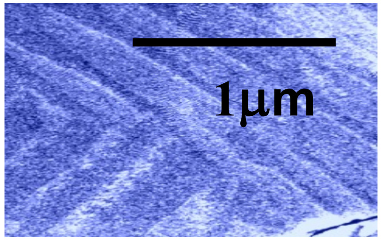
Examples of Ferroelectric domain arrangements



Ferroelectric domains (cont.)

- In general, several types of domain walls (e.g., 180^o et 90^o) are present simultaneously

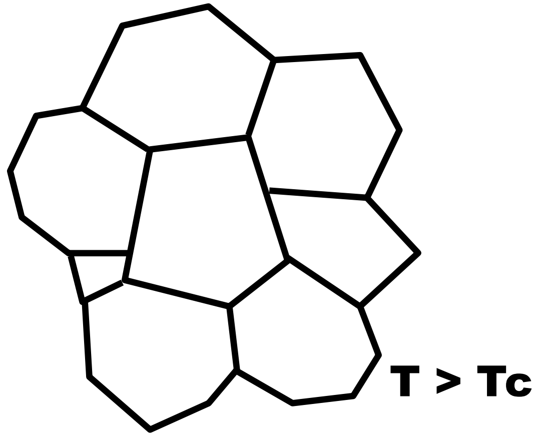




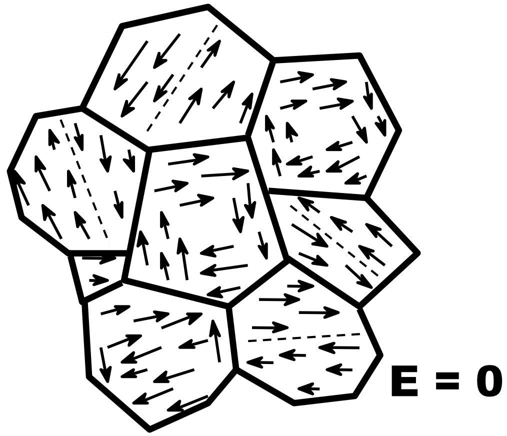
Micrograph (SEM) of a grain in a ferroelectric ceramic.

Ferroelectric ceramics

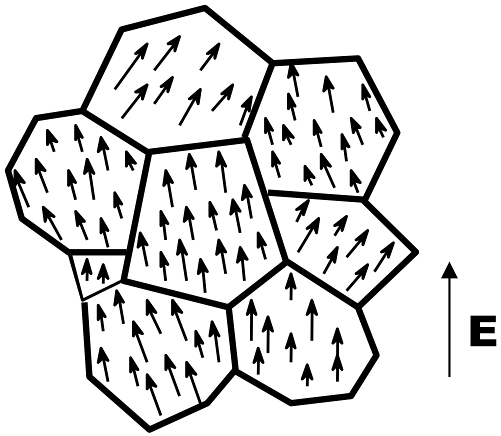
- **After sintering (T>Tc)**



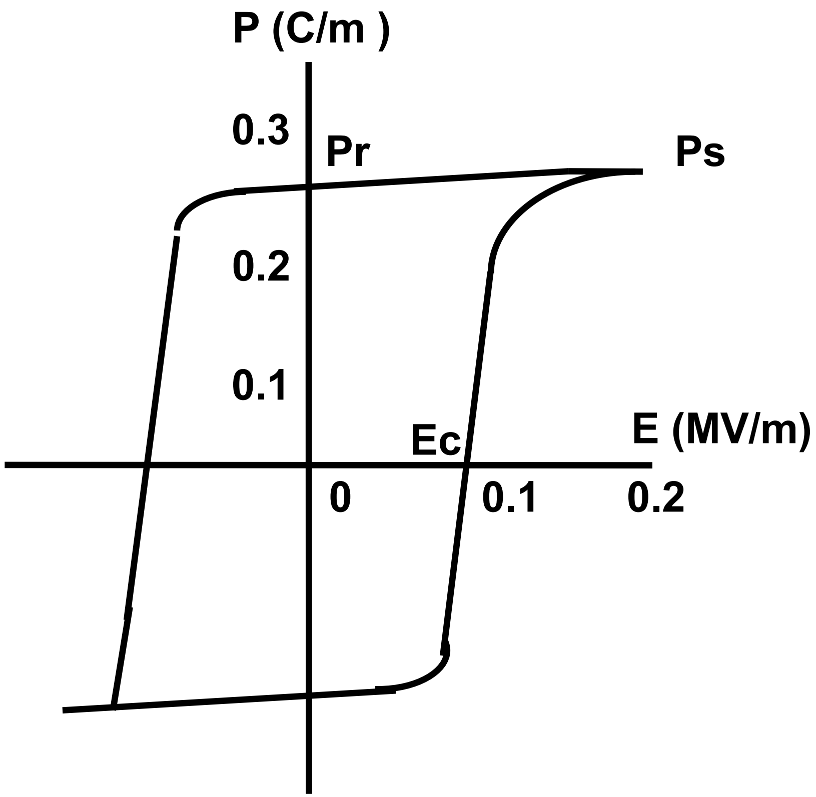
- **T<Tc**

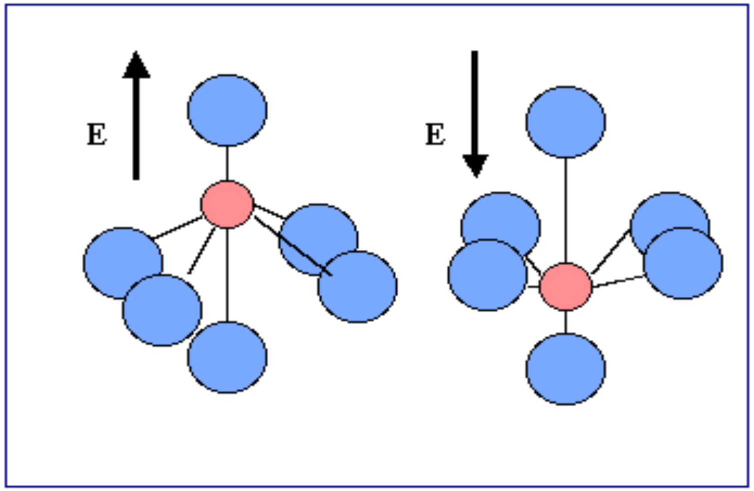


- **After poling**



Barium titanate – Ferroelectric hysteresis

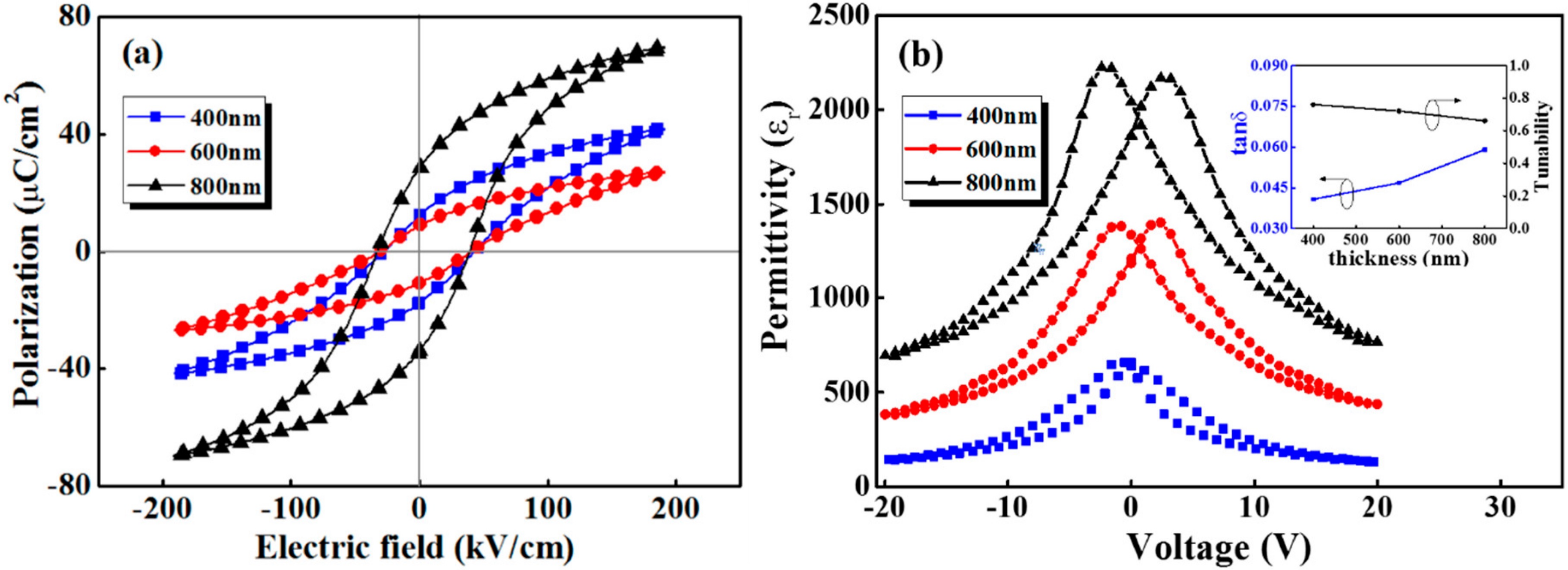




At fields higher than Ec – beginning of orientation of domaions

When the field returns to zero, the polarization has a nonzero value, Pr

Ferroelectric hysteresis and dielectric response vs voltage: domains



Dielectric permittivity is measured with small ac signal (<<Ec), while dc voltage is applied
Dielectric permittivity vs. dc voltage: distinct maxima near Ec represent domain contributions

Applications of ferroelectric materials: Capacitors with a high k

Capacitors – due to a large permittivity in the vicinity **of the Curie temperature.**

Barium tinatae **is a ferroelectric material that is** *widely used in capacitors*

>700 ceramic multilayer capacitors in a smart phone

Applications of ferroelectrics: Capacitors - $BaTiO_3$

- **The** *Curie point* ***can be adjusted*** **by dopants and modifiers***:*

  To replace Ba^{+2}**:** Pb^{+2} **increases the Curie temperature and** Sr^{+2} **decreases it.**

  To replace Ti^{+4} **:**Zr^{+4}, Hf^{+4} and Sn^{+4} **decrease the Curie temperature.**

- *A broadening of the Curie peak* **can be obtained by a mixture of compositions** *exhibiting different Curie temperatures***.**

- **Commercially, the most popular compositions are called** *Z5U***, with a large volumetric capacity and**

  X7R **with a better** *stability with temperature***.**

The dielectric breakdown

The dielectric breakdown is a sudden increase of the current when a critical electric field is reached ('short circuit').

The resistance to breakdown is the maximal voltage that a dielectric can reach without a breakdown.

Principal mechanisms of the breakdown in dielectrics:

- Intrinsic breakdown
- Thermal breakdown
- Discharge breakdown

More details on breakdown will come within the chapter on conduction

The dielectric breakdown (cont.)

The breakdown field depends on :

- material
- temperature
- porosity
- humidity
- State of the surface

In general, the resistance to breakdown is better in:

- Smaples with small dimensions, thin samples,
- Materials with a high density
- Materials which were not expose to humidity
- Materials with less defects

Breakdown field for selected materials

Material	Form	Thickness	Temperature	Resisatnce to breakdown (10^8 V/m)
Al_2O_3	Anodised film	6000 Å	25°C	1.5
Alumine porcelain	ceramic/ glass	0.63 cm	25°C	0.15
Low voltage porcelain	ceramic/ glass	0.63 cm	25°C	0.03
SiO_2 (pure)	glass	0.005 cm	20°C	6.6

Summary

- **Linear dielectric materials:**

  Important properties: dielectric losses, dielectric constant, electrical resistance (resitance to breakdown)

  Applications: insulators, capacitors, substrats, encapsulations

- **Nonlinear dielectrics:** Ferroelectrics (polar materials that change direction of polarisation by an electric field>Ec)

  Important properties: polarisation, dielectric constant, dielectric losses, coercive field,

- **Applications**: capacitors (and memories), piezoelectric applications (sensors, actuators) – to be discussed later
- Capacitors: attention to specs (temperature, frequency, voltage), non-linearity and losses maybe an issue