

Dielectrics and Ferroelectric Materials

Semiconductor Fundamentals: Band structure, indirect and direct band gap, optical properties, carrier statistics

Semiconductor Growth: semiconductor material purification and crystal growth, epitaxy, CVD and MBE,

Processing: Specific material requirements, Doping by implantation and diffusion, dielectric and insulators, ohmic and barrier contacts, band edge behaviour, empirical rule, alloy design, PN Junction, Schottky and MaS device structures,.

Dielectric & Ferroelectrics Materials: Dielectric constant and polarization, polarization mechanism, linear and nonline dielectric, pyro-piezo, and ferroelectric properties, application

Magnetism: diamagnetism paramagnelism, polypararnagnetism, ferro, antiferro, and ferrimagnatism. Soft and hard magnet materials, permanent magnet and transformers.

Books and References:

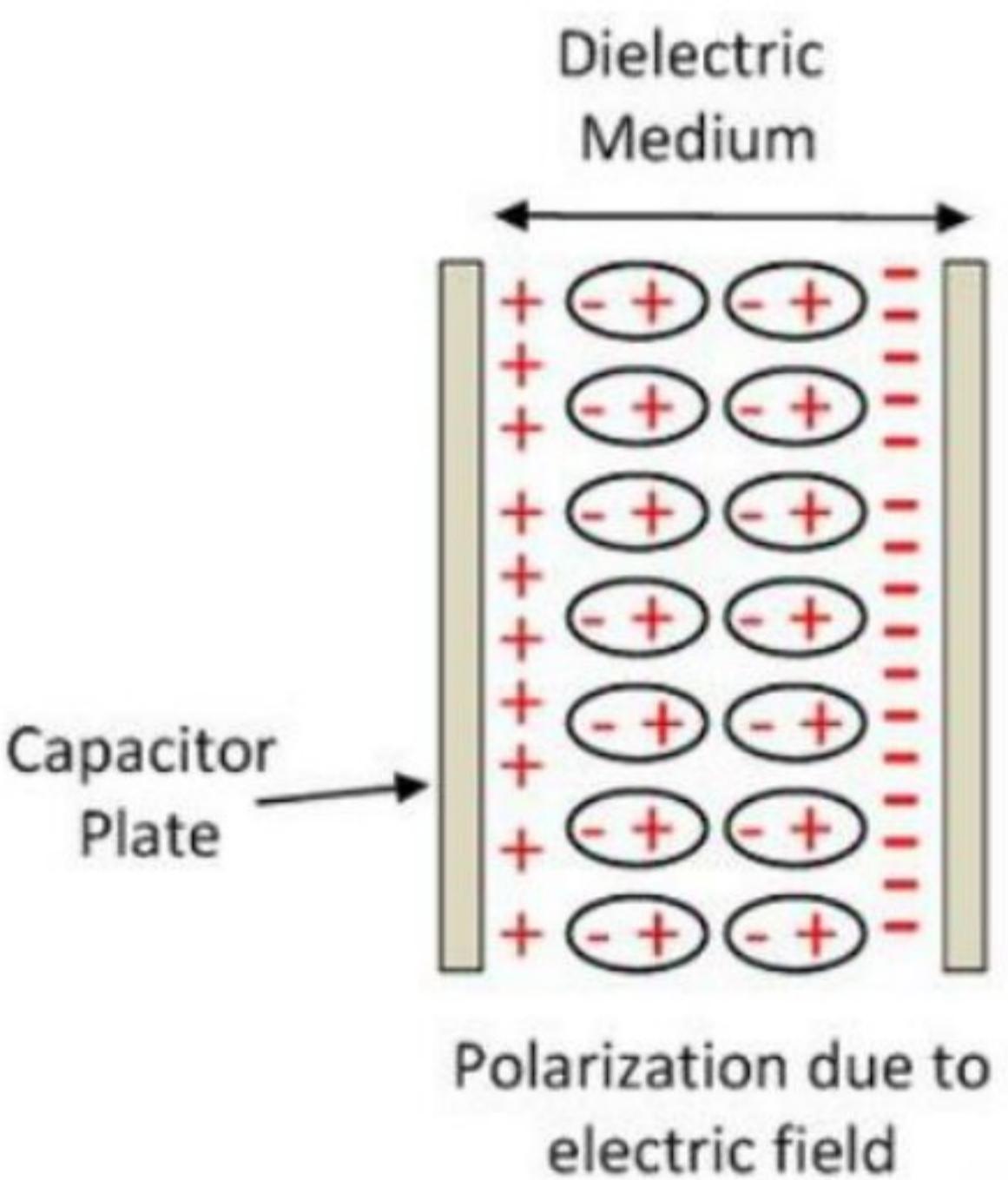
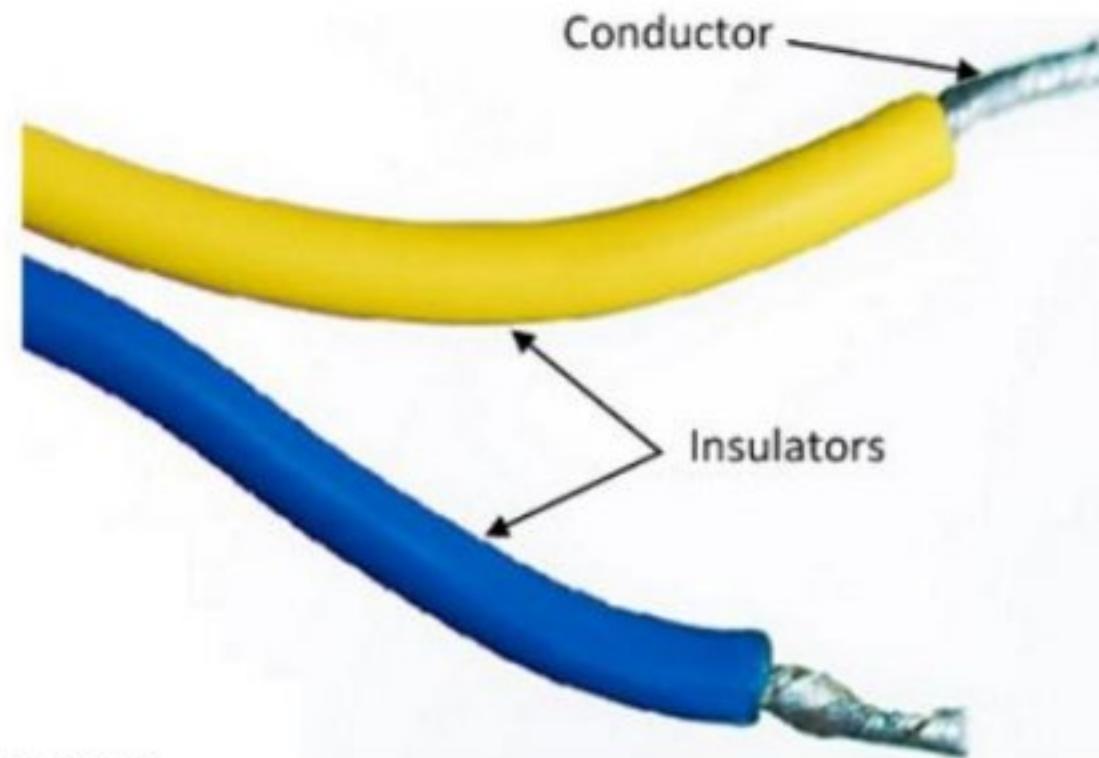
1. Elements of Materials Science and Engineering, L. H. Van Vlack (Addison-Wesley)
2. Materials Science and Engineering: An Introduction, W. D. Callister, (WILEY)
3. The Science and Engineering of Materials, Donald R. Askeland (Chapman & Hall)
4. Solid State electronic Devices, B. G. Streetman (PHI)

Dielectric Material

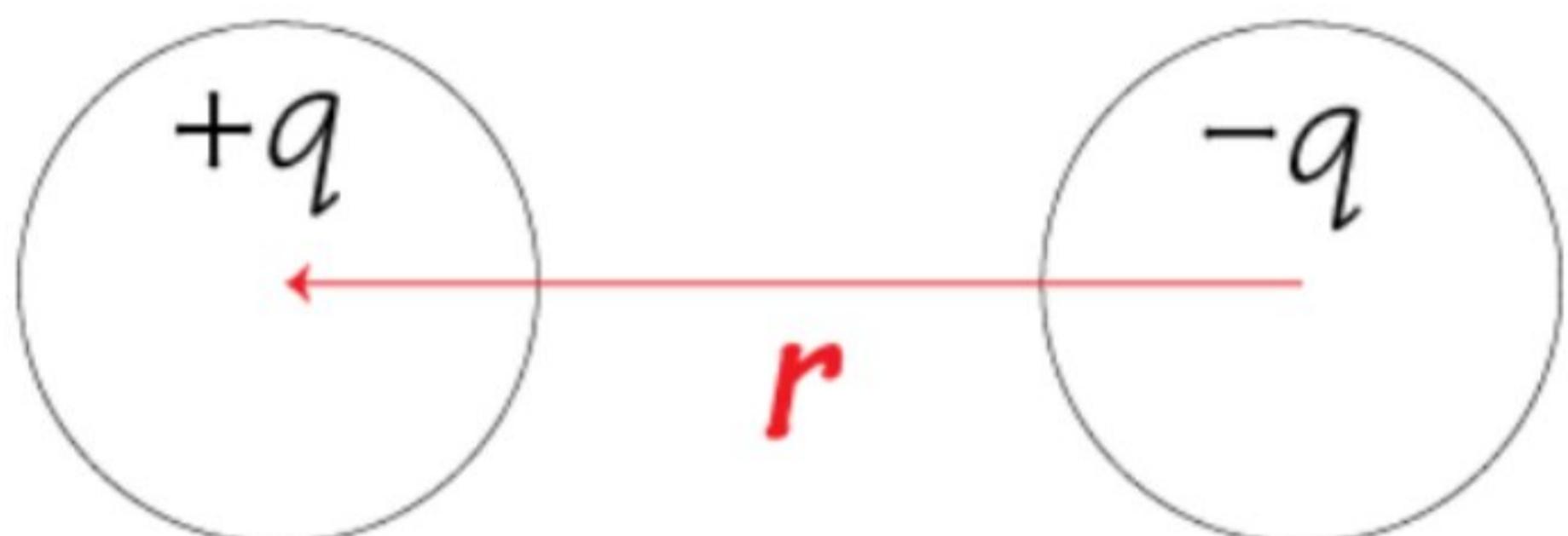
A **dielectric** material is one that is electrically insulating (nonmetallic) and exhibits or may be made to exhibit an **electric dipole** structure (molecular or atomic level).

In principle all insulators are dielectric, although the capacity to support charge varies greatly between different insulators

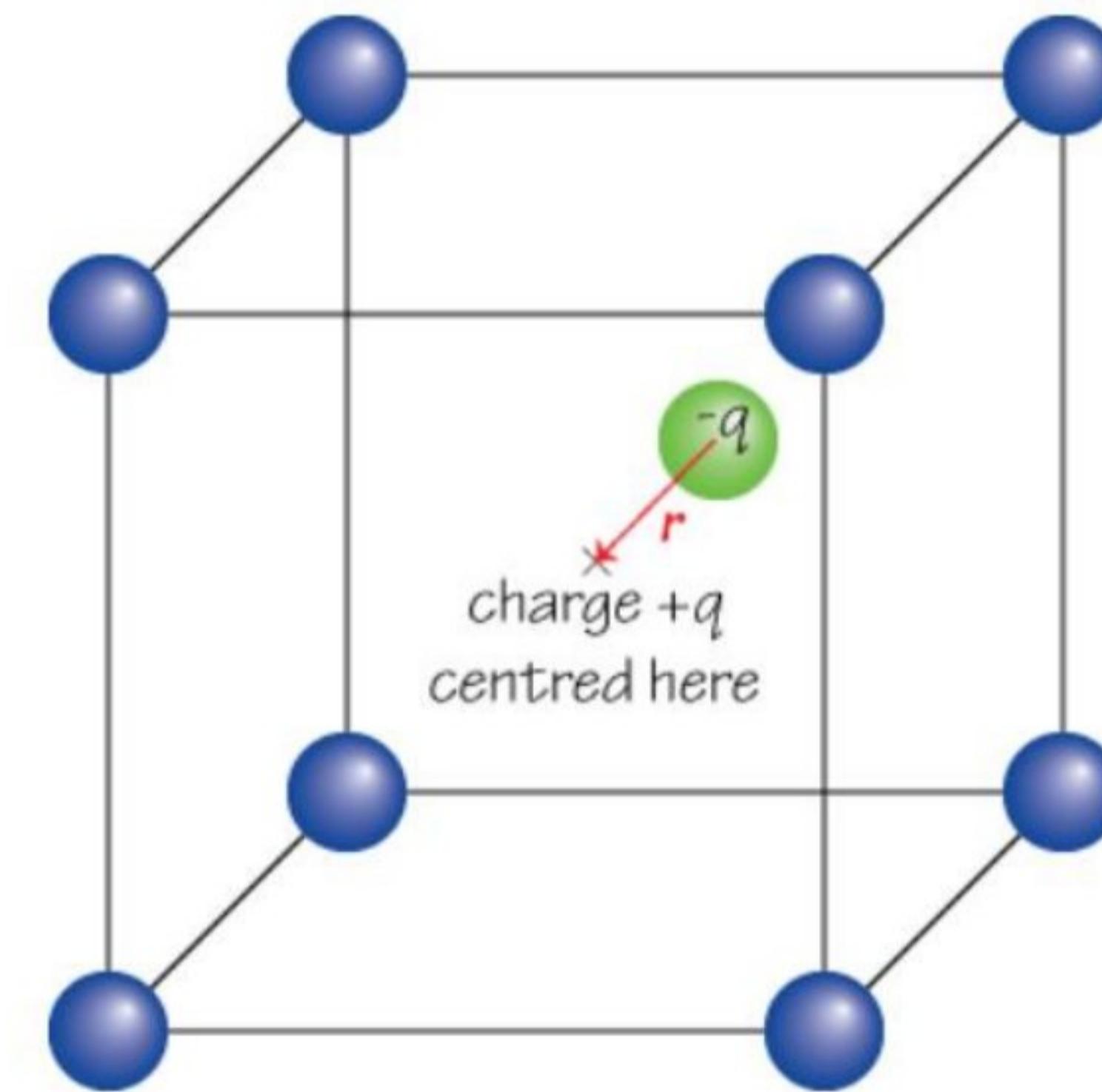
Dielectric materials are used in many applications, from simple electrical insulation to sensors and circuit components.



Electric Dipole



$$\mu = qr$$



$$\mu = qr$$

Key

- Blue circle = cation
- Green circle = anion

Dielectric Constant

Dielectric Constant: Also known as relative permittivity

$$\epsilon_r = \frac{\epsilon}{\epsilon_0}$$

ϵ = Permittivity of medium

ϵ_0 Permittivity of vacuum ($8.854 \times 10^{-12} F/m$)

Material	Dielectric Constant		Dielectric Strength (V/mil) ^a
	60 Hz	1 MHz	
<i>Ceramics</i>			
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
<i>Polymers</i>			
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.

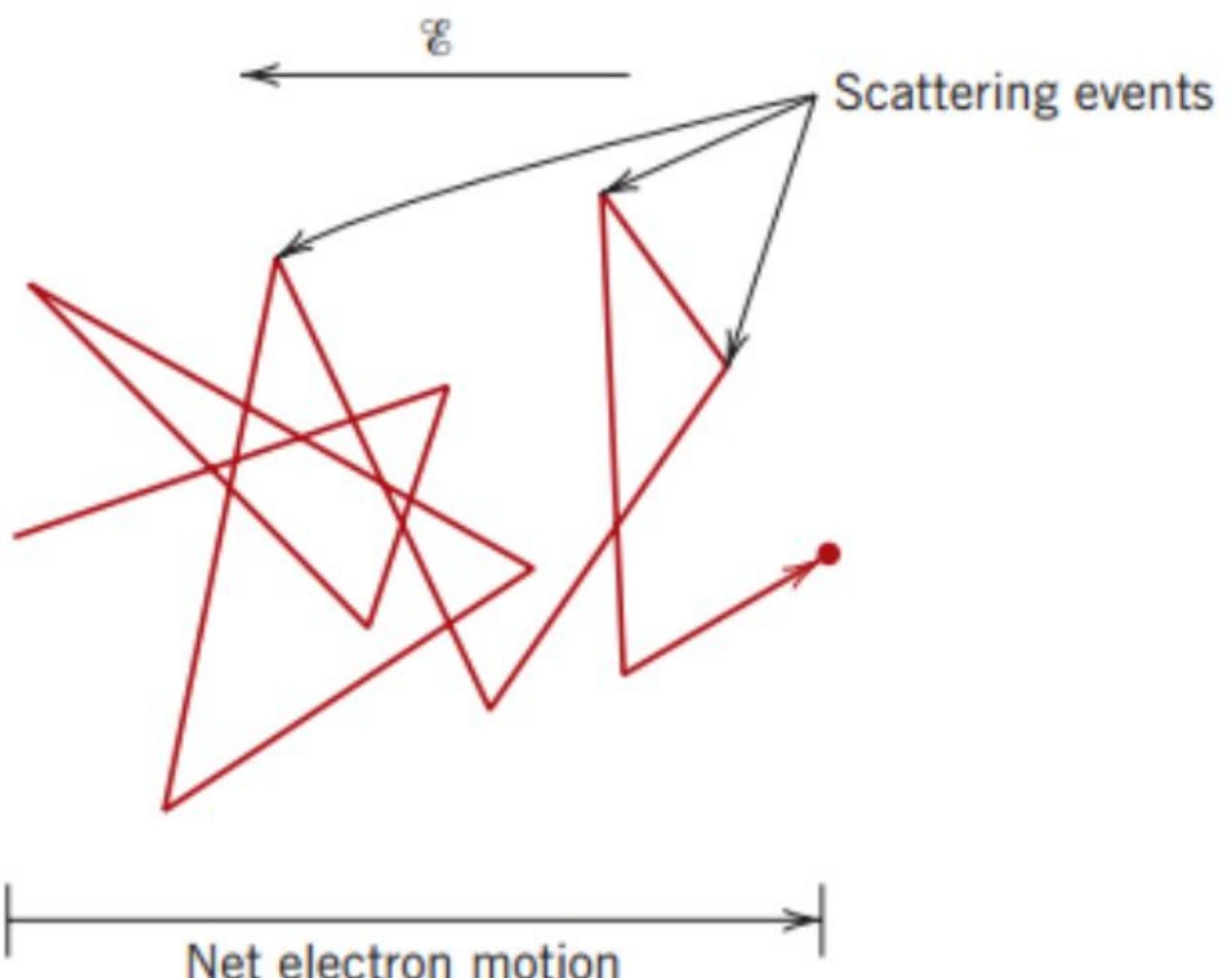
Electron Mobility

These frictional forces result from the scattering of electrons by imperfections in the crystal lattice, including impurity atoms, vacancies, interstitial atoms, dislocations, and even the thermal vibrations of the atoms themselves.

To describe the extent of this scattering; these include the *drift velocity* and the **mobility** of an electron. The drift velocity represents the average electron velocity in the direction of the force imposed by the applied field.

$$v_e = \mu_e E$$

$$\sigma = n|e|\mu_e$$



THE HALL EFFECT

To determine the material's majority charge carrier type, concentration, and mobility.

MAGNETIC FIELD applied perpendicular to the direction of motion of a Charged particle exerts a FORCE ON THE PARTICLE PERPENDICULAR to both the magnetic field and the particle motion directions.

$$V_H = \frac{R_H I_x B_z}{d}$$

V_H = Hall Voltage

d = Specimen thickness

In this expression R_H is termed the *Hall coefficient*, which is a constant for a given material. For metals, wherein conduction is by electrons, R_H is negative and equal to

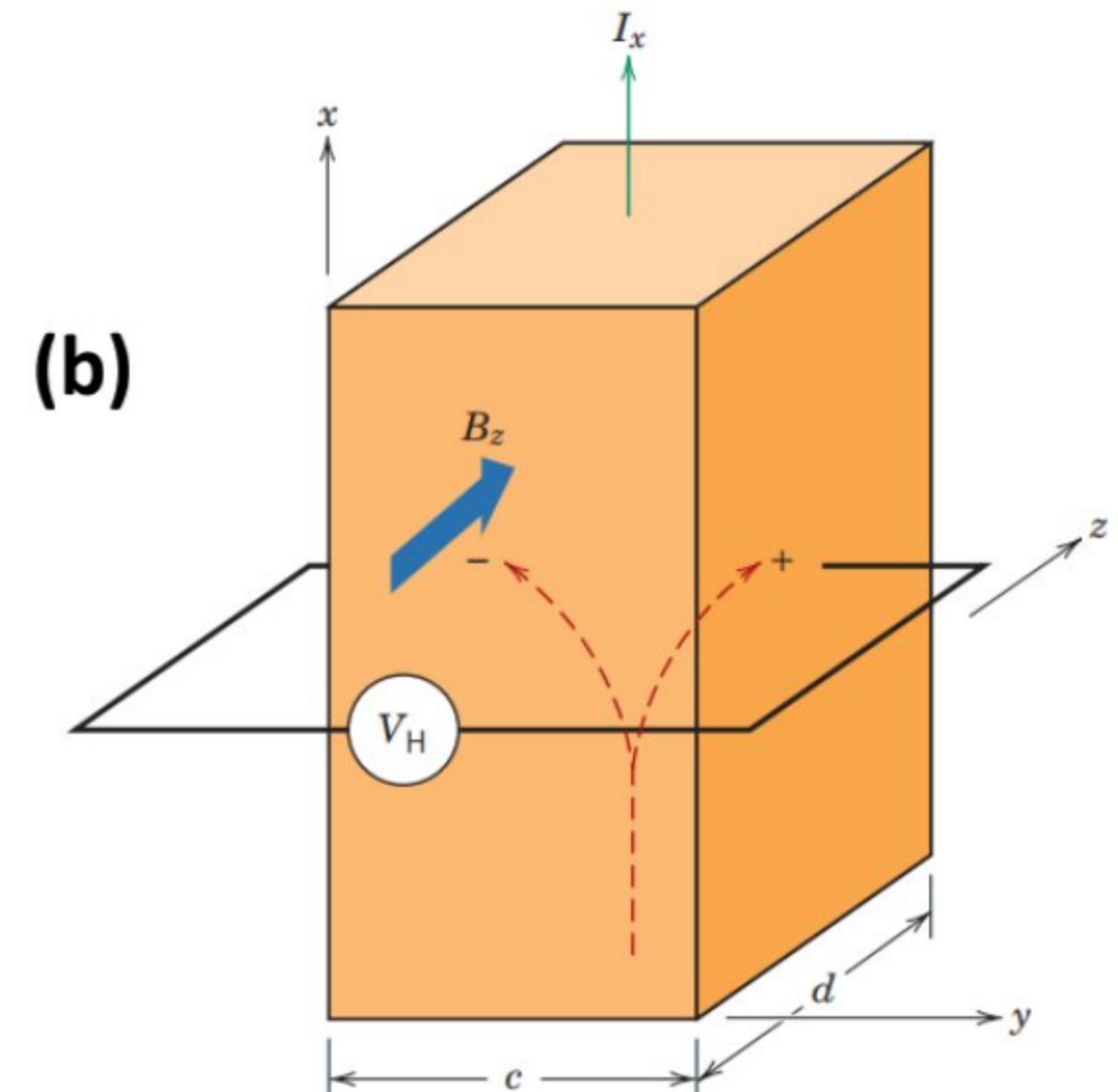
$$R_H = \frac{1}{n|e|}$$

electron mobility μ_e

conductivity σ

$$\mu_e = \frac{\sigma}{n|e|}$$

$$\mu_e = |R_H|\sigma$$



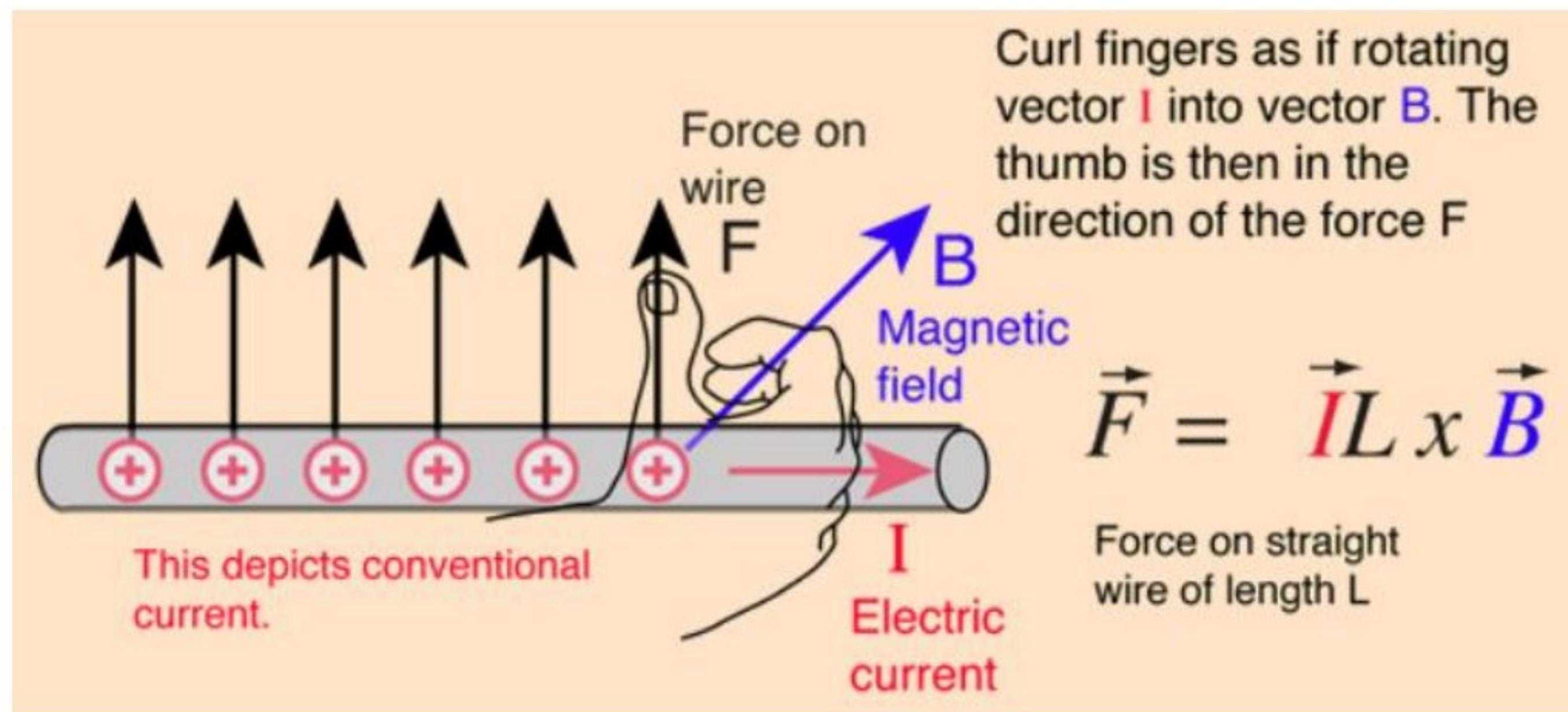
$$\vec{F} = q\vec{v} \times \vec{B}$$

Positive test charge q

\vec{F}

\vec{v}

\vec{B}

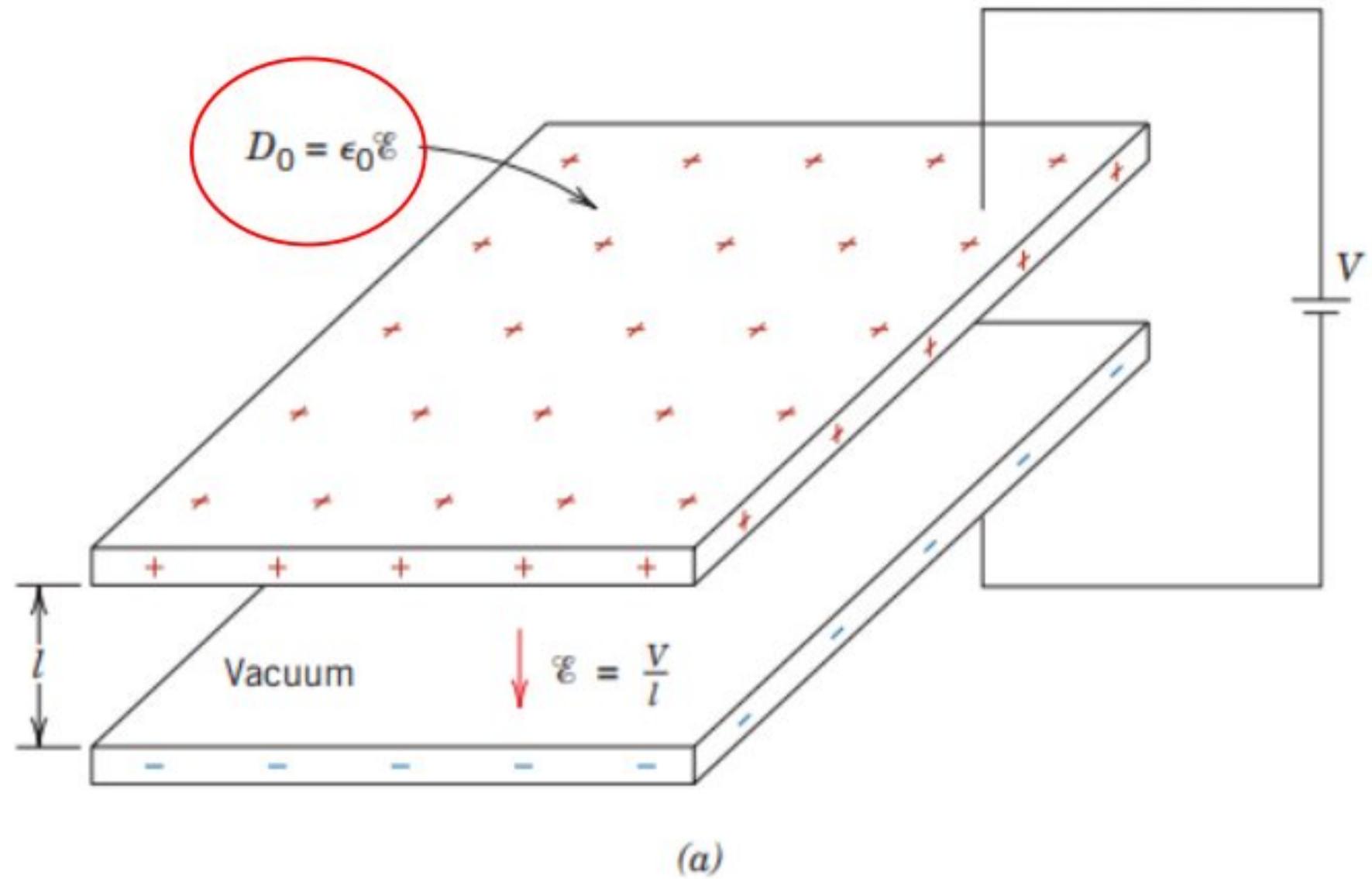


Dielectric Strength

The **dielectric strength**, sometimes called the breakdown strength, represents the magnitude of an electric field necessary to produce breakdown.

Sometimes localized melting, burning, or vaporization produces irreversible degradation and perhaps even failure of the material

Electric Displacement



Charge per unit area that would be displaced across a layer of conductor placed across an electric field.

Also known as **electric flux density** or **Surface charge density**.

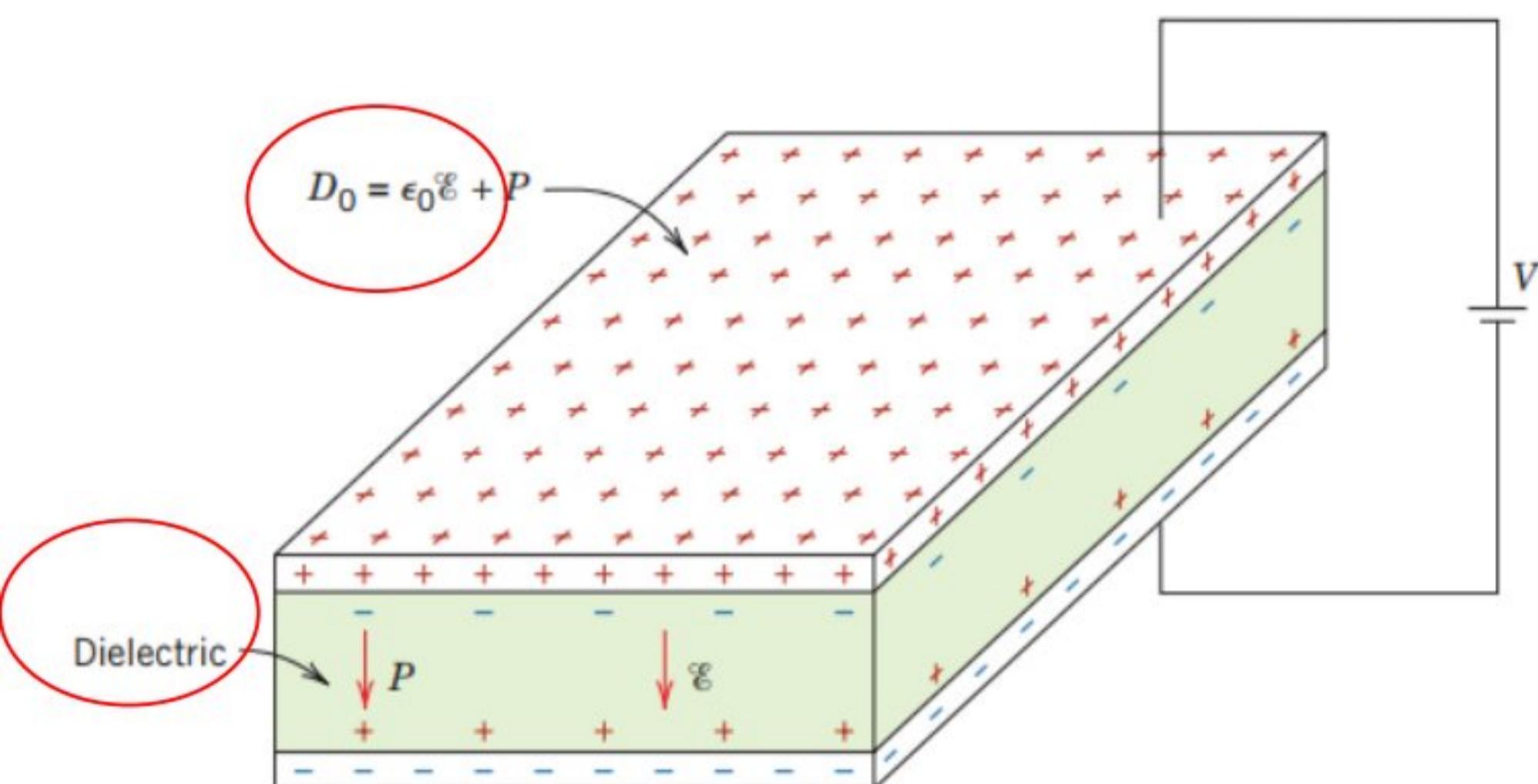
Electric displacement is used in the dielectric material to find the response of the materials on the application of an electric field \mathbf{E} .

The **SI unit Coulomb per meter square ($C\ m^{-2}$)**.

$$\mathbf{D} = \epsilon_0 \mathbf{E} + \mathbf{P}$$

- ϵ_0 : Vacuum permittivity
- \mathbf{P} : Polarization density
- \mathbf{E} : Electric field
- \mathbf{D} : Electric displacement field

The surface charge density D , or quantity of charge per unit area of capacitor plate (C/m^2), is proportional to the electric field



The **electric displacement field \mathbf{D}** represents how an electric field \mathbf{E} influences the organization of electric charges in a given medium, including charge migration and electric **dipole** reorientation.

Electric flux Density (D):

Electric flux density is defined as charge per unit area and it has same units of dielectric polarization.

Electric flux density D at a point in a free space or air in terms of Electric field strength is

$$D_0 = \epsilon_0 E \quad \text{--> (1)}$$

At the same point in a medium is given by

$$D = \epsilon E \quad \text{--> (2)}$$

As the polarization measures the additional flux density arising from the presence of material as compared to free space

$$\text{i.e., } D = \epsilon_0 E + P \quad \text{--> (3)}$$

Using equations 2 & 3 we get

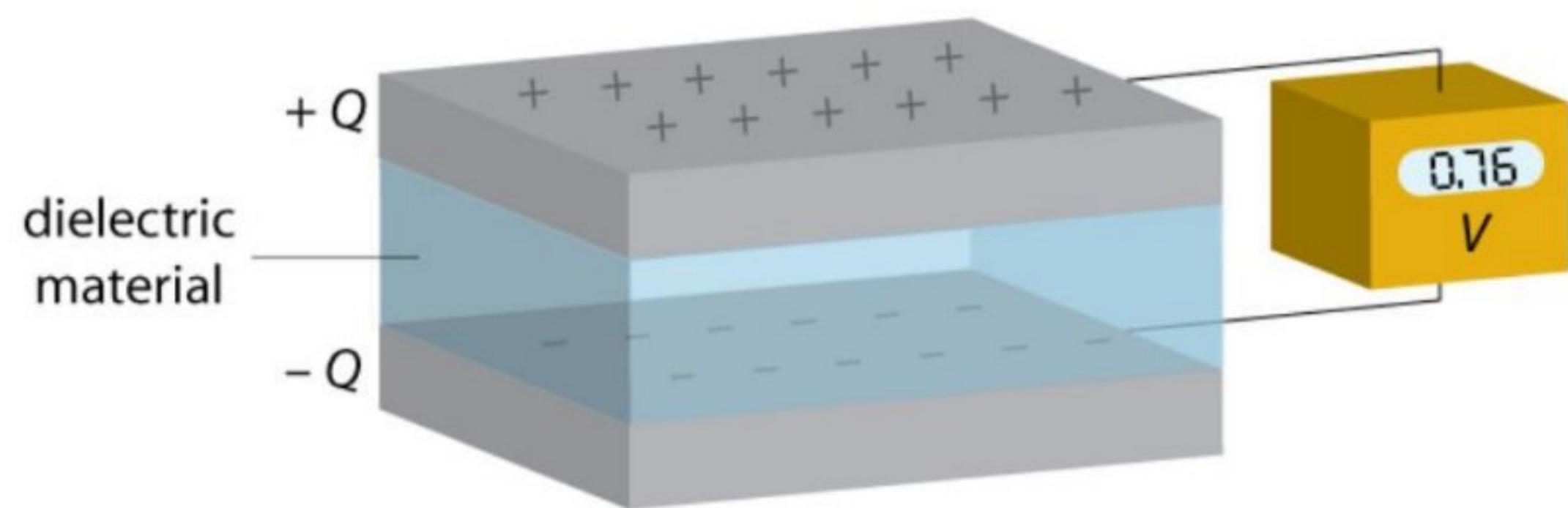
$$\epsilon E = \epsilon_0 E + P$$

$$(\epsilon - \epsilon_0) E = P$$

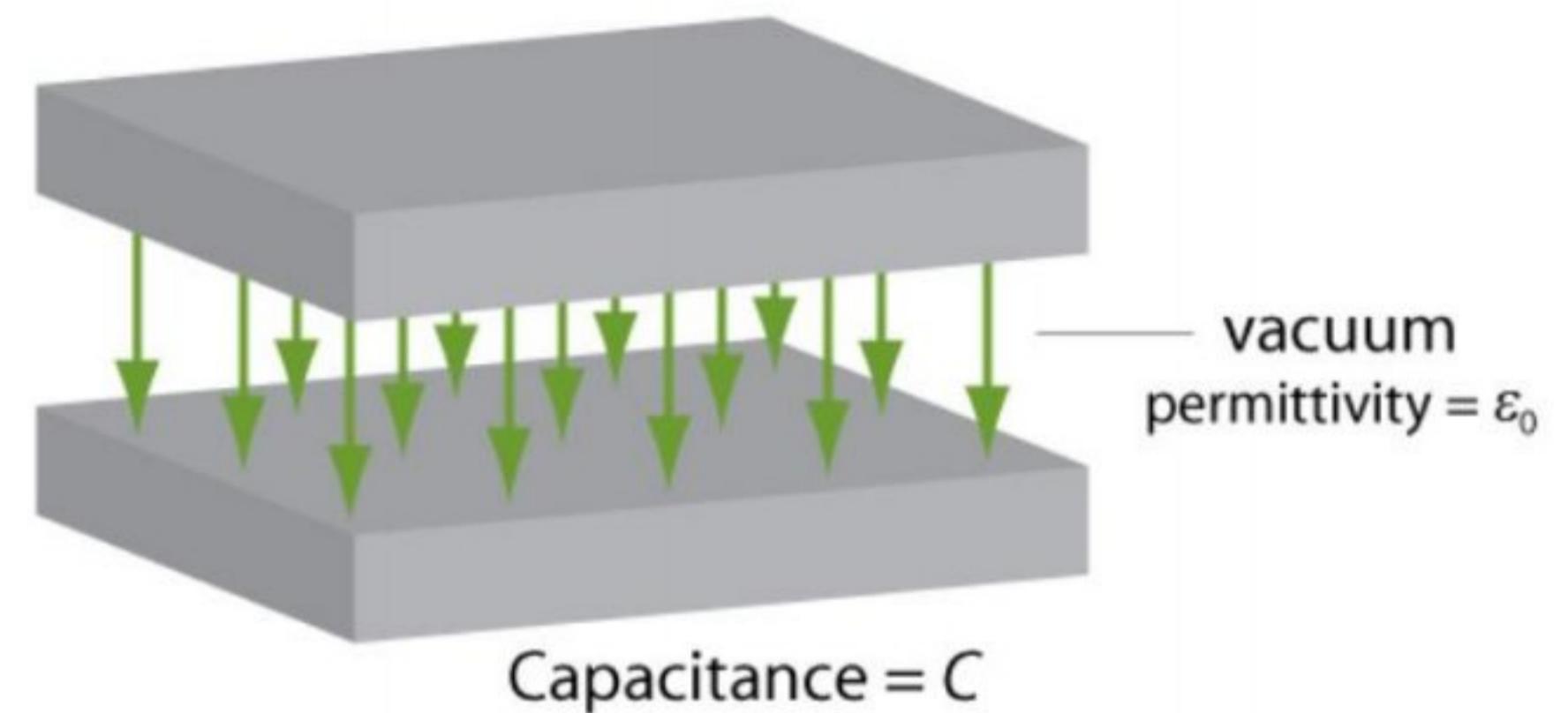
$$(\text{or}) \quad (\epsilon_r \cdot \epsilon_0 - \epsilon_0) E = P$$

$$(\epsilon_r - 1) \epsilon_0 \cdot E = P$$

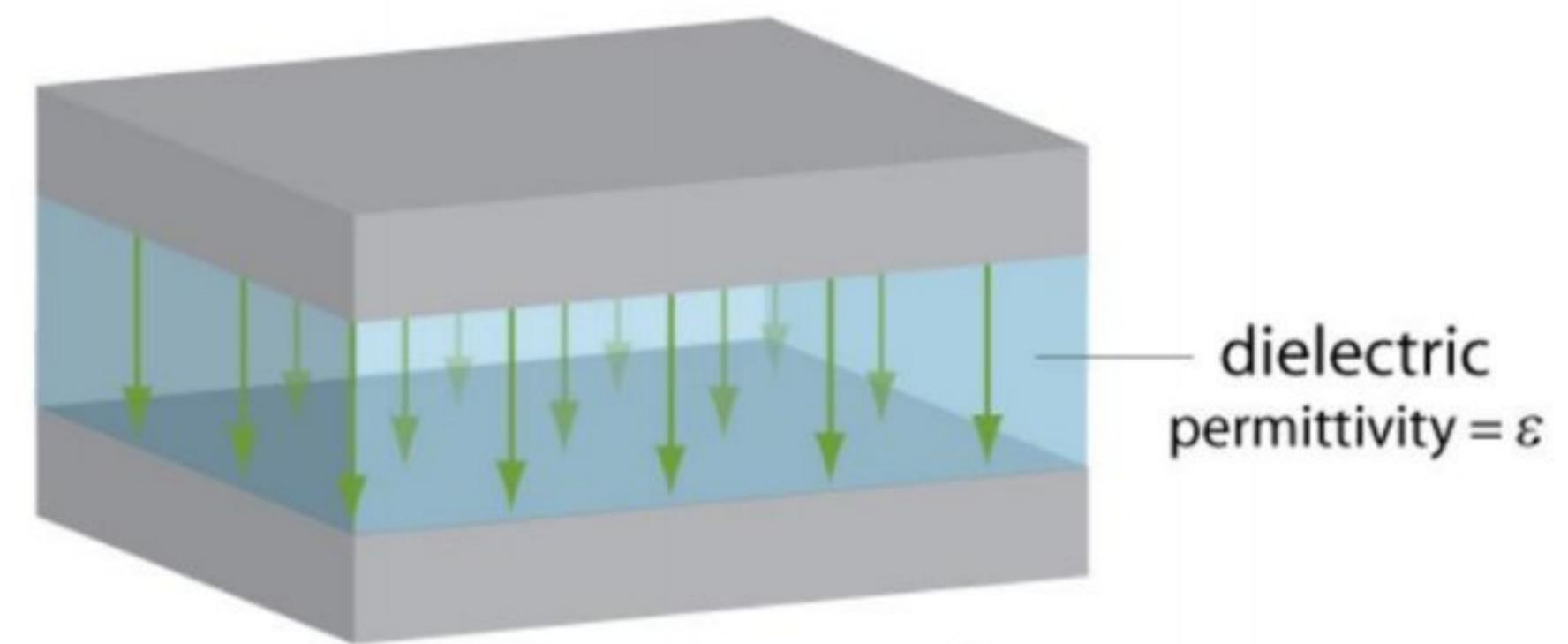
Capacitor



$$Q = CV$$



$$\text{Capacitance} = C$$

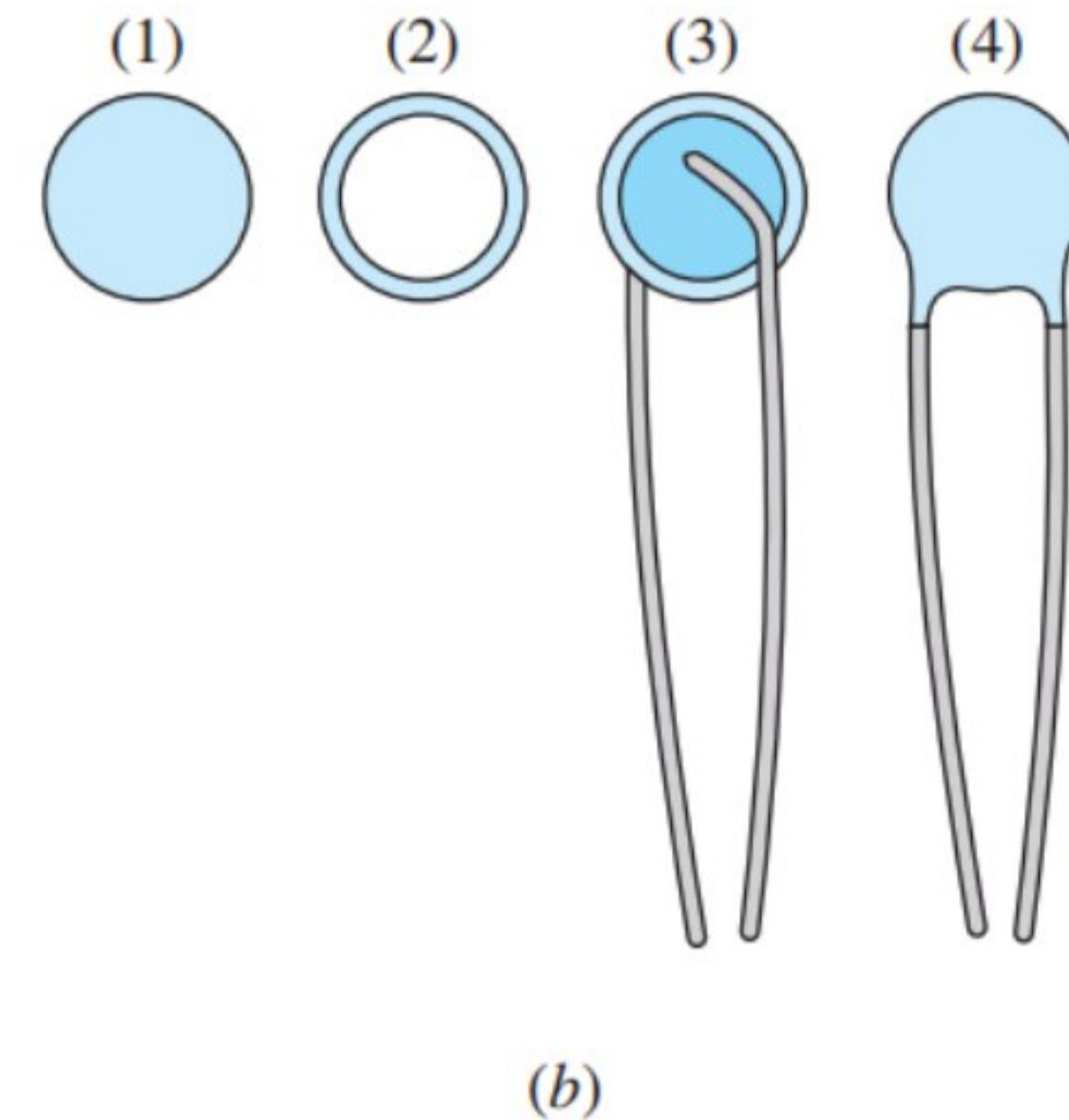
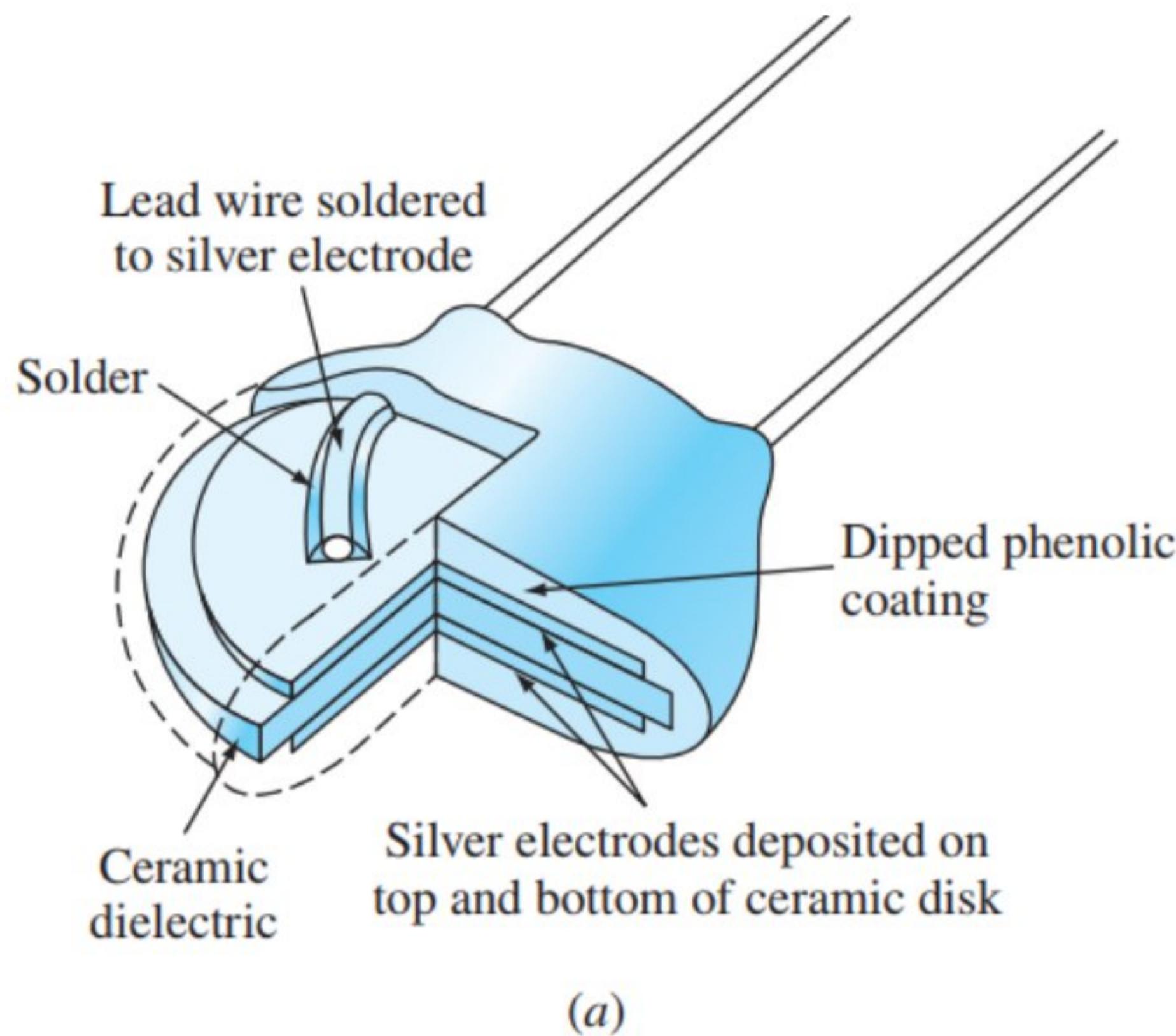


$$\text{Capacitance} = C'$$

$$\kappa = C'/C$$

$$\kappa = \epsilon/\epsilon_0$$

Capacitor

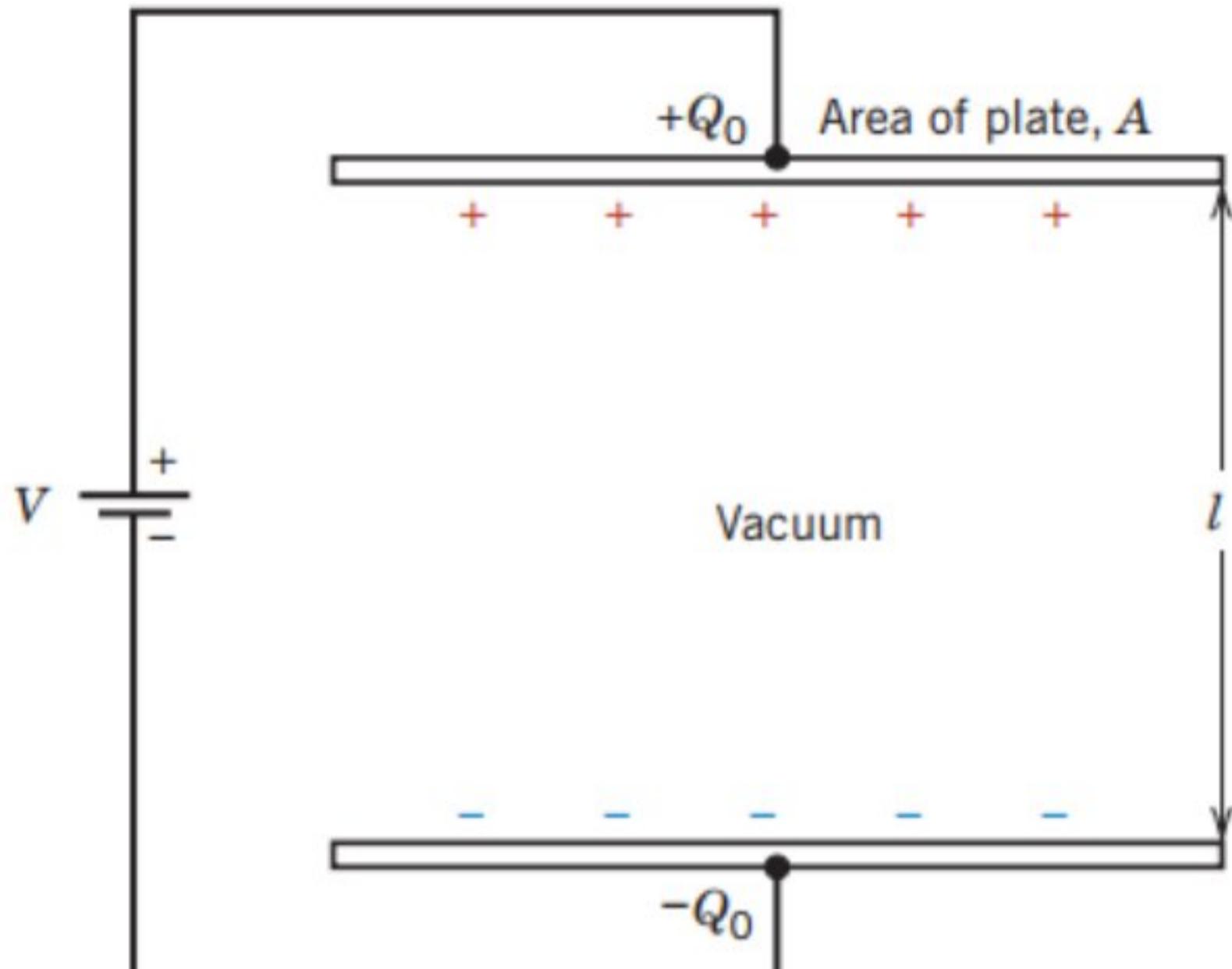


Ceramic capacitors. (a) Section showing construction. (b) Steps in manufacture: (1) after firing ceramic disk; (2) after applying silver electrodes; (3) after soldering leads; (4) after applying dipped phenolic coating.

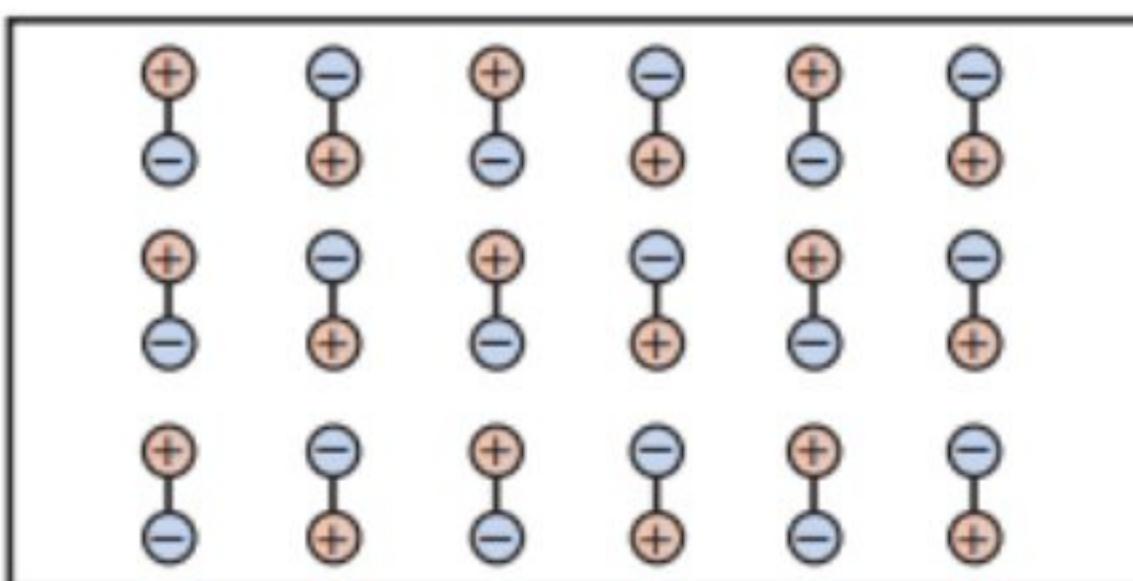
Representative formulations for some ceramic dielectric materials for capacitors

Dielectric Constant κ	Formulation
325	$\text{BaTiO}_3 + \text{CaTiO}_3 + \text{low \% Bi}_2\text{Sn}_3\text{O}_9$
2100	$\text{BaTiO}_3 + \text{low \% CaZrO}_3$ and Nb_2O_5
6500	$\text{BaTiO}_3 + \text{low \% CaZrO}_3$ or $\text{CaTiO}_3 + \text{BaZrO}_3$

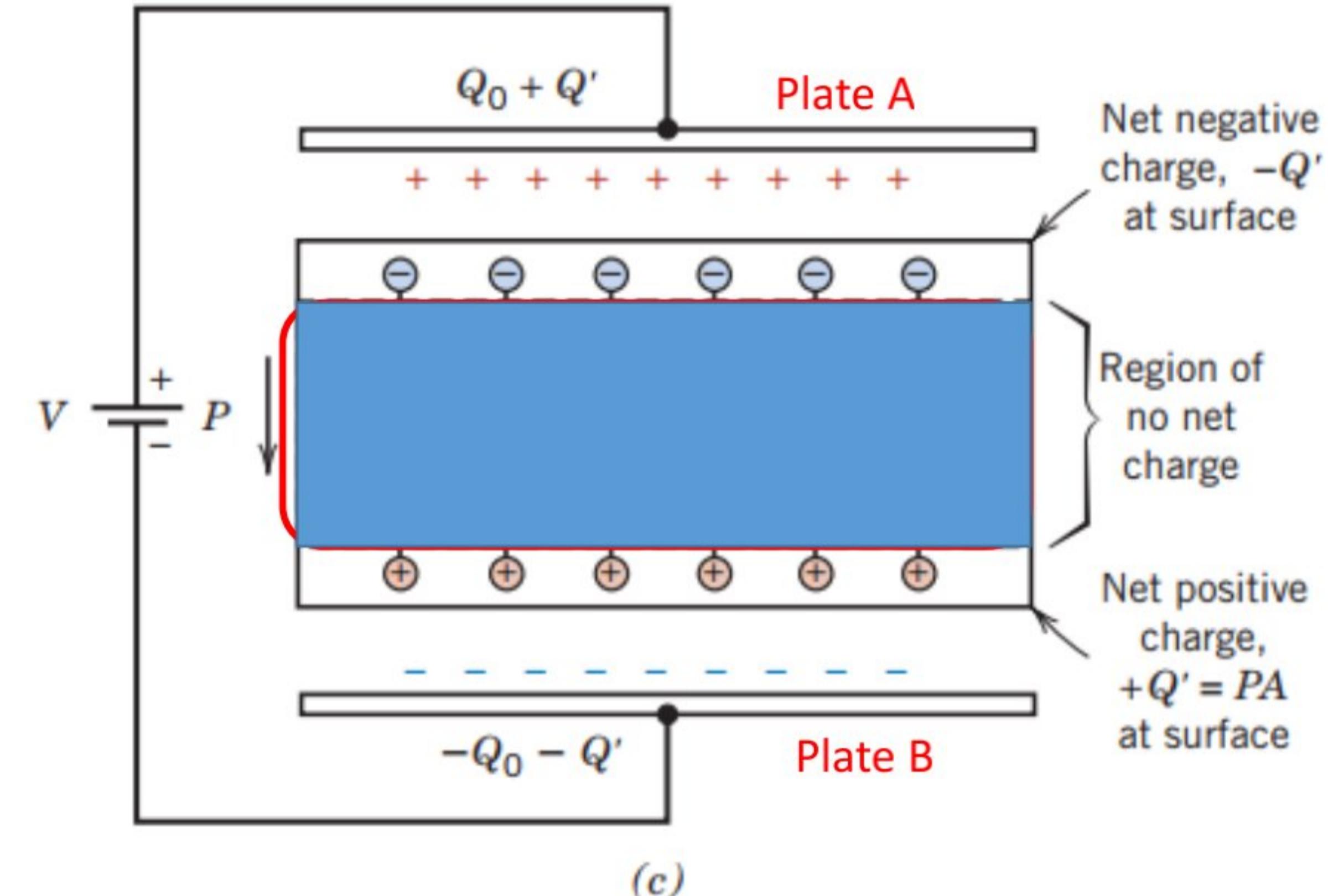
Parallel Plate Capacitor in the presence of dielectric



(a)

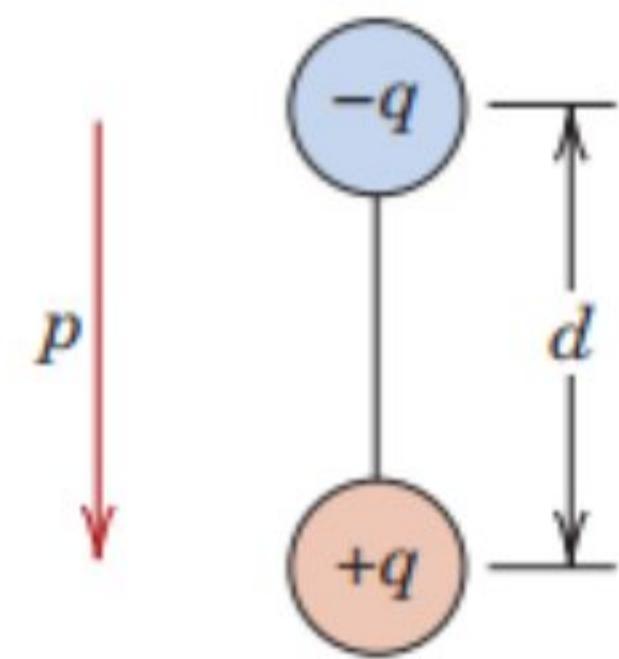


(b)



$$\mathbf{D} = \mathbf{E}\epsilon_0 + \mathbf{P}$$

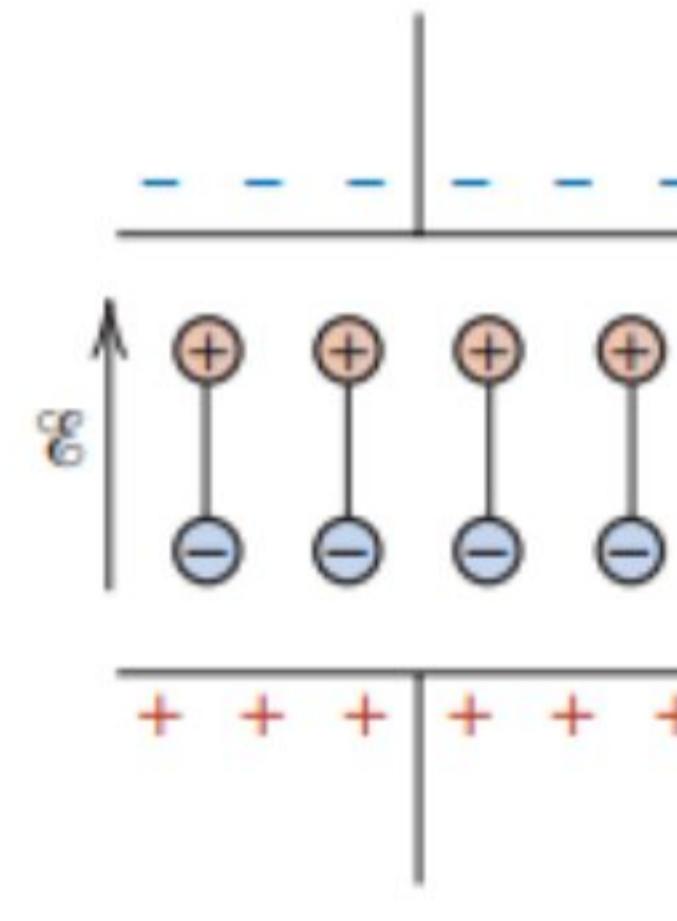
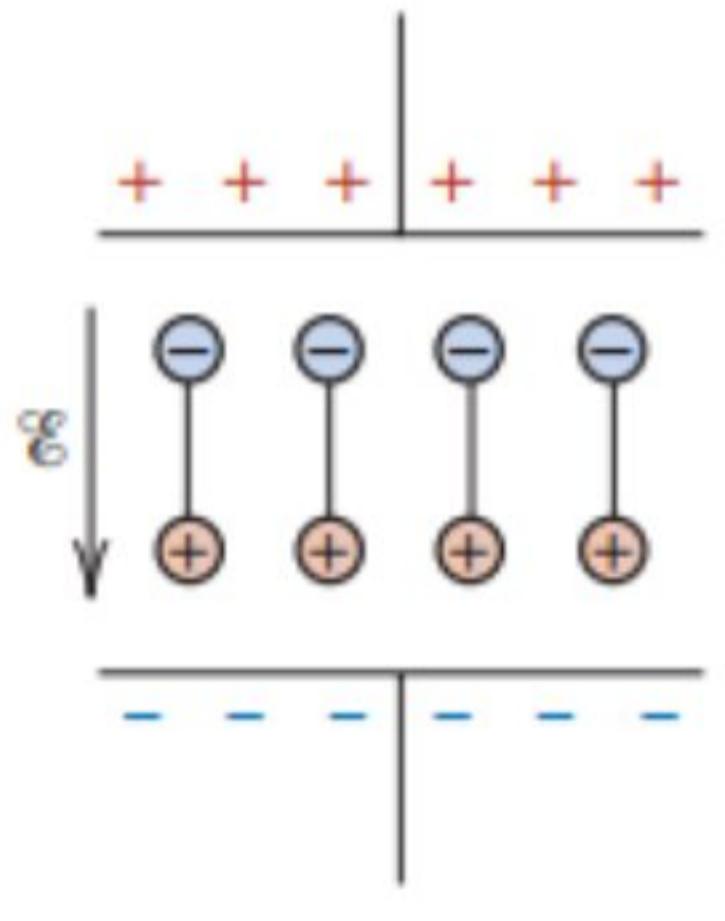
Dipole orientations for change in orientation of electric field.



In reality, a dipole moment is a vector that is directed from the negative to the positive charge

In the presence of an electric field E , which is also a vector quantity, a force (or torque) will come to bear on an electric dipole to orient it with the applied field.

The process of dipole alignment is termed **polarization**.



(a)

(b)

<i>Quantity</i>	<i>Symbol</i>	<i>Derived</i>	<i>SI Units</i>	<i>Primary</i>
Electric potential	V	volt		$\text{kg}\cdot\text{m}^2/\text{s}^2\cdot\text{C}$
Electric current	I	ampere		C/s
Electric field strength	\mathcal{E}	volt/meter		$\text{kg}\cdot\text{m}^2/\text{s}\cdot\text{C}$
Resistance	R	ohm		$\text{kg}\cdot\text{m}^2/\text{s}\cdot\text{C}^2$
Resistivity	ρ	ohm-meter		$\text{kg}\cdot\text{m}^3/\text{s}\cdot\text{C}^2$
Conductivity	σ	$(\text{ohm-meter})^{-1}$		$\text{s}\cdot\text{C}^2/\text{kg}\cdot\text{m}^3$
Electric charge	Q	coulomb		C
Capacitance	C	farad		$\text{s}^2\cdot\text{C}^2/\text{kg}\cdot\text{m}^2$
Permittivity	ϵ	farad/meter		$\text{s}^2\cdot\text{C}^2/\text{kg}\cdot\text{m}^3$
Dielectric constant	ϵ_r	dimensionless		dimensionless
Dielectric displacement	D	farad-volt/ m^2		C/m^2
Electric polarization	P	farad-volt/ m^2		C/m^2

Polarization

Polarization direction -ve to +ve

Polarization is dipole moment per unit volume

Polarization is the alignment of permanent or induced atomic or molecular dipole moments with an externally applied electric field.

Electronic polarization

Results from a displacement of the center of the negatively charged electron cloud relative to the positive nucleus of an atom by the electric field

This polarization type is found in all dielectric materials and, of course, exists only while an electric field is present.

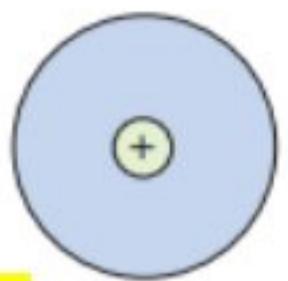
Ionic Polarization

Ionic polarization occurs only in materials that are ionic. An applied field acts to displace **cations in one direction and anions in the opposite direction**, which gives rise to a net dipole moment.

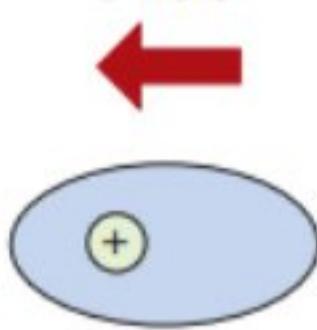
Orientation or dipolar Polarization

It is found only in substances that possess permanent dipole moments. Polarization results from a rotation of the permanent moments into the direction of the applied field, This alignment tendency is counteracted by the thermal vibrations of the atoms, such that polarization decreases with increasing temperature.

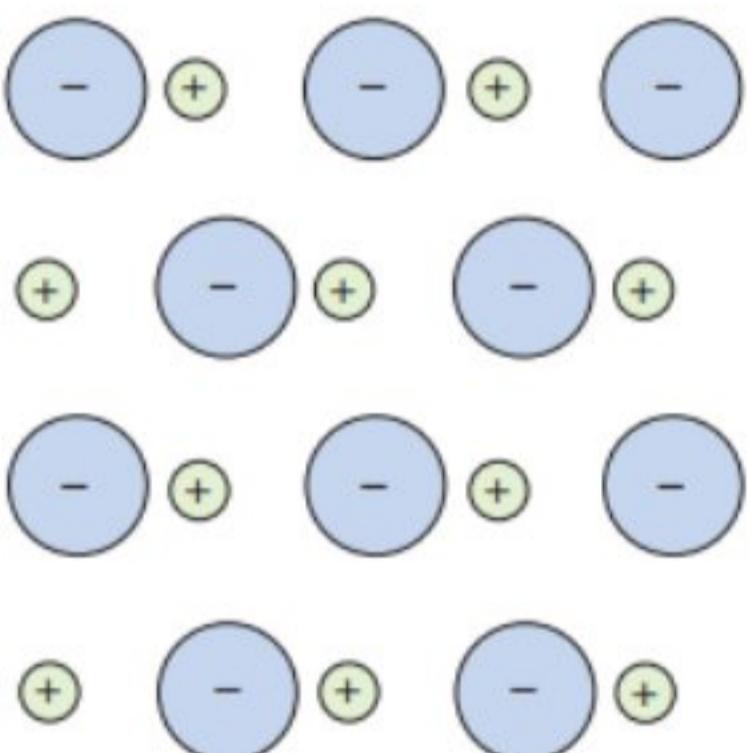
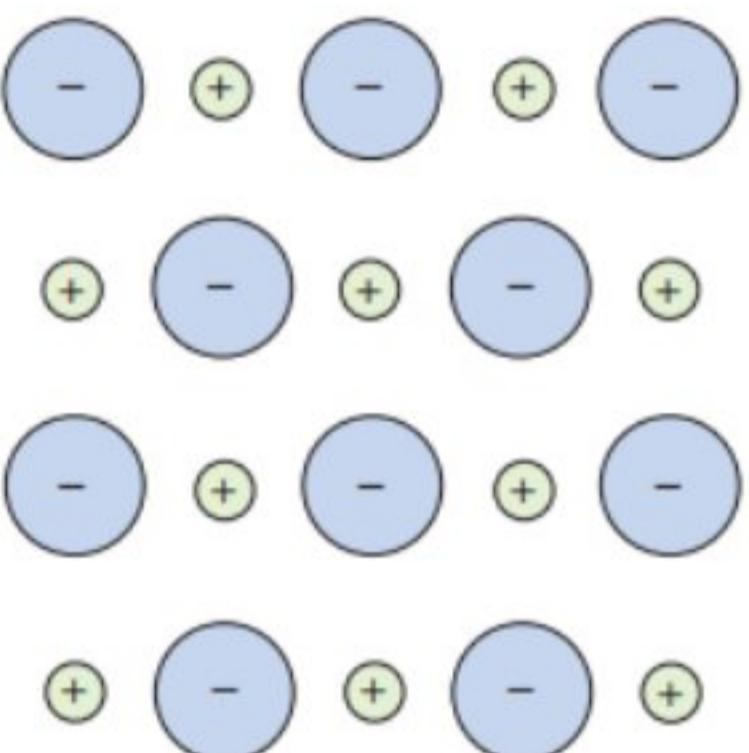
No field



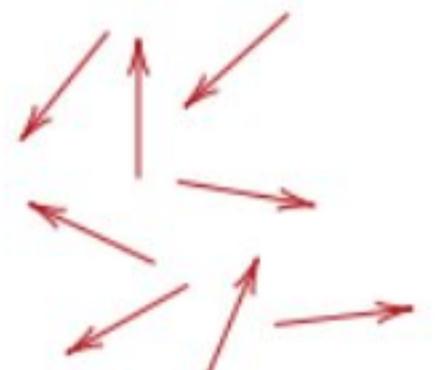
Applied
E field



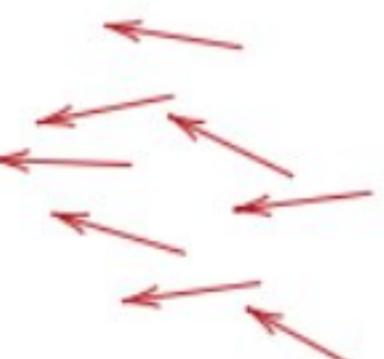
(a)



(b)



(c)



Schematic Illustrations

$$\mathbf{P} = \chi_e \epsilon_0 \mathcal{E}$$

Electric field

χ_e is the **electric susceptibility** and $\epsilon_0 = 8.854 \times 10^{-12} \text{ C}^2 \text{ J}^{-1} \text{ m}^{-1}$

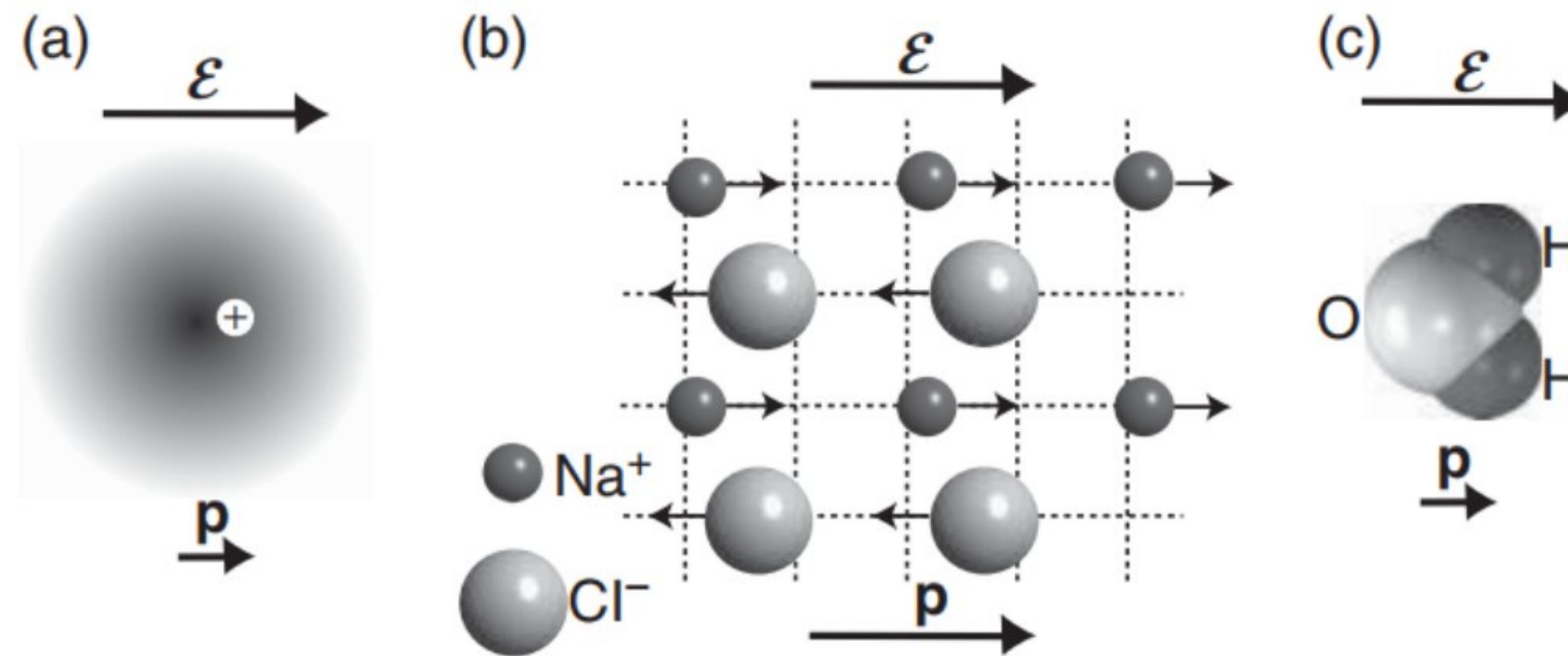


Figure 9.2 Mechanisms leading to microscopic electric polarization. (a) The electric field polarizes all the atoms in the solid. (b) In ionic solids, like NaCl, the lattice can be polarized, giving rise to local electric dipoles. The dashed grid gives the position of the

ions without an applied field. (c) If there are permanent dipoles in the solid and these are free to rotate, they orient themselves parallel to the field. A molecule with a permanent dipole is, for example, water.

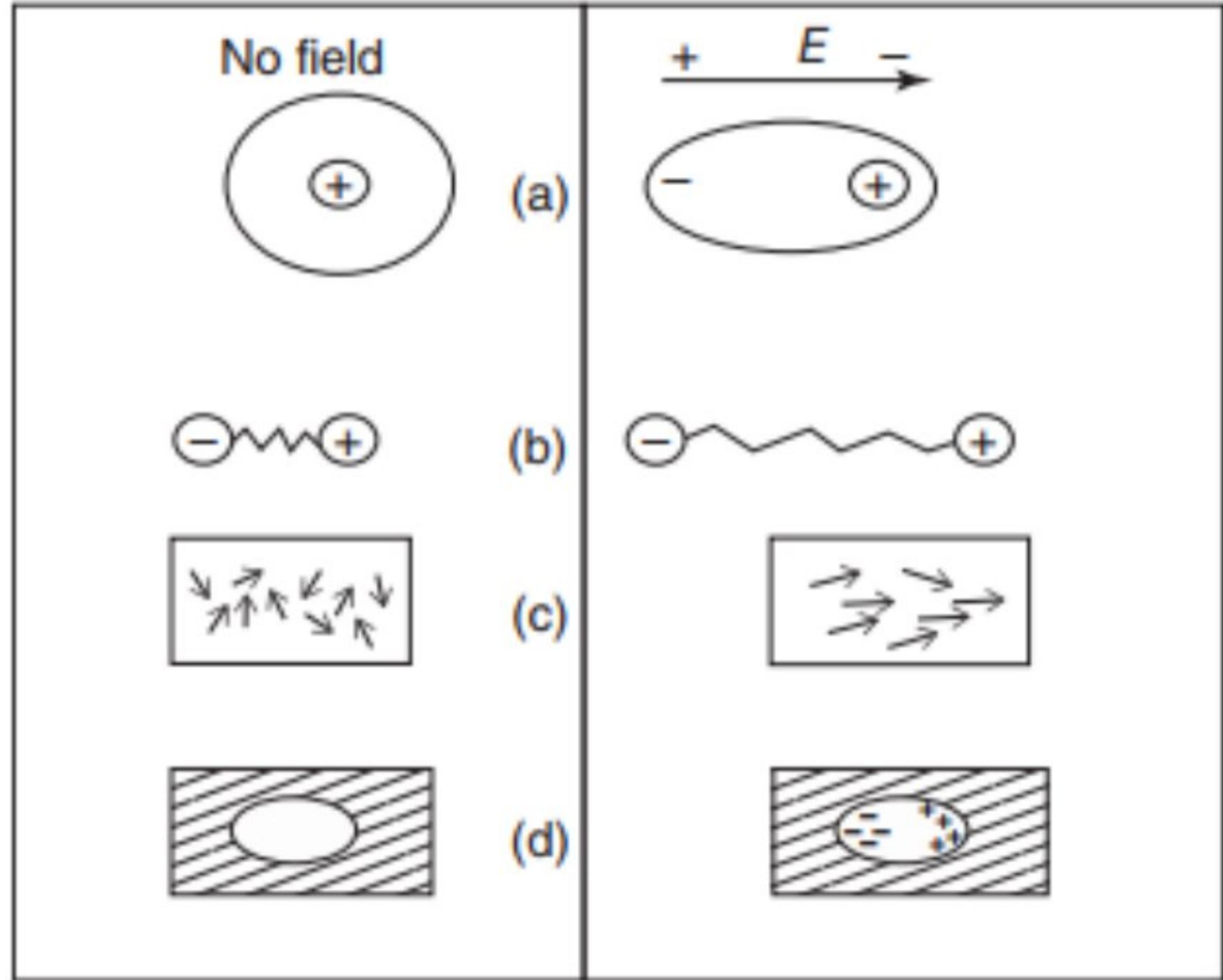
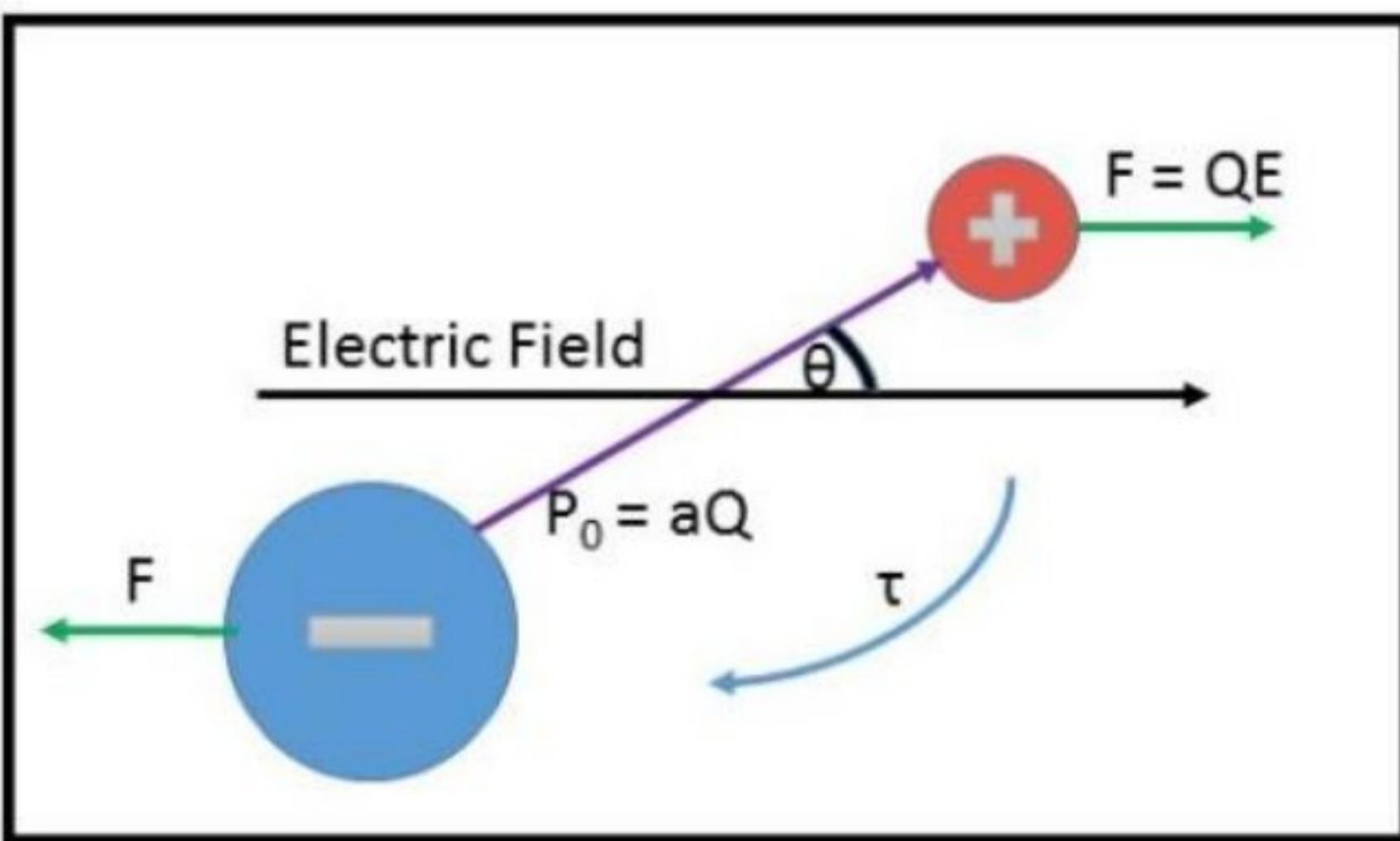
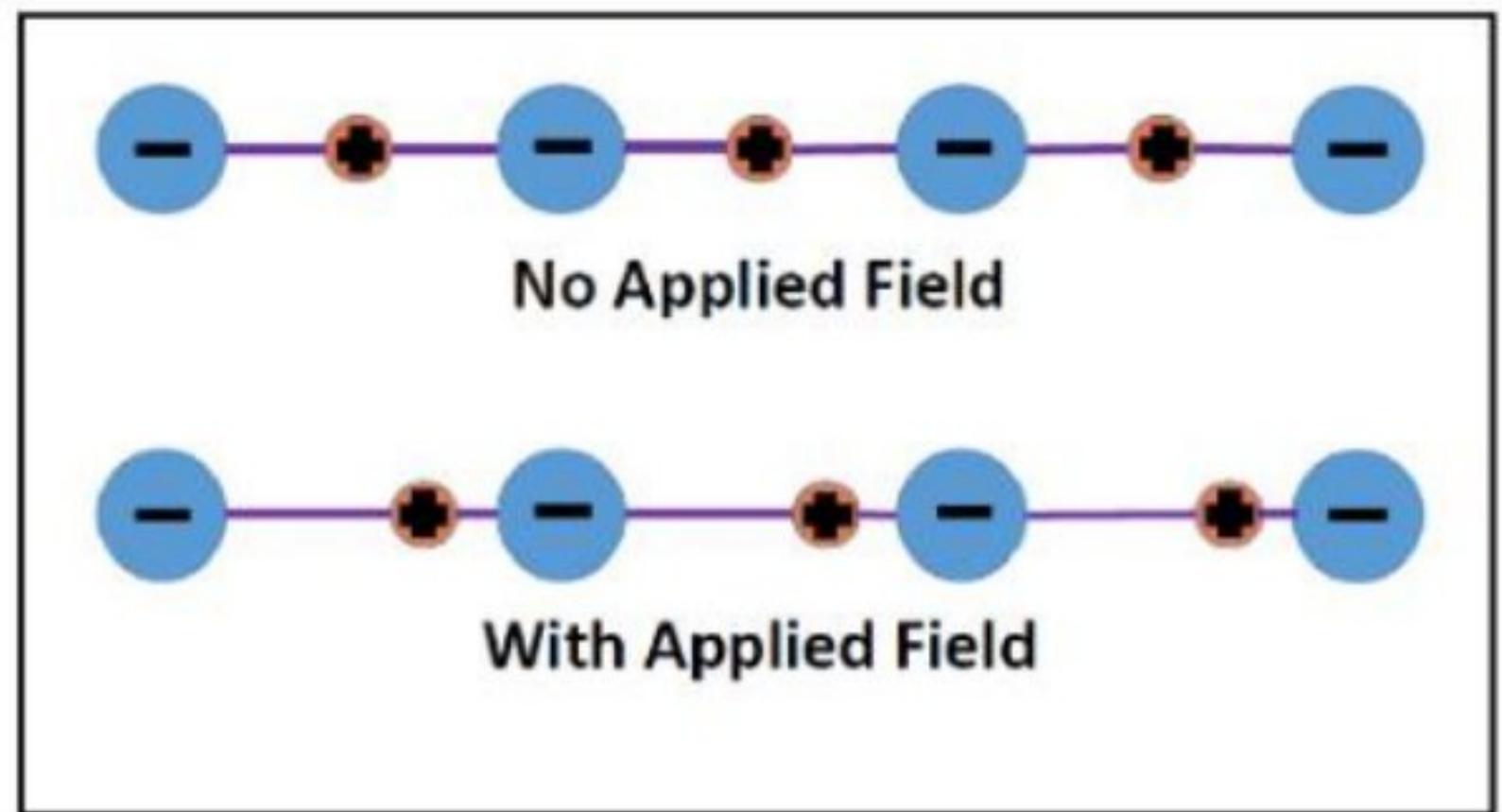
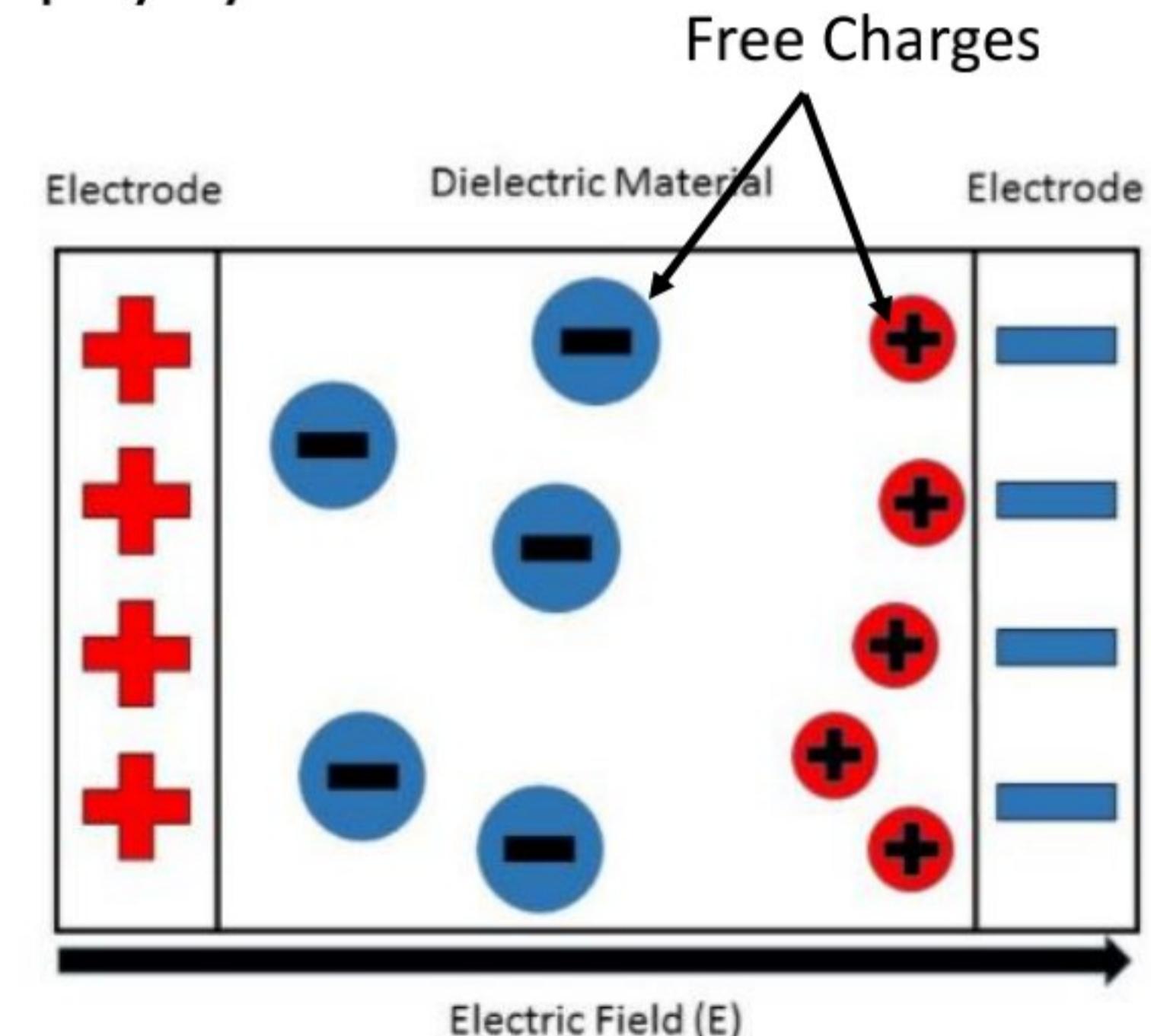


Figure 1.8 Polarization processes:
 (a) electronic polarization, (b) ionic polarization, (c) orientational polarization, and (d) space charge polarization.

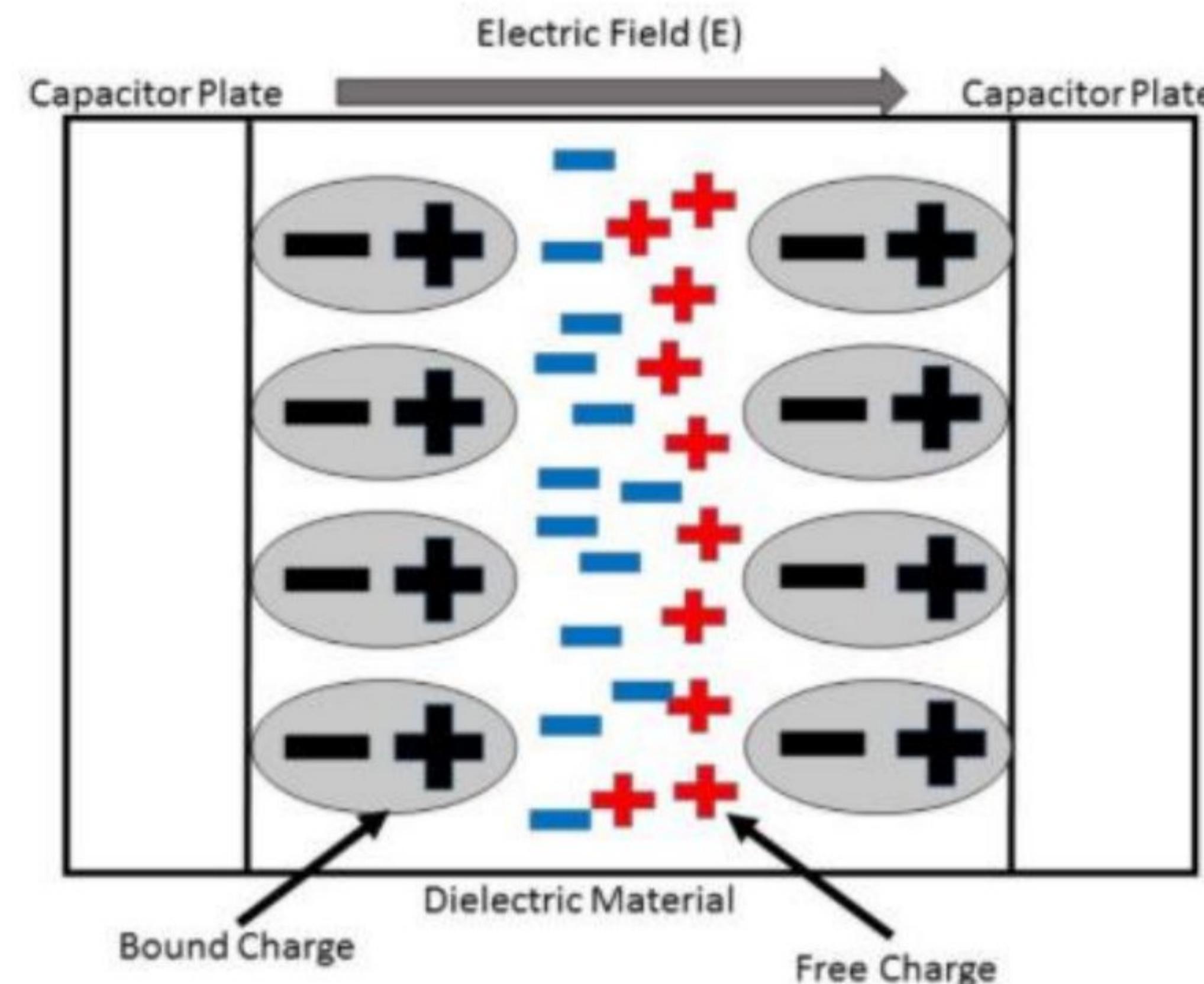
Interfacial Polarization or Space Charge Polarization

- It occurs when there is an accumulation of charge at an interface between two materials or between two regions within a material because of an external field. This can occur when there is a compound dielectric, or when there are two electrodes connected to a dielectric material.
- This type of electric polarization is different from orientational and ionic polarization because instead of affecting bound positive and negative charges i.e. ionic and covalent bonded structures, interfacial polarization also affects free charges as well.
- As a result interfacial polarization is usually observed in amorphous or polycrystalline solids.

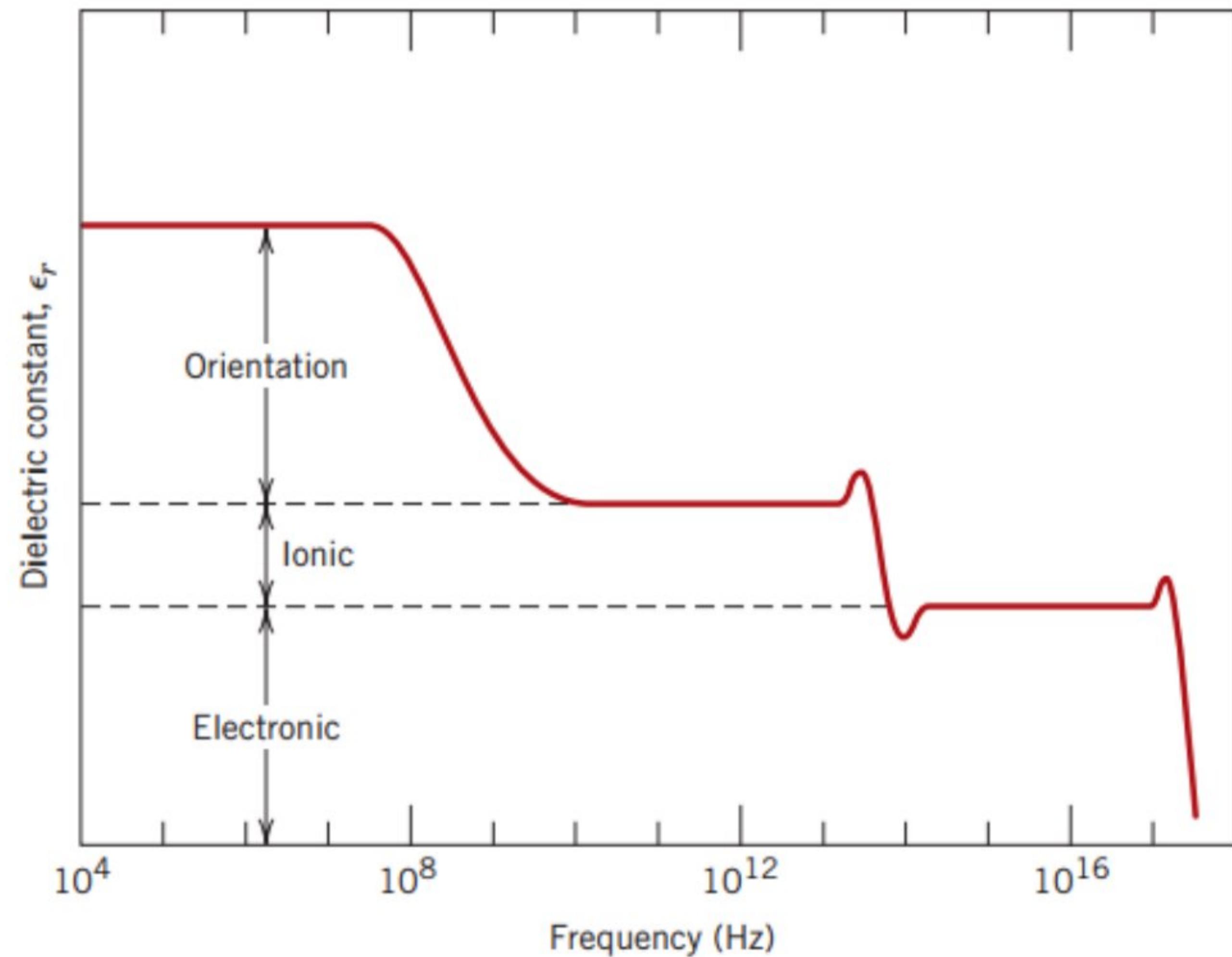
- The electric field will cause a charge imbalance because of the dielectric material's insulating properties.
- However, the mobile charges in the dielectric will migrate over maintain charge neutrality. This then causes interfacial polarization



Dielectric Polarization



Dielectric Constant



Dielectric constant of some well known substances

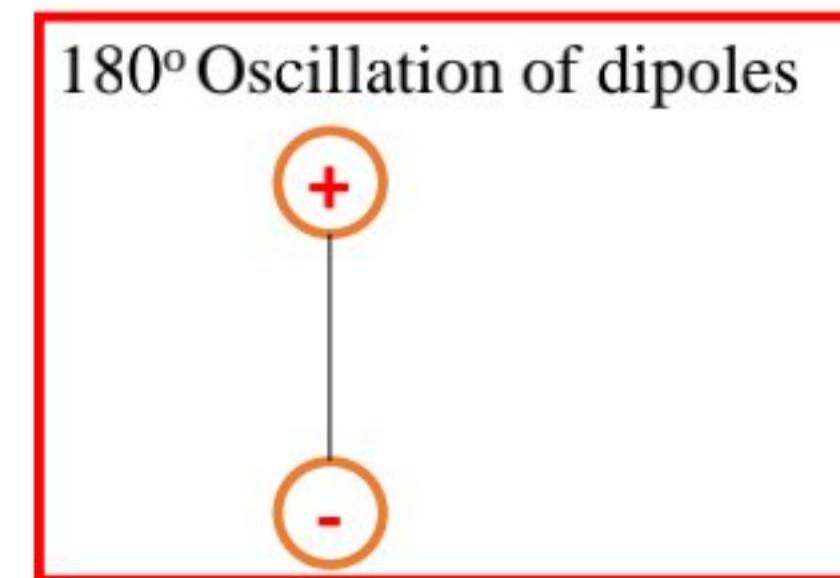
Material	ϵ_r
Air (1 atm)	1.00054
Water (20°C)	80.4
C ₂ H ₅ OH	25
Diamond	6.6
Glass	19
Paper	3.5
Polystyrene	6.2

- A dielectric becomes polarised in an electric field. Now imagine switching the direction of the field. The direction of the polarisation will also switch in order to align with the new field. This cannot occur instantaneously: some time is needed for the movement of charges or rotation of dipoles.
- If the field is switched, there is a characteristic time that the orientational polarisation (or average dipole orientation) takes to adjust, called the relaxation time.
- Typical relaxation times are $\sim 10^{-11}$ s.
- Therefore, if the electric field switches direction at a frequency higher than $\sim 10^{11}$ Hz, the dipole orientation cannot ‘keep up’ with the alternating field, the polarisation direction is unable to remain aligned with the field, and this polarisation mechanism ceases to contribute to the polarisation of the dielectric.

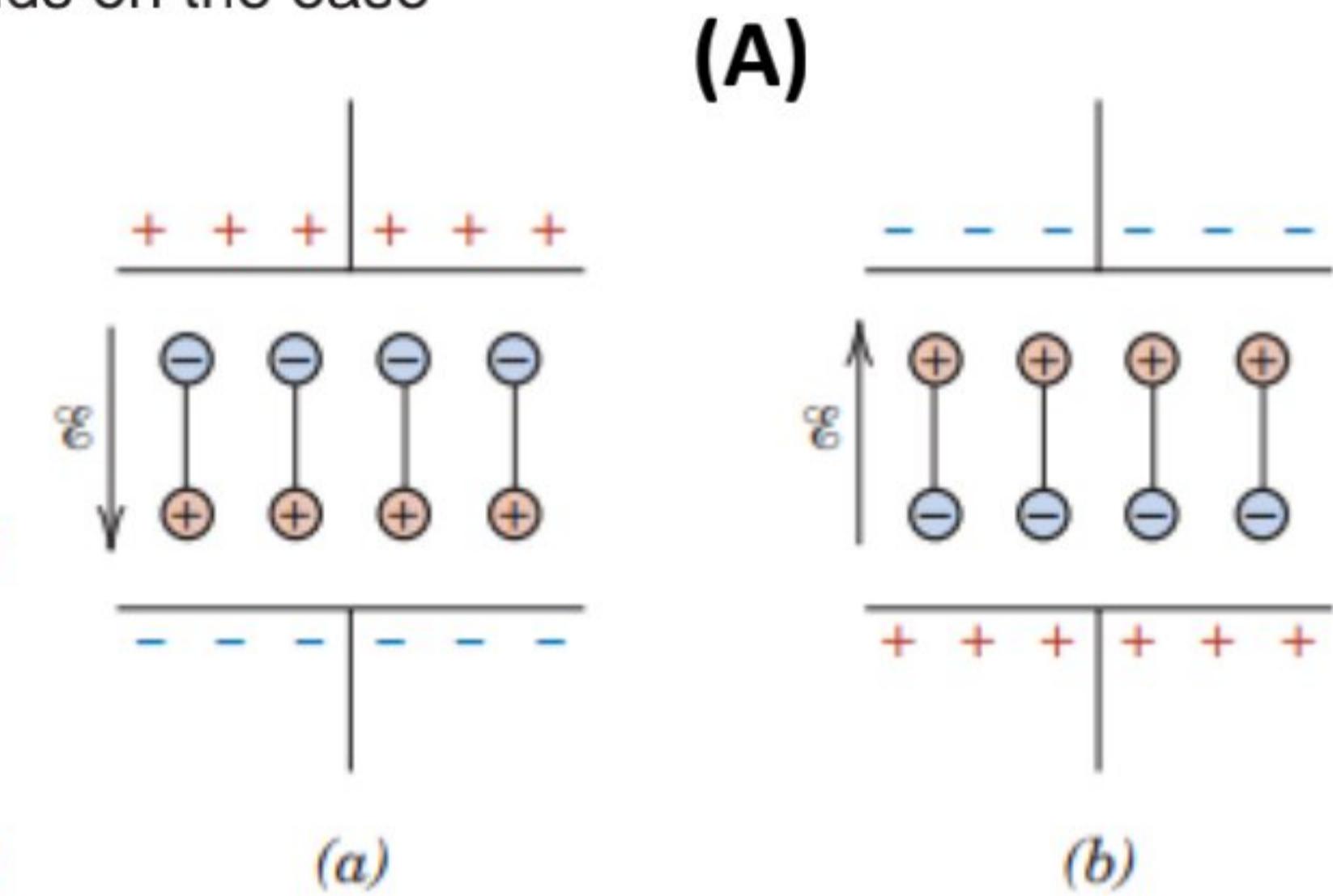
Dielectrics Losses

- For each polarization type, some **minimum reorientation time exists**, which depends on the ease with which the particular dipoles are capable of realignment.
- A **relaxation frequency** is taken as the reciprocal of this minimum reorientation time
- A dipole cannot keep shifting orientation direction when the frequency of the applied electric field exceeds its relaxation frequency and, therefore, will not make a contribution to the dielectric constant.
- The absorption of electrical energy by a dielectric material that is subjected an alternating electric field is termed *dielectric loss*.**
- A low dielectric loss is desired at the frequency of utilization.

(B)



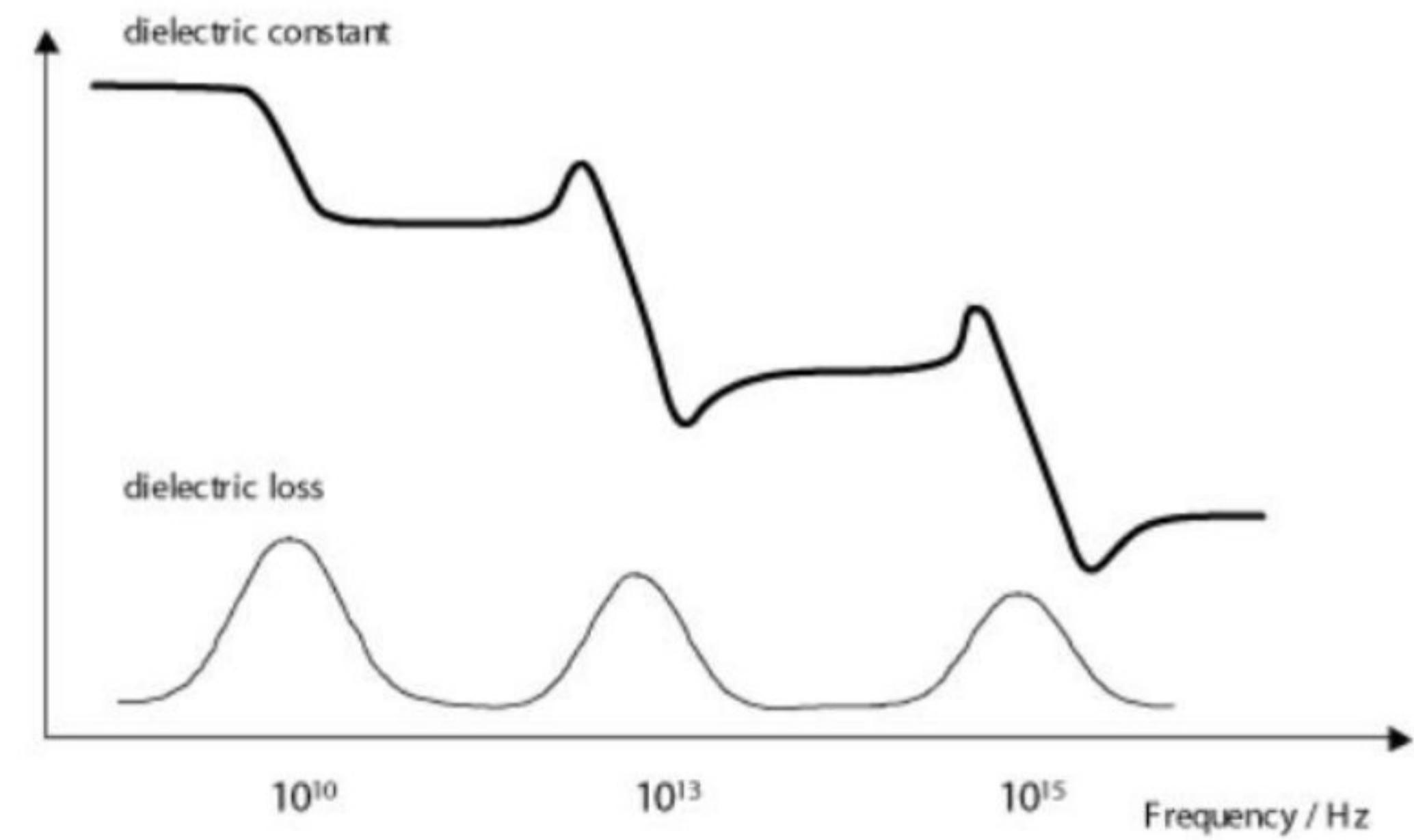
Animation



Dielectric Loss

- Dielectric loss is the dissipation of energy through the movement of charges in an alternating electromagnetic field as polarisation switches direction.
- Dielectric loss is especially high around the relaxation or resonance frequencies of the polarisation mechanisms as the polarisation lags behind the applied field, causing an interaction between the field and the dielectric's polarisation that results in heating.
- Dielectric loss tends to be higher in materials with higher dielectric constants. This is the downside of using these materials in practical applications.
- Dielectric loss is utilized to heat food in a microwave oven

the frequency of the microwaves used is close to the relaxation frequency of the orientational polarisation mechanism in water, meaning that any water present absorbs a lot of energy that is then dissipated as heat. The exact frequency used is slightly away from the frequency at which maximum dielectric loss occurs in water to ensure that the microwaves are not all absorbed by the first layer of water they encounter, therefore allowing more even heating of the food.



Dielectric Loss Factor

- If the voltage used to maintain the charge on a capacitor is sinusoidal, as is generated by an alternating current, **the current leads the voltage by 90 degrees when a loss-free dielectric is between the plates of a capacitor.**
- However, when a real dielectric is used in the capacitor, the current leads the voltage by $(90^\circ - \delta)$, where the angle δ is called the **dielectric loss angle**.
- The product of dielectric constant(κ) $\tan \delta$ is designated the **loss factor** and is a **measure of the electric energy lost (as heat energy)** by a capacitor in an ac circuit.

In circuits with primarily capacitive loads, current leads the voltage. This is true because current must first flow to the two plates of the capacitor, where charge is stored. Only after charge accumulates at the plates of a capacitor is a voltage difference established.

Dielectric Breakdown

If the electric field across an insulator is too high, the insulator will start to conduct a current. This phenomenon is known as dielectric breakdown.

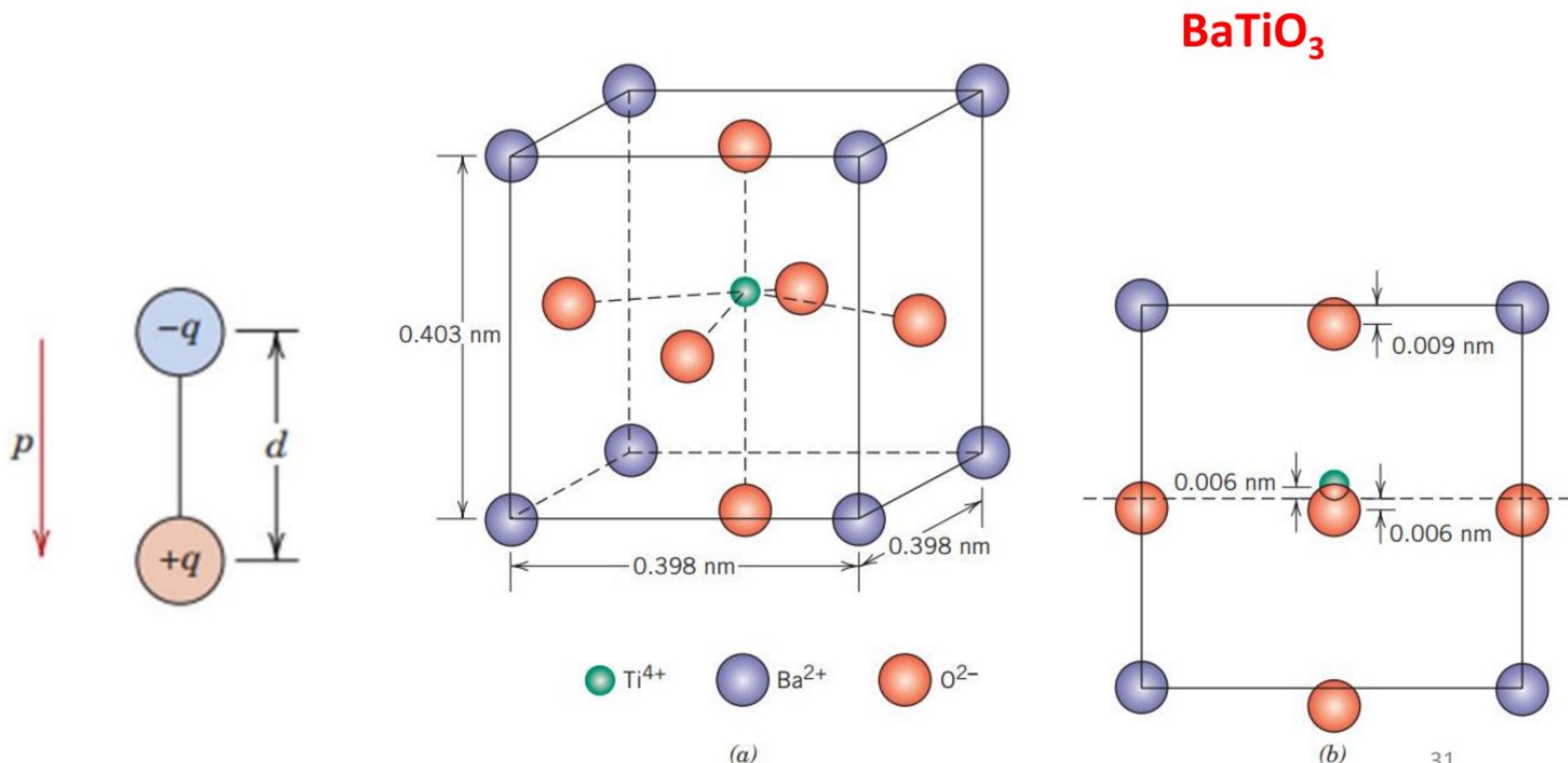
The mechanism for the breakdown is that some free carriers (e.g., caused by impurities) are accelerated in the field, so much that they can ionize other atoms and generate more free carriers. Then, the breakdown proceeds like an avalanche.

The breakdown can be facilitated by operating the material close to a resonance frequency where much energy is dissipated, the material is heated, and the probability of having free carriers is increased.

Ferroelectric Materials

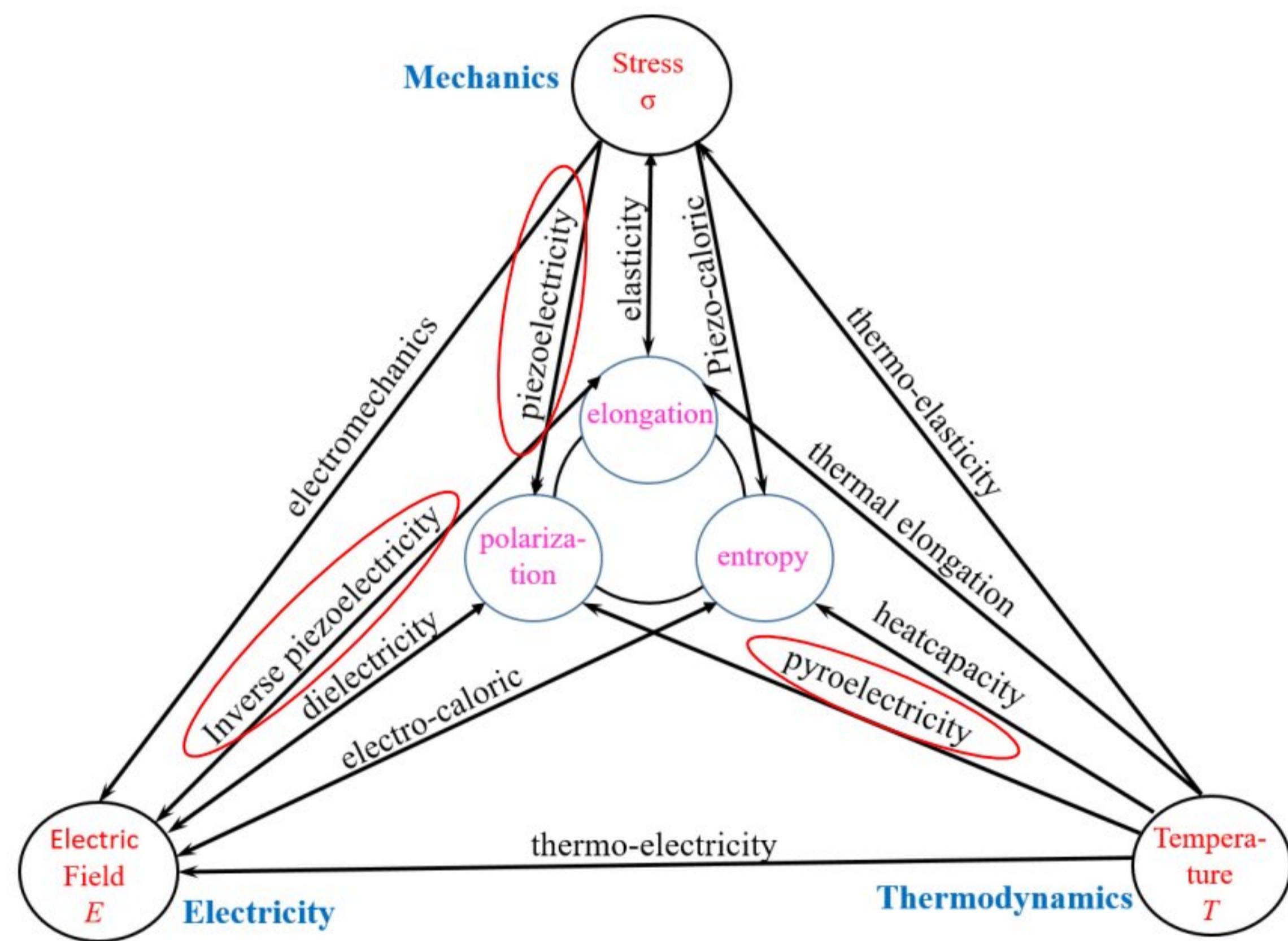
FERROELECTRICITY

The group of dielectric materials called **ferroelectrics** exhibit spontaneous polarization—that is, polarization in the absence of an electric field. They are the dielectric analogue of ferromagnetic materials, which may display permanent magnetic behavior.



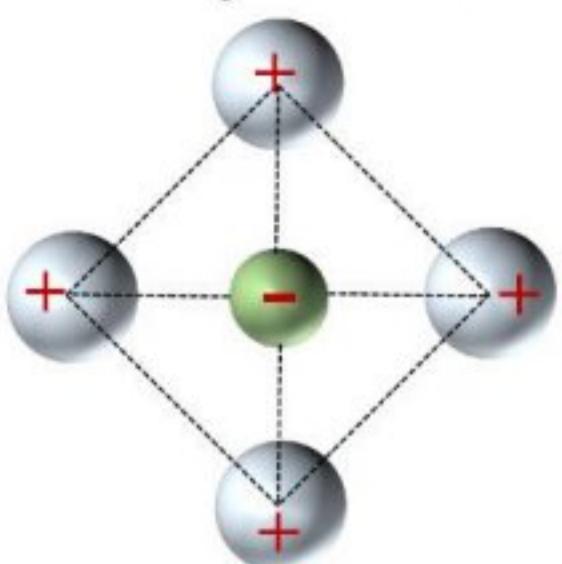
Ferroelectric materials:

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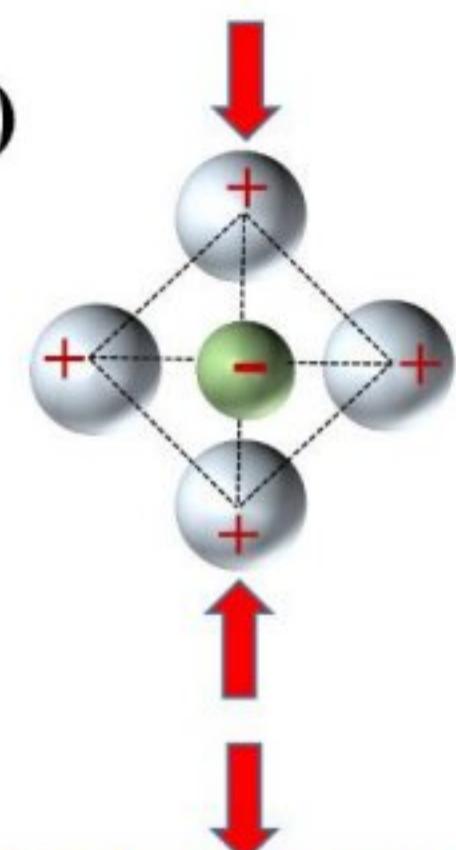


Conversion of energy in ferroelectric materials (Heckmann diagram).

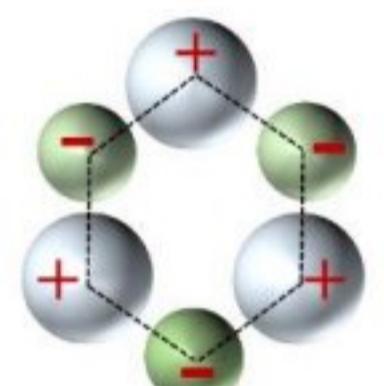
Centrosymmetric



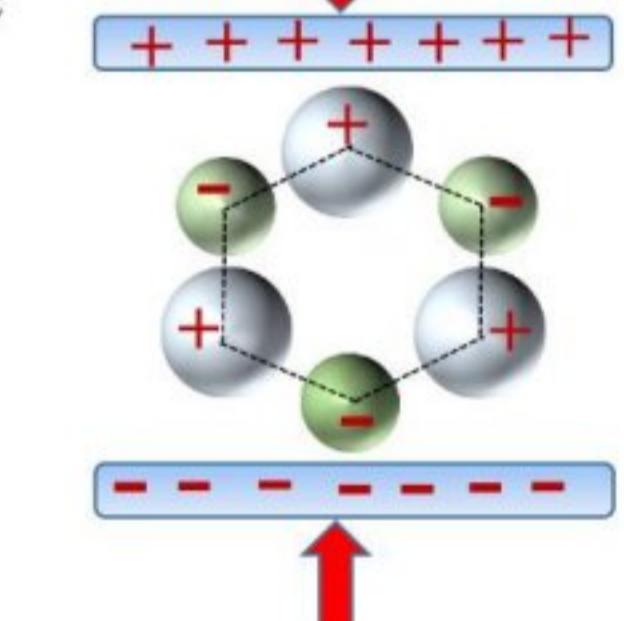
(a)



Non-Centrosymmetric



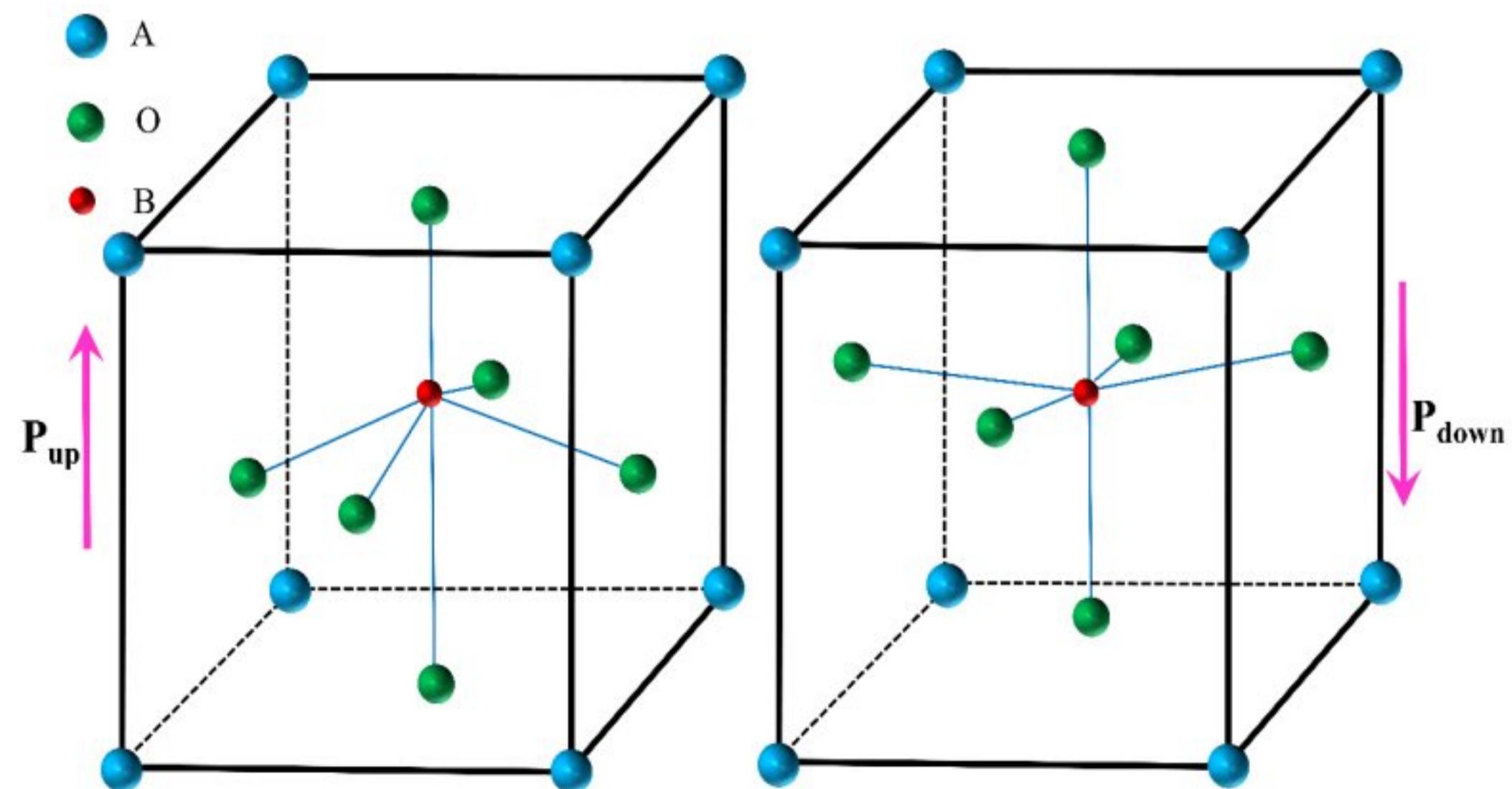
(b)

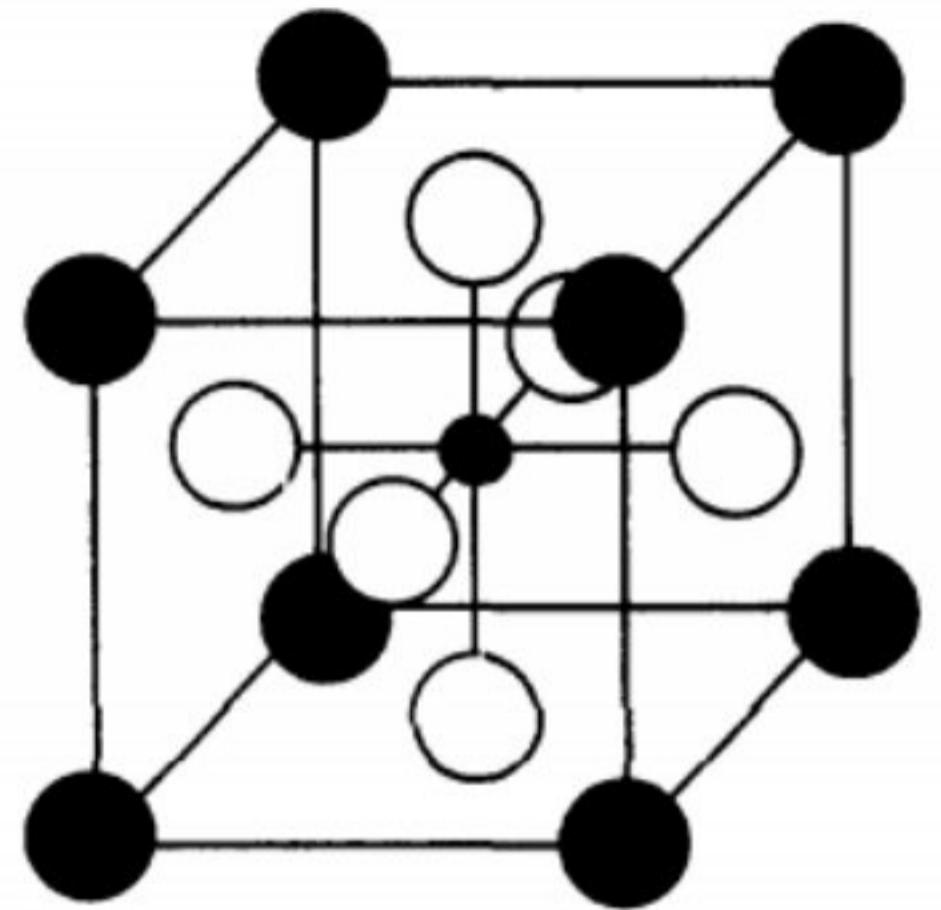


Perovskite structure of oxides ABO_3
ferroelectric

phase with upward and downward polarization.

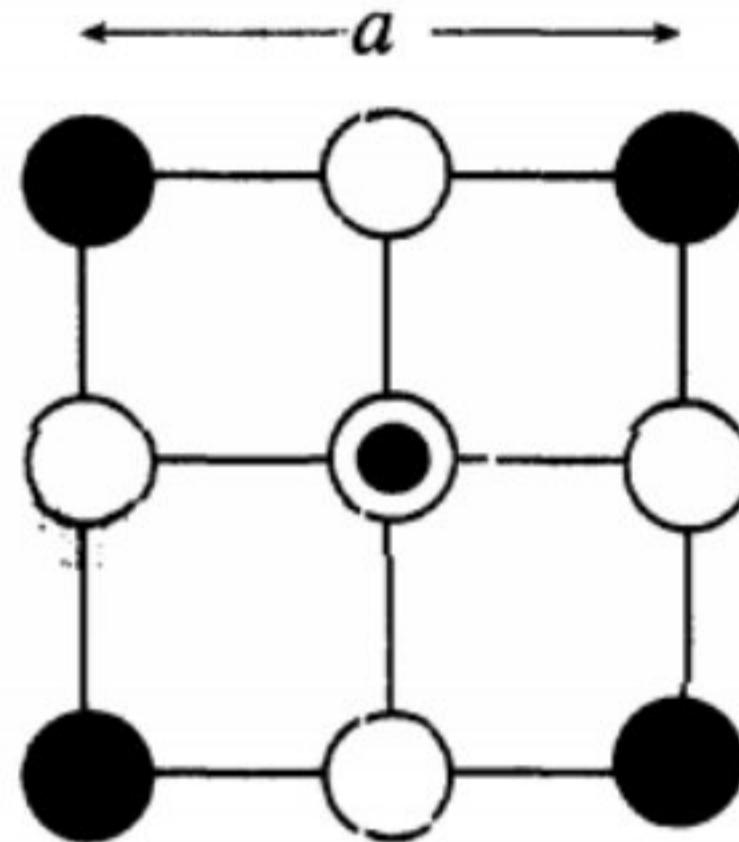
Non-centrosymmetric structure and origin of
piezoelectricity (a) centrosymmetric structure and
(b) non-centrosymmetric structure



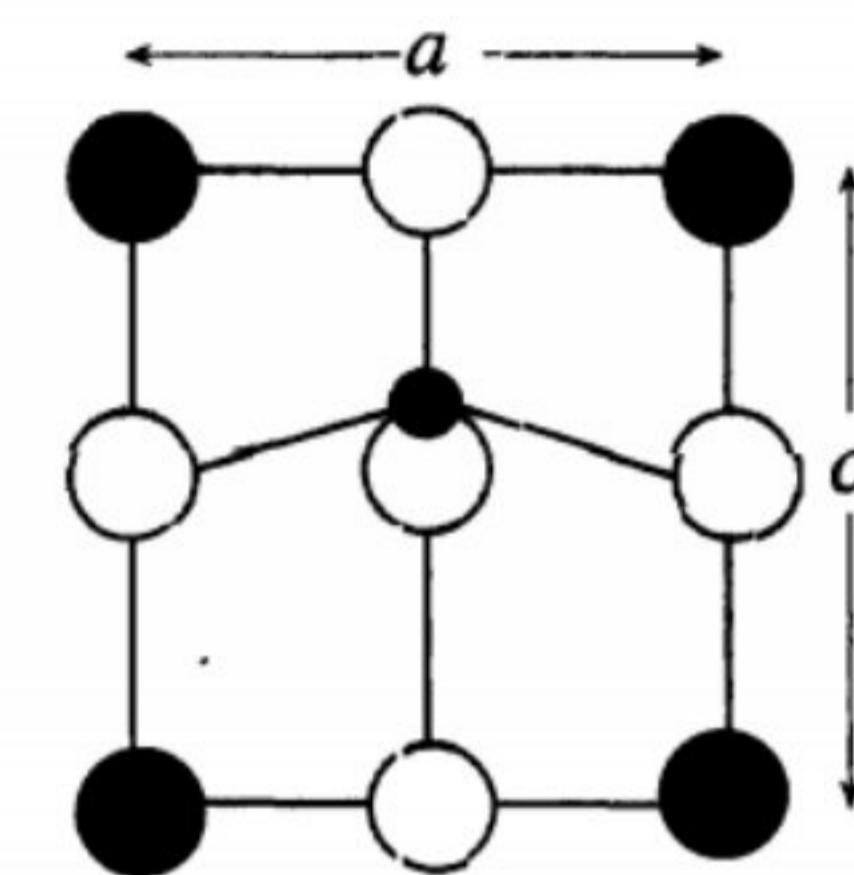


(a) BaTiO_3 cubic crystal structure
above $130\text{ }^\circ\text{C}$

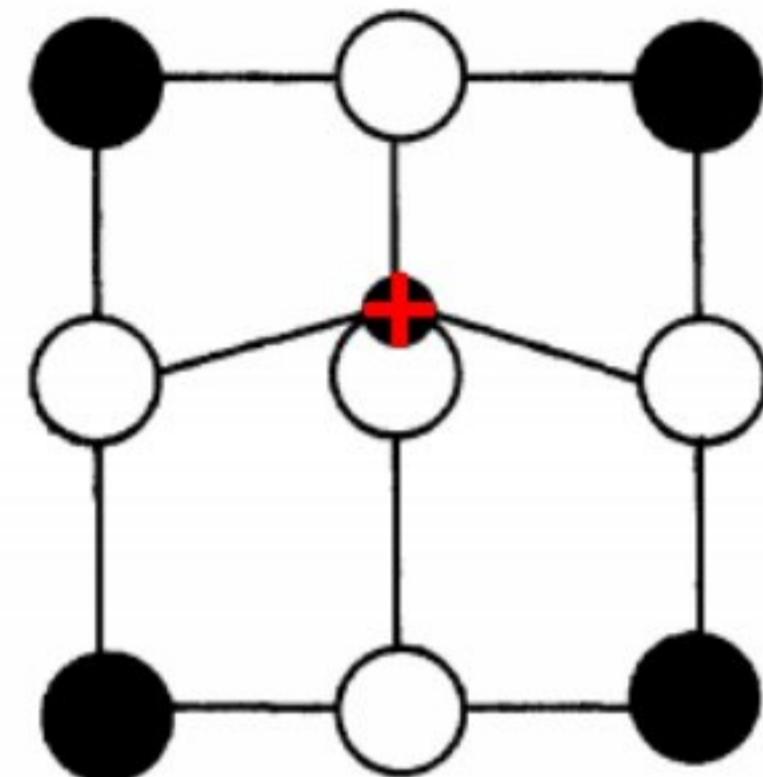
● Ba^{2+}
○ O^{2-}
● Ti^{4+}



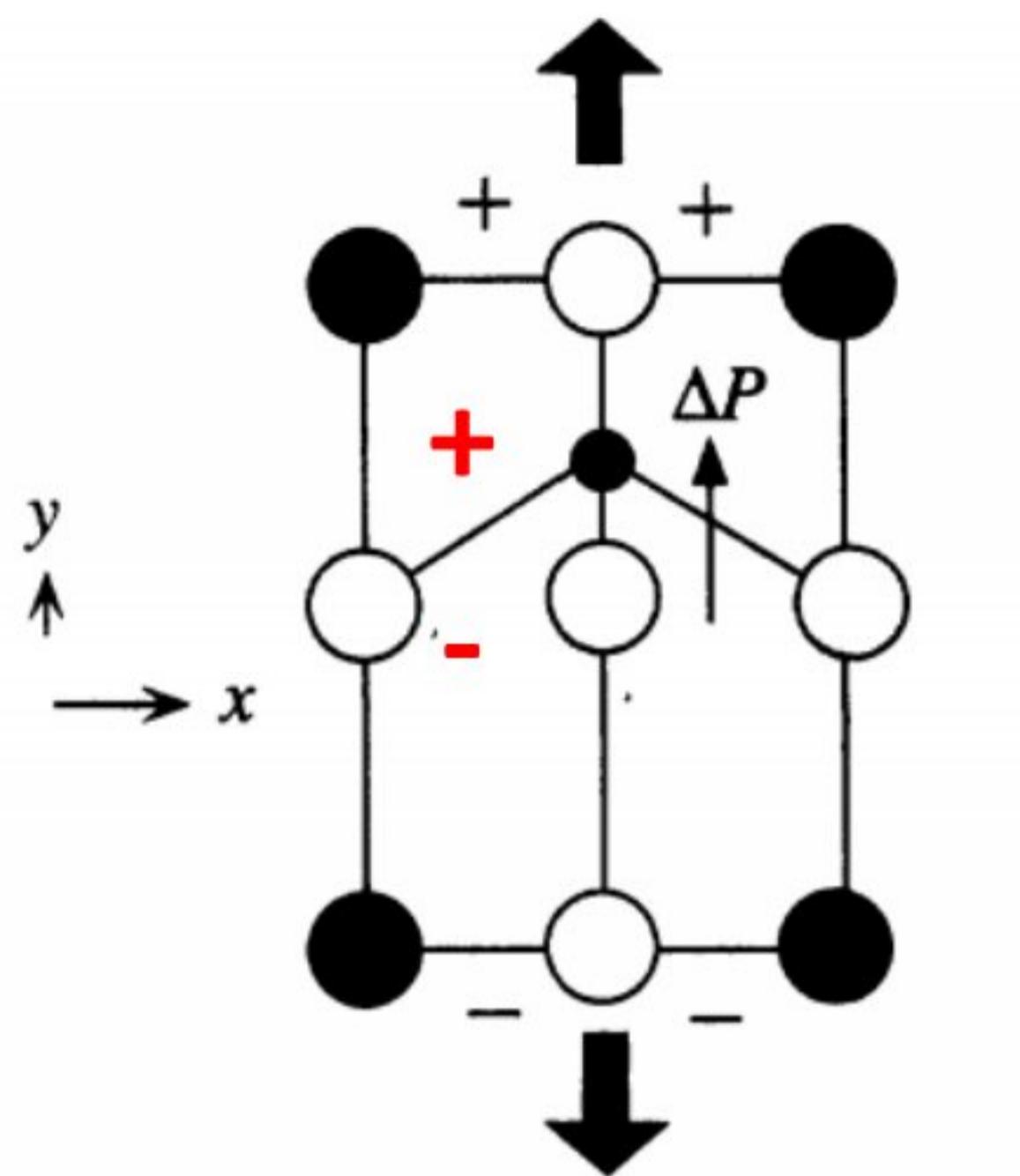
(b) BaTiO_3 cubic structure
above $130\text{ }^\circ\text{C}$



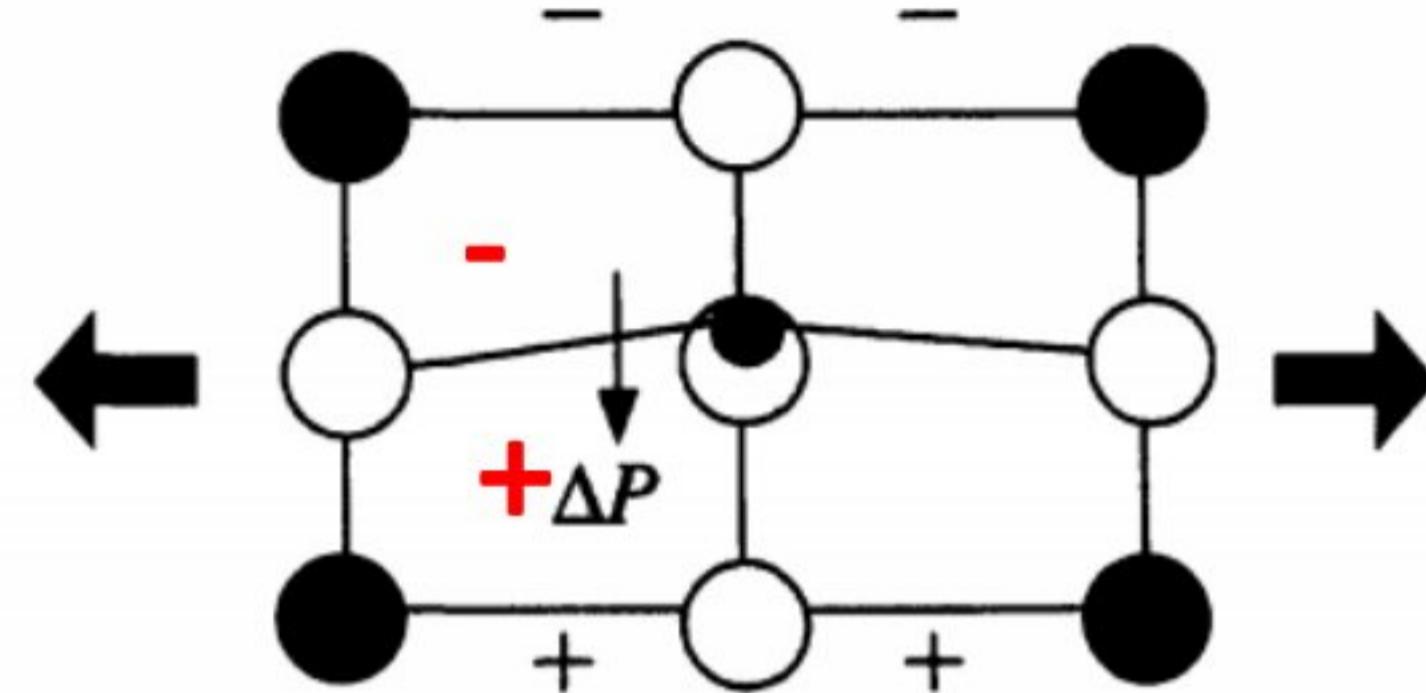
(c) BaTiO_3 tetragonal structure
below $130\text{ }^\circ\text{C}$



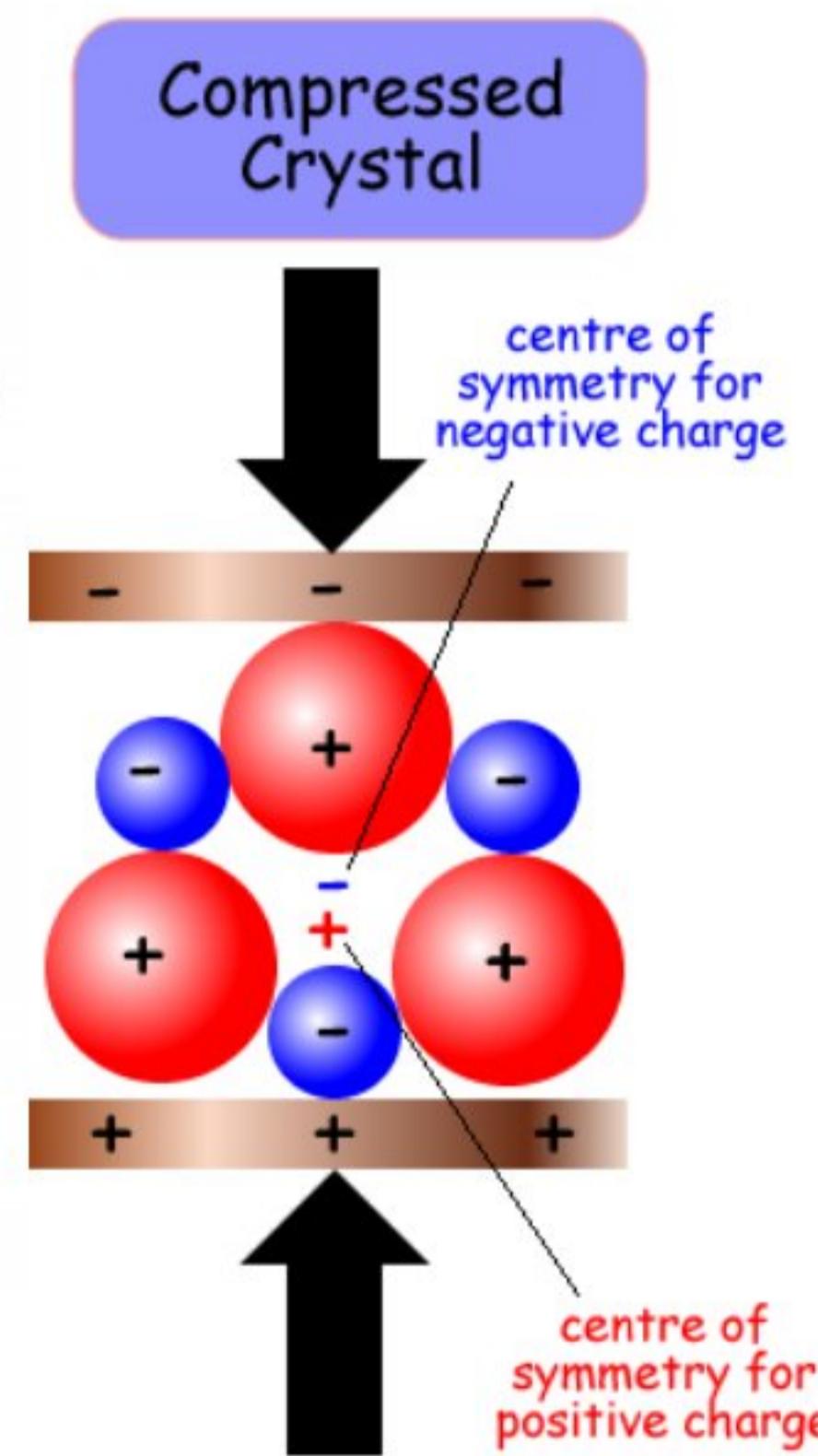
(a) BaTiO_3 tetragonal structure below 130 °C



(b) BaTiO_3 crystal under stress along y



(c) BaTiO_3 crystal under stress along x



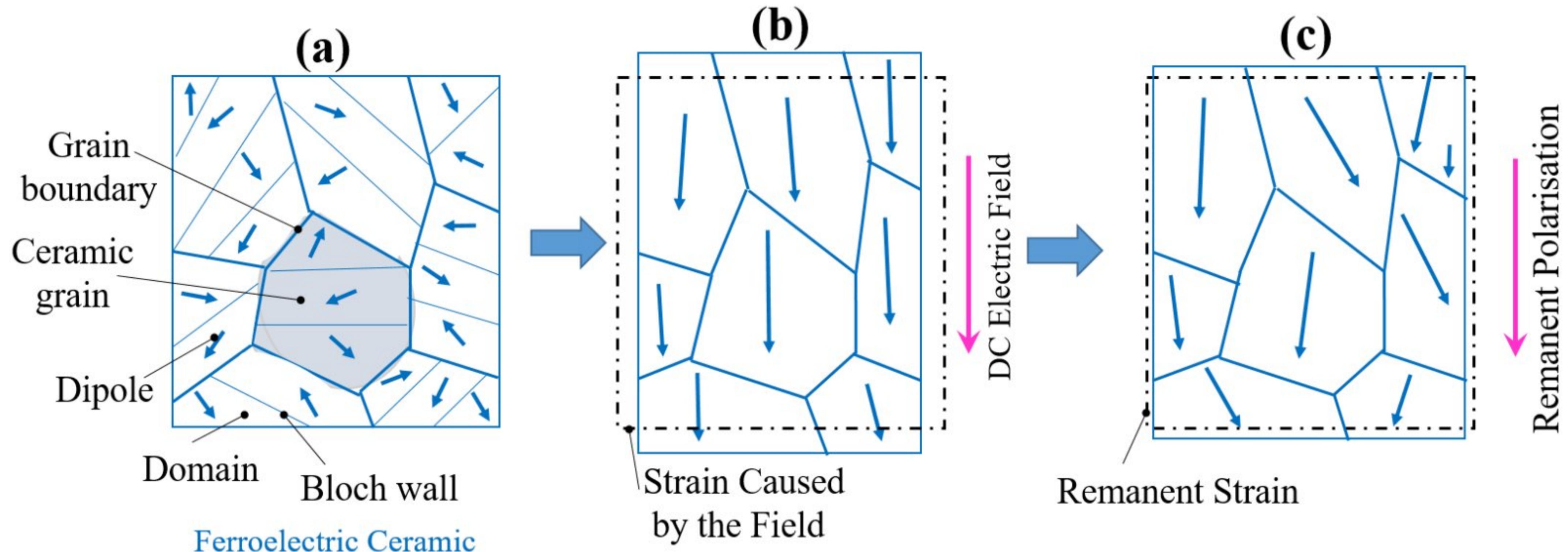
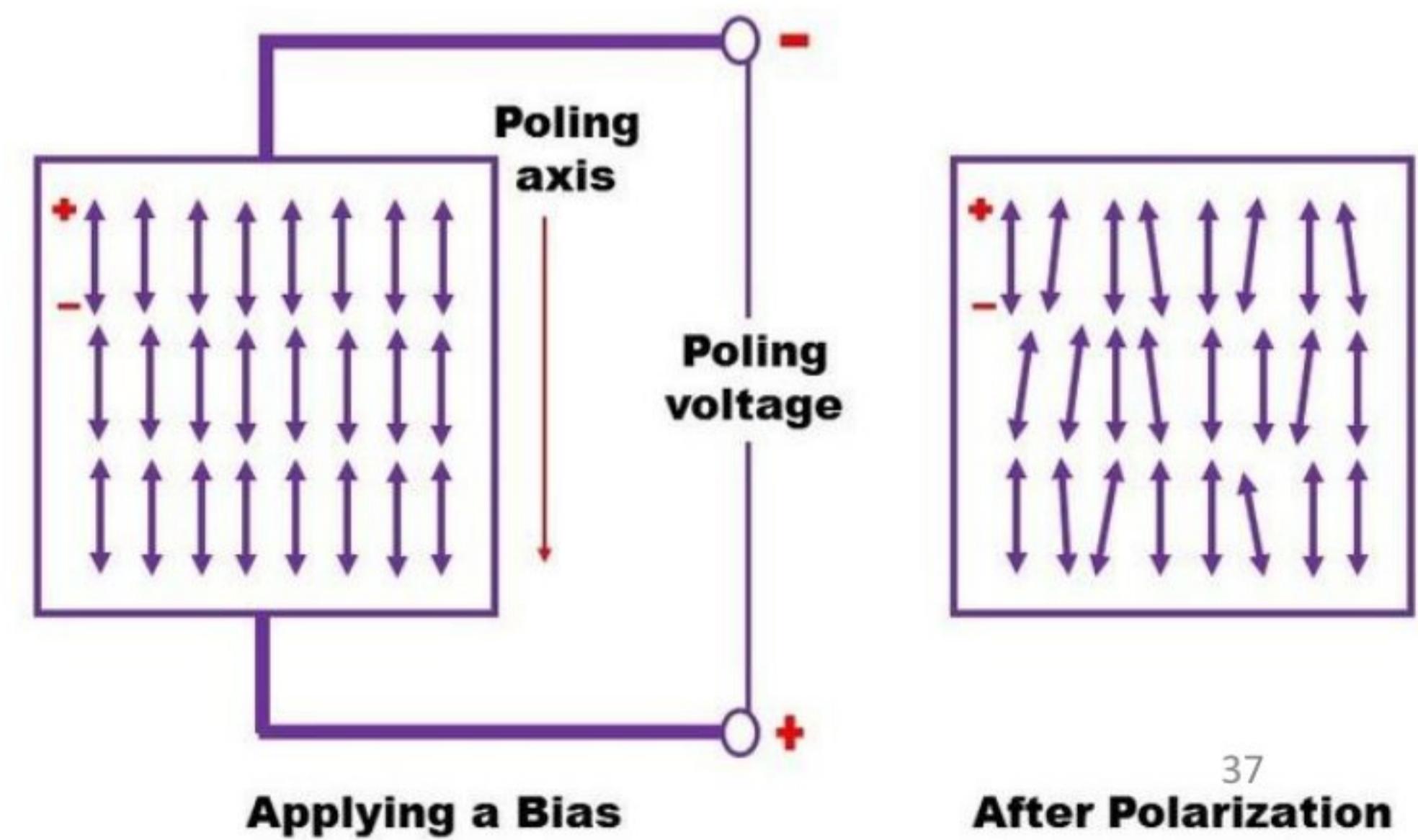
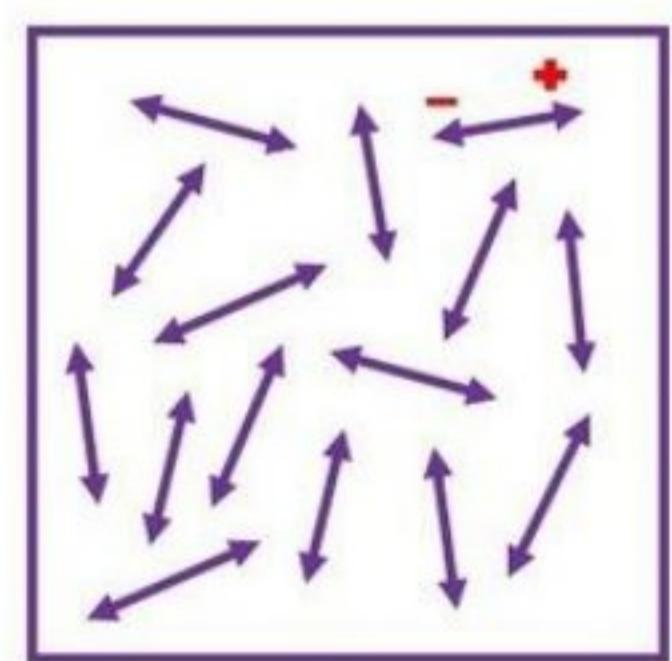
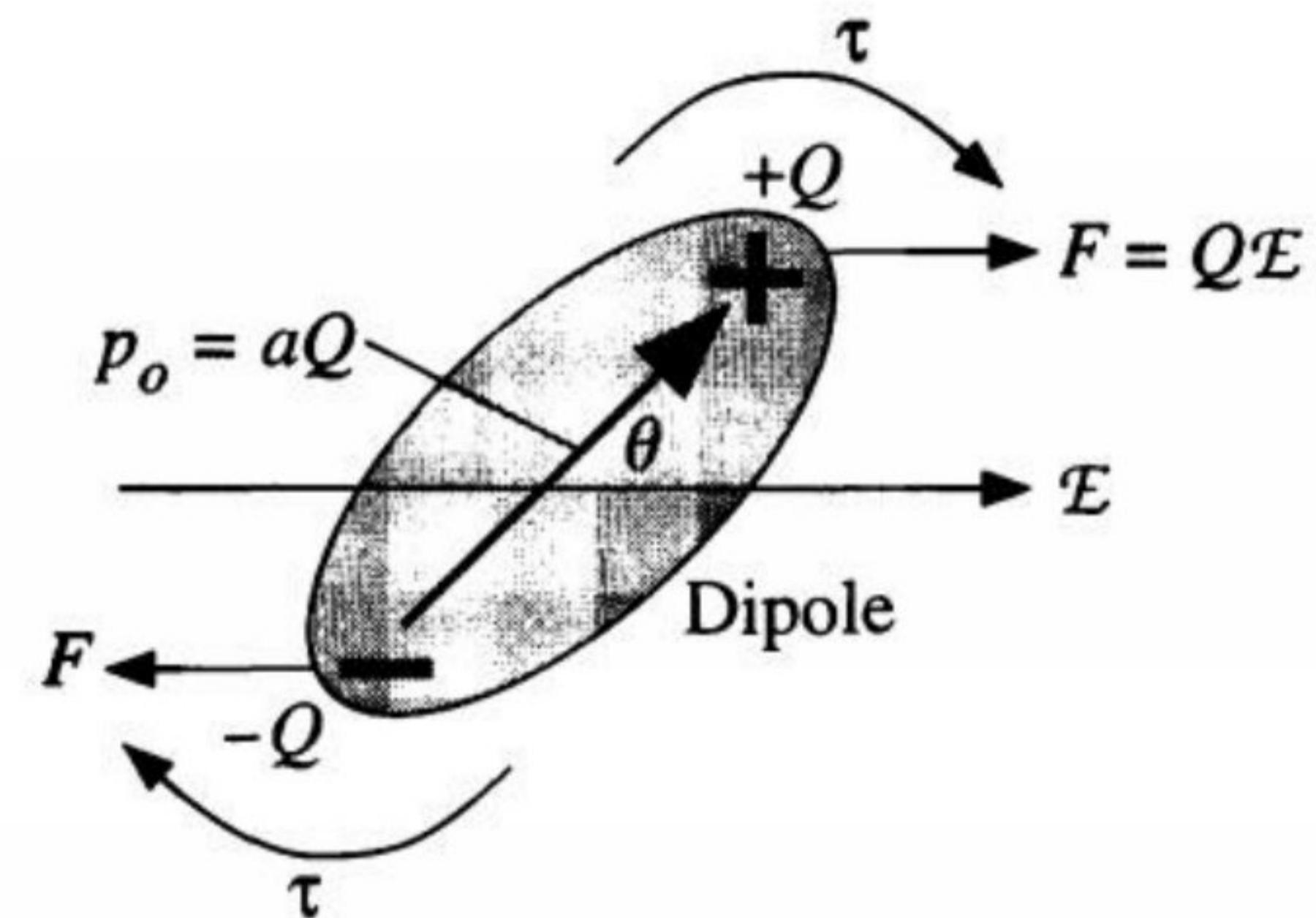
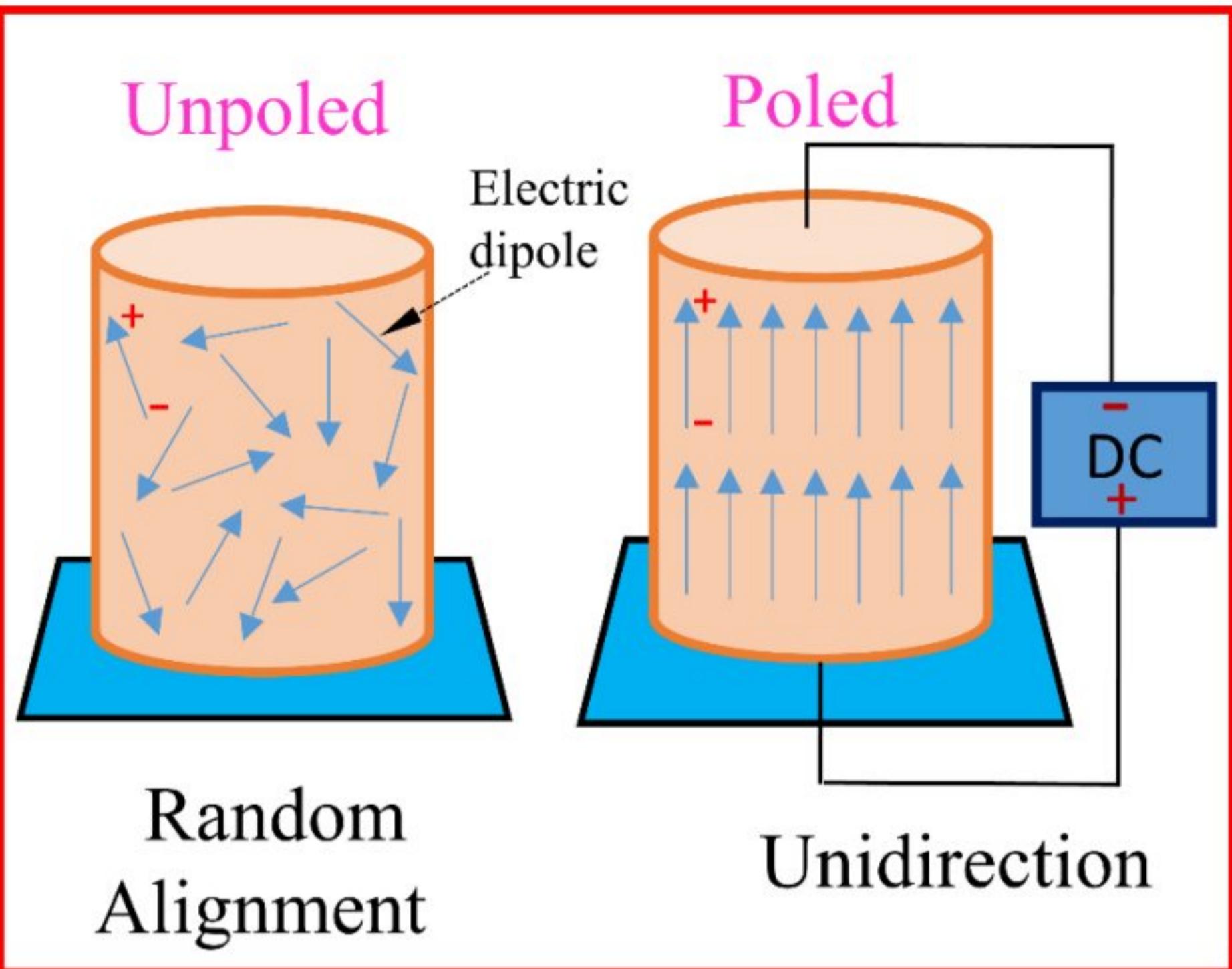
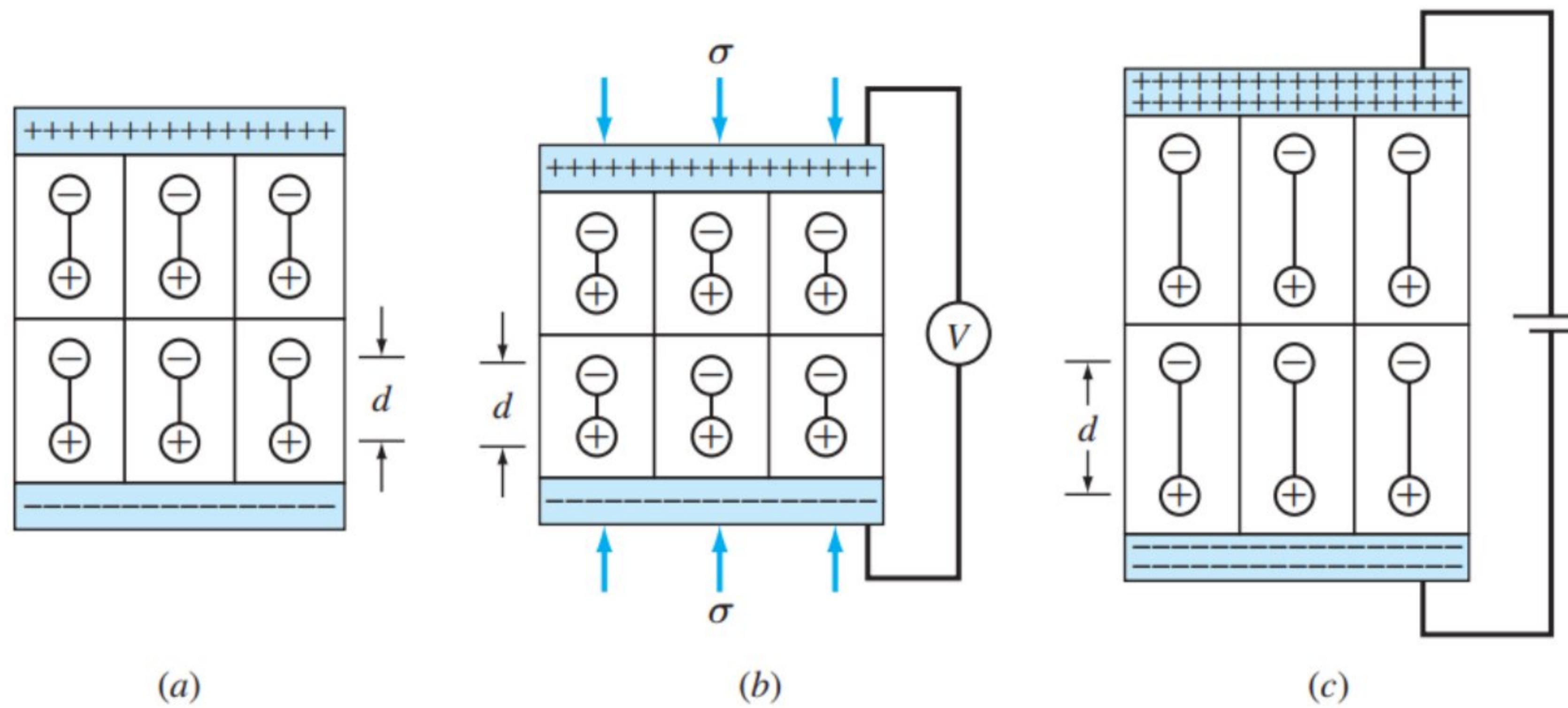


Fig. 5 Dipole configuration in ferroelectric mateirals.

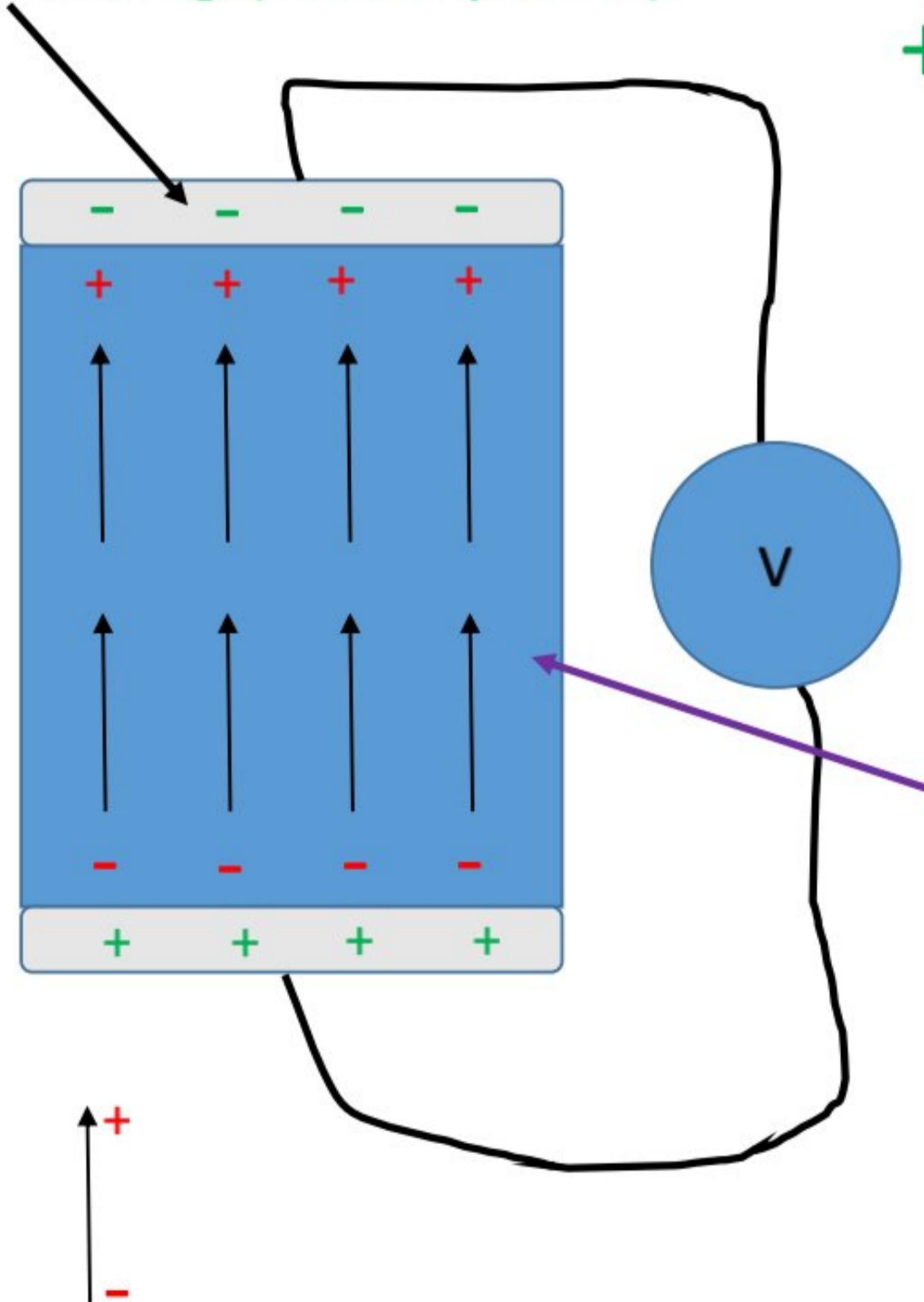




- (a) Schematic illustration of electric dipoles within a piezoelectric material.
- (b) Compressive stresses on material cause a voltage difference to develop due to change in electric dipoles.
- (c) Applied voltage across ends of a sample causes a dimensional change and changes the electric dipole moment.

Review of Voltage or Charge Measurement in Piezo and Pyroelectrics

Electroding (Silver paste)



+ - = Bounded Charge

+ - = Free Charge

Bounded Charge density changes due to the change in the Polarisation state of the sample which is further dependent on the external stimulus such as mechanical force or change in temperature

Insulating Material
(Dielectric)

Depolarisation

1. Thermal depoling

If the material is exposed to excessive heat, such that its temperature approaches its Curie temperature, the dipole moments regain their unaligned state. At the Curie temperature, a ferroelectric becomes entirely unaligned. In order to prevent this occurring, it is sensible to use piezoelectrics well below their Curie temperature.

2. Electrical depoling

A strong electric field, when applied in the reverse direction to the already poled material, will lead to depoling. If an alternating field is used to produce ultrasound waves (see later) the field will depolarise the piezoelectric during the periods in which it is opposing the polarisation.

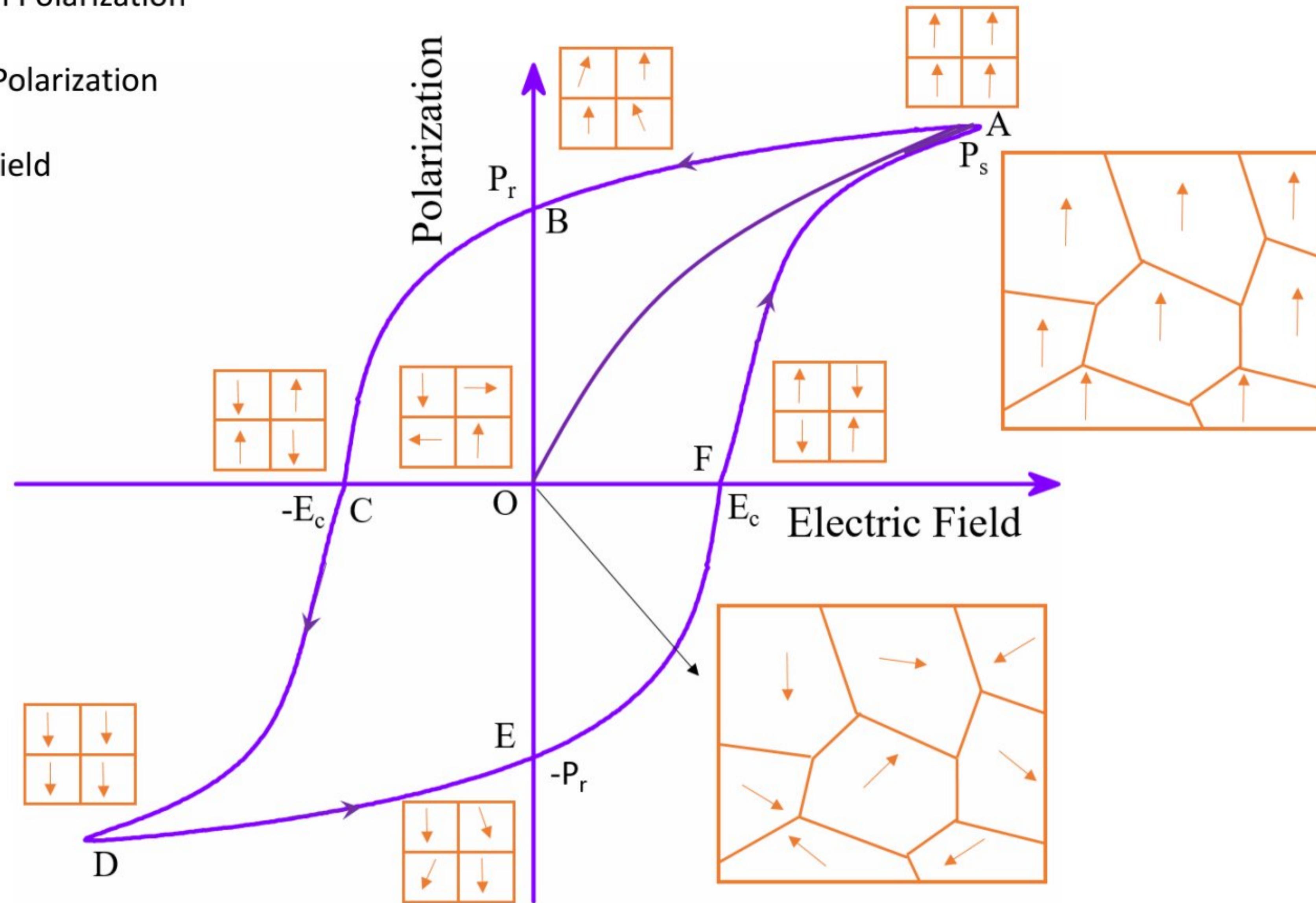
3. Mechanical depoling

If the stress placed on a piezoelectric is too high, it is possible to immediately depolarise the piezoelectric as the atom positions are altered. This completely ruins its properties.

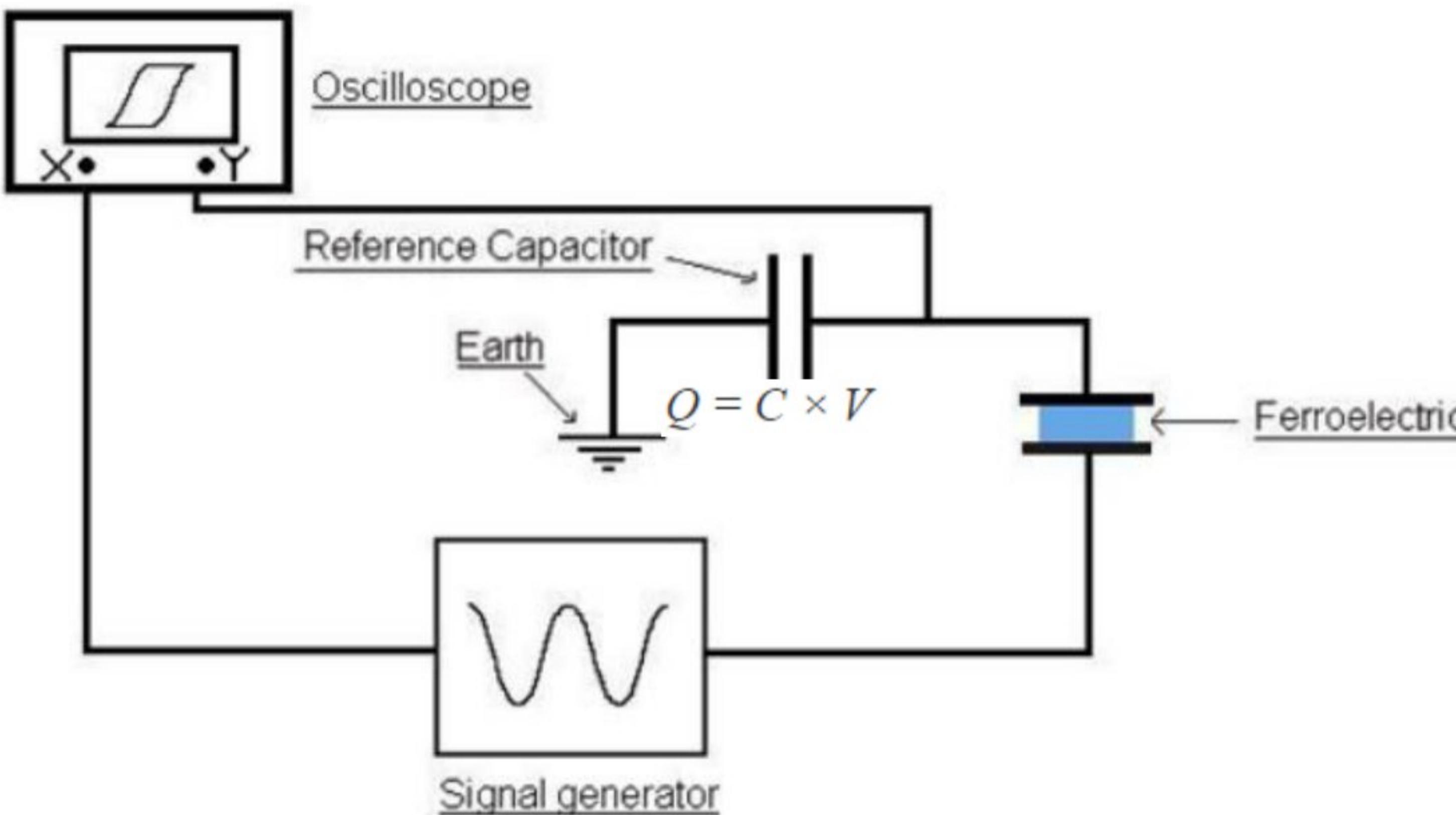
A = Saturation Polarization

B= Remnant Polarization

C= Coercive Field



Sawyer Tower Circuit for P-E loop measurement



Polarization = Dipole moment / Volume

= C.m /m³

= C/m²

= Charge/ Area

Explanation:

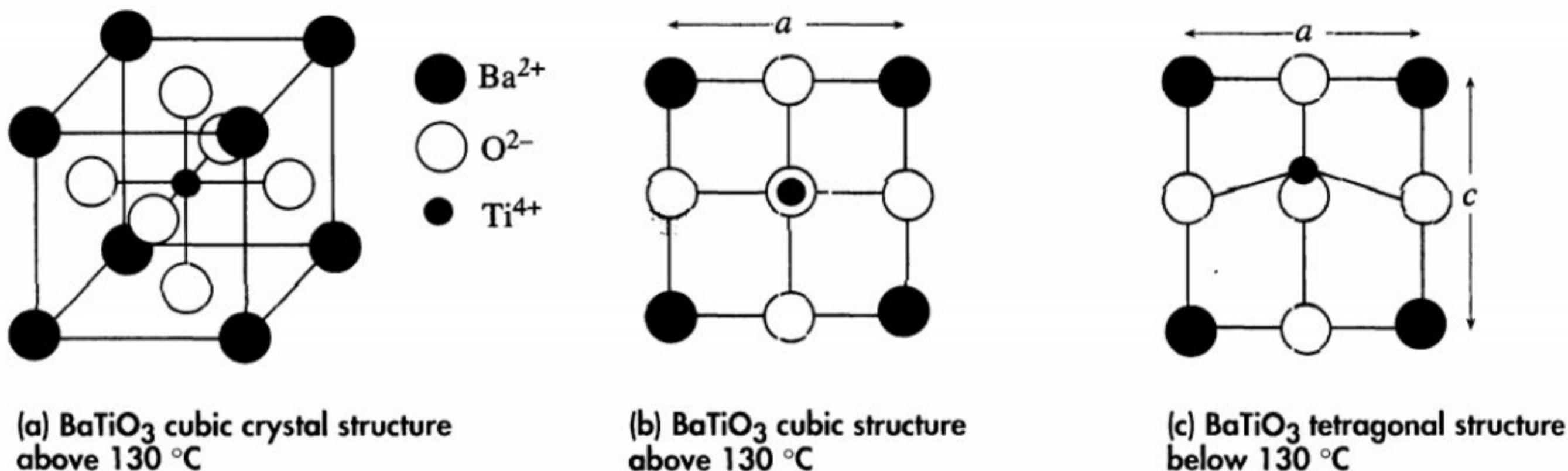
- In this experiment, the voltage is cycled by the signal generator. Its direction is reversed at high frequency, and the voltage across the reference capacitor is measured.
- The charge on the capacitor must be the same as the charge over the ferroelectric capacitor, as they are in series. This means the charge on the ferroelectric can be found by:

$$Q = C \times V$$

where C is the capacitance of the reference capacitor, and V is the voltage measured over this capacitor.

- We can therefore represent the polarisation of a material in an oscillating electric field, by plotting the voltage applied to the material on the x-axis of the oscilloscope, and the surface charge on the y-axis.
- This can be done because the capacitance of the reference capacitor is much higher than the capacitance of the ferroelectric, so most of the voltage lies over the ferroelectric. It is only possible to measure P by cycling the polarisation through cycling the voltage across the ferroelectric. We cannot measure absolute values instantaneously , but can deduce absolute values from the changes measured when cycling the polarisation.

Curie Temperature: The temperature at which the Ferroelectric properties or the capability to get spontaneous polarization is lost.

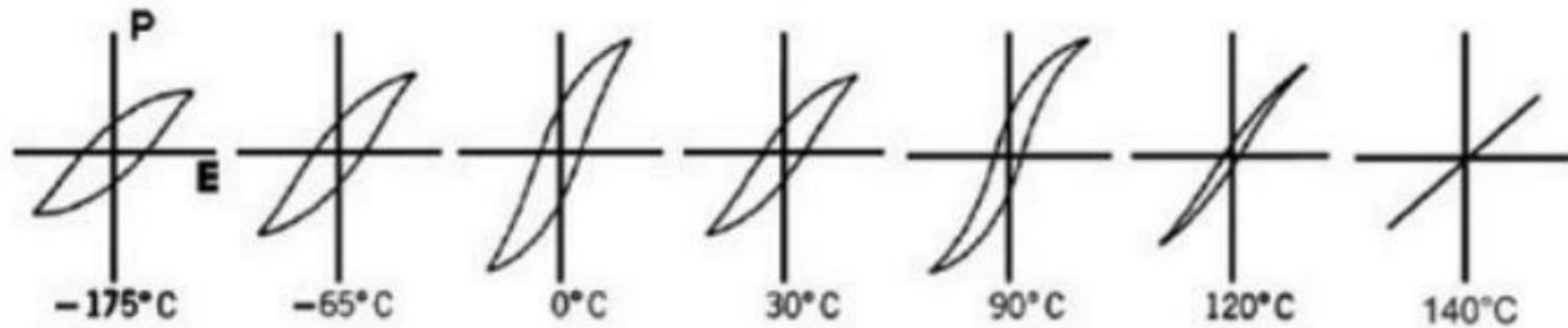


Material	$T_c / ^\circ\text{C}$
Barium titanate, BaTiO_3	120
Rochelle salt, $\text{KNaC}_4\text{H}_4\text{O}_6 \cdot 4\text{H}_2\text{O}$	Between -18 and $+24$
Potassium niobate, KNbO_3	434
Potassium dihydrogenphosphate, KDP, KH_2PO_4	-150
Lead titanate, PbTiO_3	490
Lithium niobate, LiNbO_3	1210
Bismuth titanate, $\text{Bi}_4\text{Ti}_3\text{O}_{12}$	675
Gadolinium molybdate, GMO, $\text{Gd}_2(\text{MoO}_4)_3$	159
Lead zirconate titanate, PZT, $\text{Pb}(\text{Zr}_x\text{Ti}_{1-x})\text{O}_3$	Depends on x

Temperature dependence of the Hysteresis loop

We have only observed it at one particular temperature, one at which the material is ferroelectric. What happens if the temperature is raised?

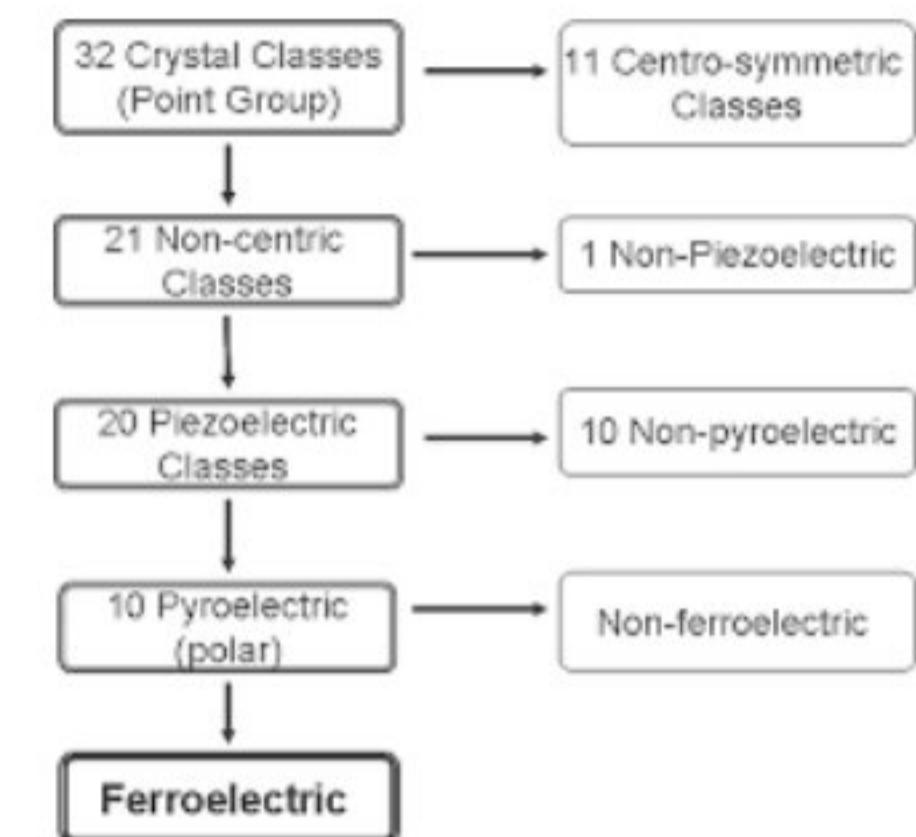
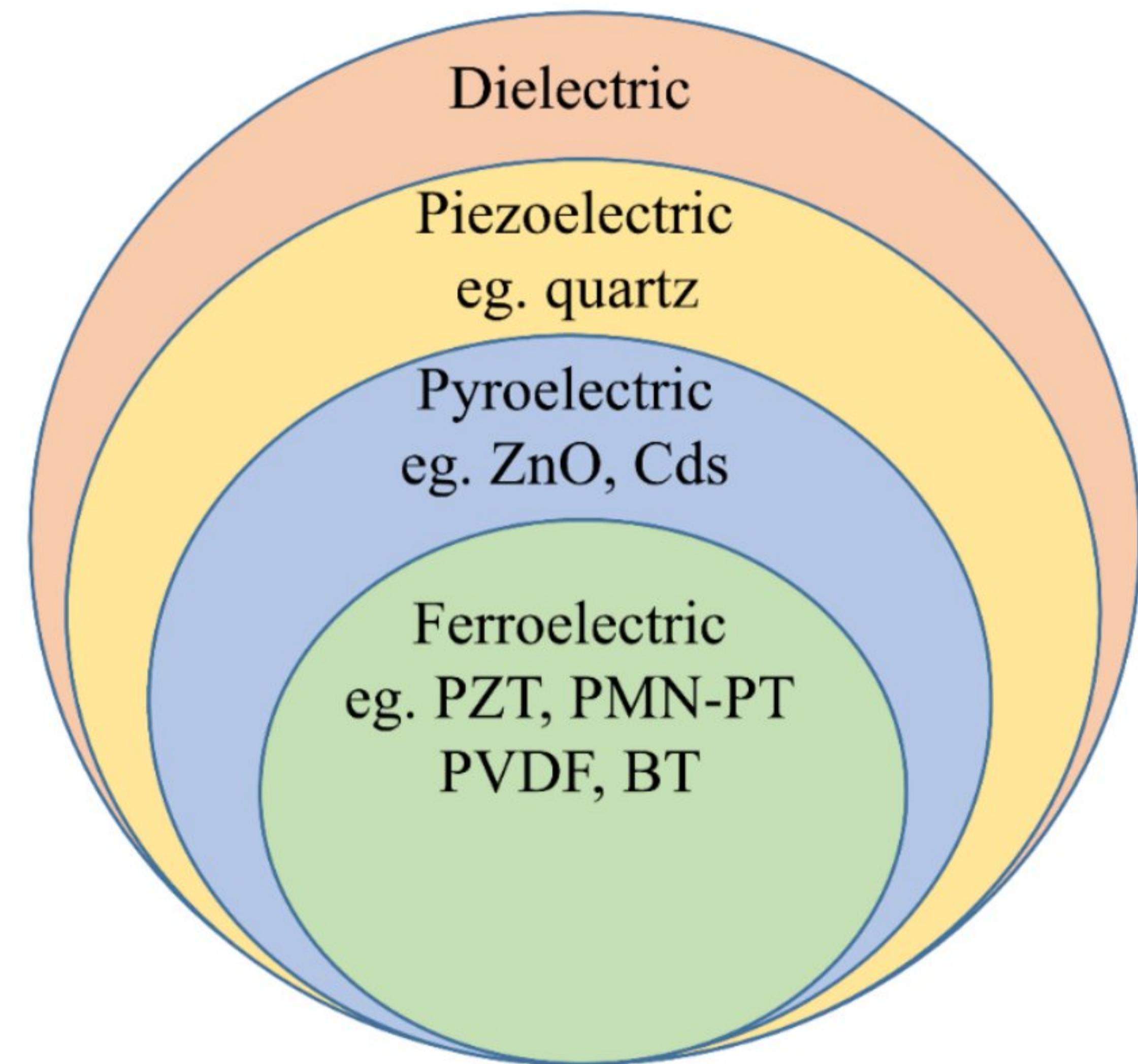
The hysteresis loop changes with temperature, becoming sharper and thinner, and eventually disappearing



As you can see, the polarisation increases at 90°C , as a result of a phase transition. Between this temperature and room temperature, the polarisation increases steadily, as a direct relation with temperature, such that:

$$\Delta P = p \Delta T$$

where p = pyroelectric coefficient ($\text{C m}^{-2} \text{T}^{-1}$).



Brief History of Pyroelectricity

Pyroelectricity as a phenomenon has been known for 24 centuries—the Greek philosopher **Theophrastus** probably wrote the earliest known account. He described a stone, called *lyngourion* in Greek or *lyncurium* in Latin, that had the **property of attracting straws and bits of wood.**

Those attractions were no doubt the effects of electrostatic charges produced by temperature changes most probably in the mineral tourmaline.

Theophrastus and other writers of the two millennia that followed were far more interested in the origin of the stone and its physical explanations. Theophrastus proposed that lyngourion was formed from the urine of a wild animal .

Introduction

- Pyroelectrics are the bridge between ferroelectrics and piezoelectrics.
- They possess a spontaneous polarisation which is not necessarily switchable by an electric field.
- If their polarisation is switchable, i.e. they are ferroelectric, then they are mainly used in situations in which ferroelectric properties are required.
- However, if they are not ferroelectric, then their properties as pyroelectrics are more useful.
- Whether a given sample possesses a net dipole moment depends on domain configurations, which in turn depend on sample history. This polarisation will change when a stress is applied to the material, as pyroelectrics are a sub-set of piezoelectrics.
- But it will not reverse under the application of an electric field because it will breakdown first, i.e. the coercive field exceeds the breakdown field.
- This is only true for a pyroelectric material which is not ferroelectric, whereas if it is ferroelectric, the coercive field is smaller than the breakdown field. In other words, ferroelectrics are a subset of pyroelectrics.

Pyroelectricity

Pyro = "fire," "heat," "high temperature"

Pyroelectricity is the property presented by certain materials that exhibit an electric polarization ΔP when a temperature variation ΔT is applied uniformly:

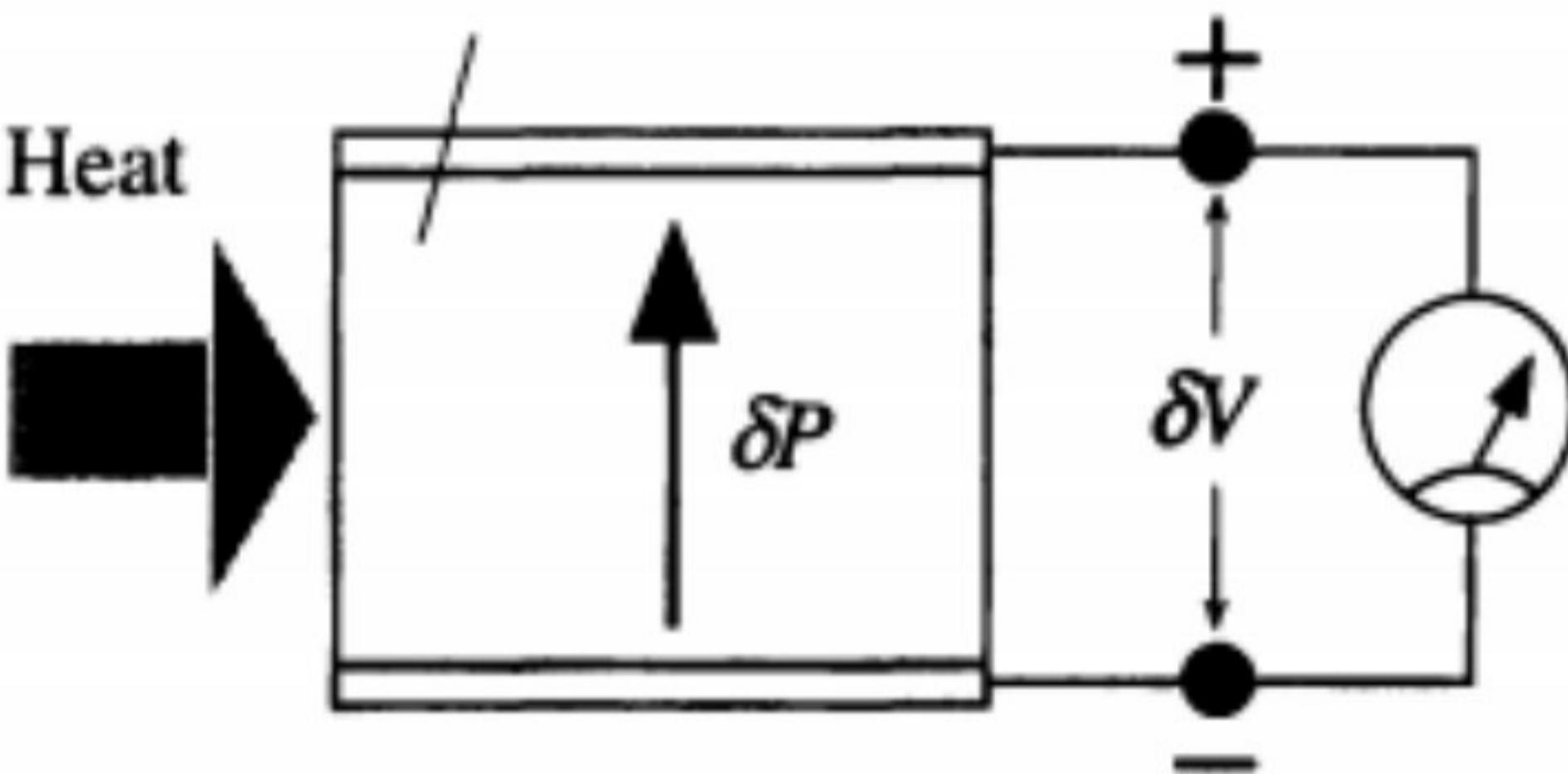
$$\Delta P = \gamma \cdot \Delta T$$

where γ is the pyroelectric coefficient at constant stress.

Pyroelectric crystals actually have a spontaneous polarization,

but the pyroelectric effect can only be observed during a temperature change (ΔT).

Temperature change = δT



- If a spontaneous polarization is already present, a change of temperature alters it.
- The change in temperature modifies the positions of the atoms slightly within the crystal structure, such that the polarization of the material changes.
- This polarization change gives rise to an electric polarization across the crystal.
- If the temperature stays constant at its new value, the pyroelectric polarization gradually disappears due to leakage current (the leakage can be due to electrons moving through the crystal, ions moving through the air, current leaking through a voltmeter attached across the crystal, and so on)

- To observe pyroelectricity, we can heat a crystal uniformly and observe the change in polarization.
- This experiment can be performed in **two different ways**:
- Either the shape and size of the crystal can be held fixed during the heating or,

OR

- The crystal may be released so that thermal expansion can occur quite freely. The magnitude of the effect observed in the two experiments would be different.
- In the first case, with the crystal clamped, the effect observed is called ***primary pyroelectricity***.
- In the second case, with free expansion, which is much easier to achieve experimentally, there is an additional effect called ***secondary pyroelectricity***; what is observed in this case is the primary effect plus the **secondary** effect.

CASE I

If a pyroelectric crystal with an intrinsic dipole moment (top) is fashioned into a circuit with electrodes attached on each surface (FIG. 1), an increase in temperature T prompts the spontaneous polarization P_S to decrease as the dipole moments, on average, diminish in magnitude. The horizontal tilting of the dipoles, (pictured at bottom of FIG. 1), signifies the effect. A current flows to compensate for the change in bound charge that accumulates on the crystal edges.

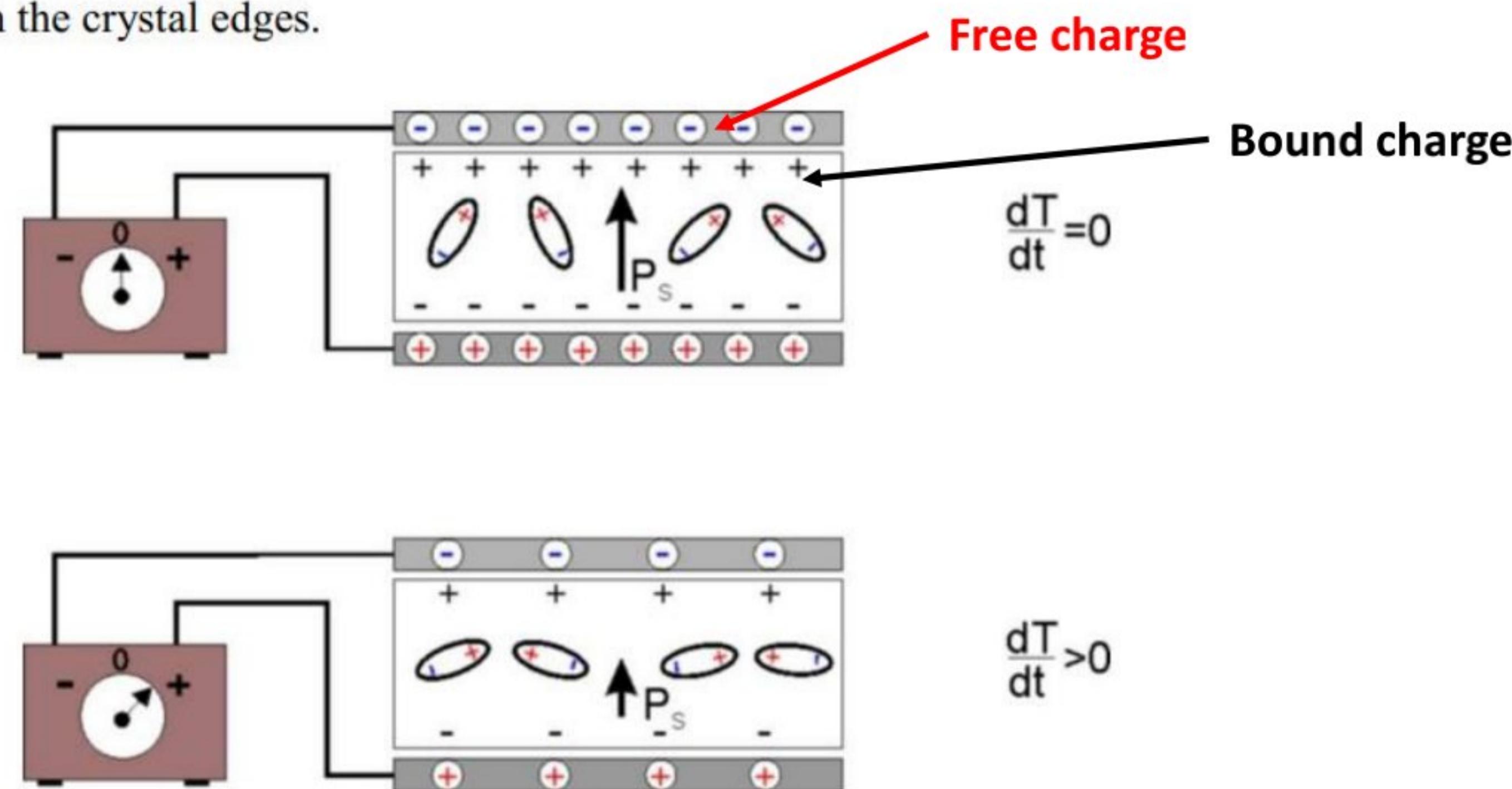


FIG. 1 Schematic drawing showing the origin of the pyroelectric current.

CASE II

Another definition of pyroelectricity is ability to generation of induced charges on the crystal surface when they are heated or cooled. It is explained as a migration of positive and negative charges (and therefore establishment of electric polarization) to opposite ends of a crystal's polar axis as a result of change in temperature. This can be expressed as follows:

$$\Delta Q = \gamma \cdot S \Delta T \quad (3)$$

where:

ΔQ – charges generated on the crystal surface,

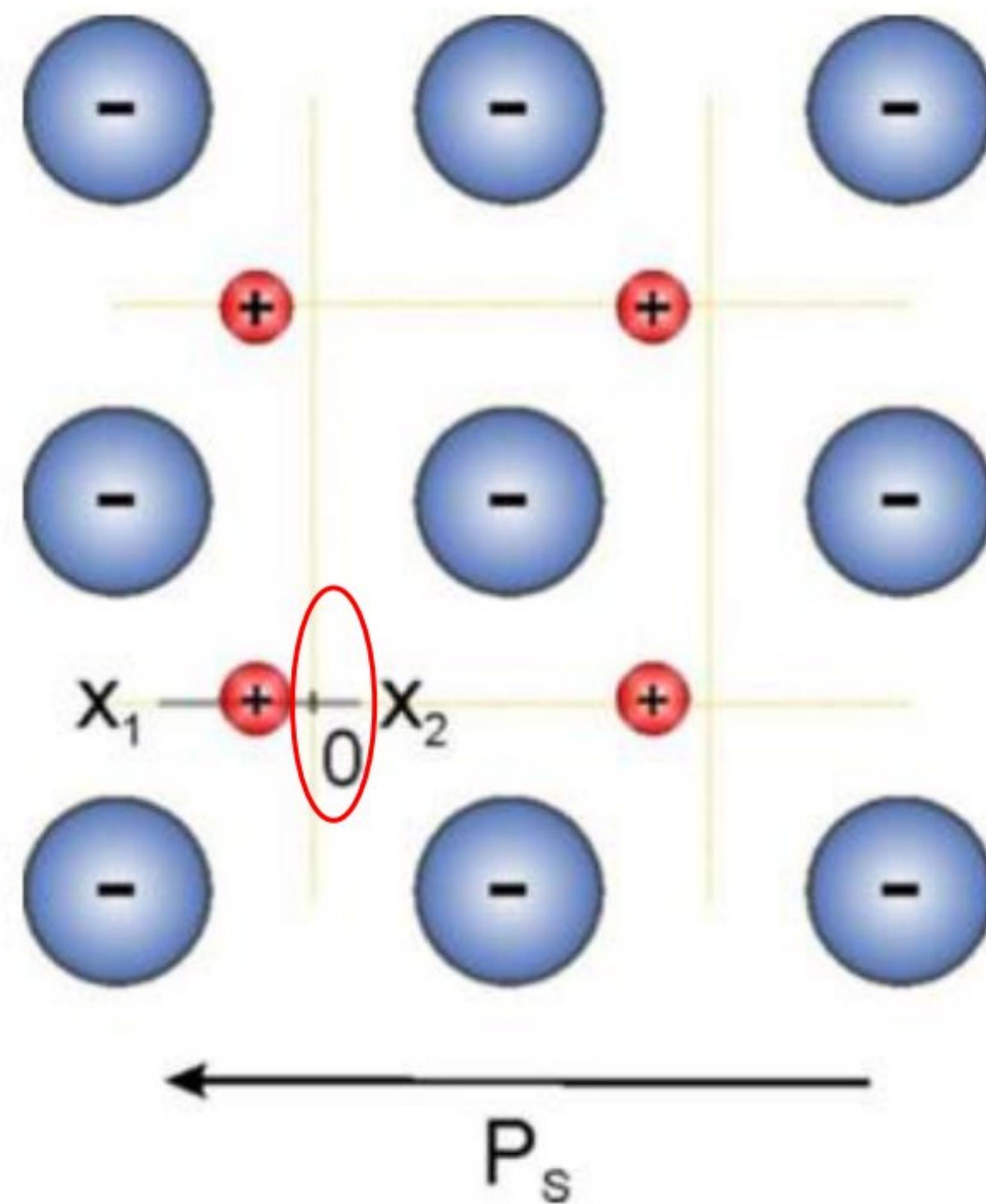
S – surface of the crystal.

The relation between generated charges and polarization is:

$$Q = \Delta P \cdot S \quad (4)$$

The unit of the polarization is $\left[\frac{C}{m^2} \right]$.

Simple model of the pyroelectric effect



Types of Ferroelectric Materials and Their Applications

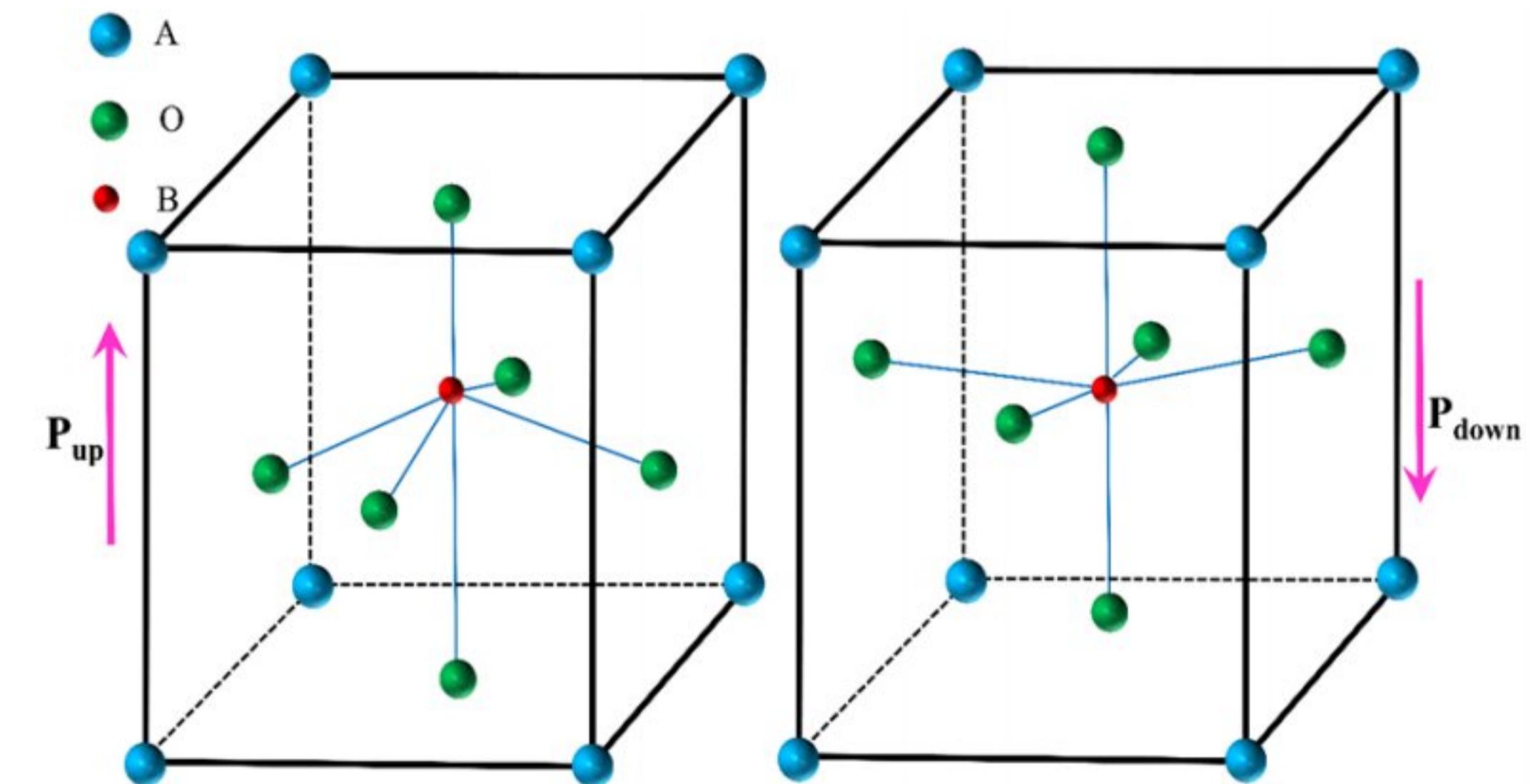
Types of Ferroelectric Materials

Perovskite-Type Structures

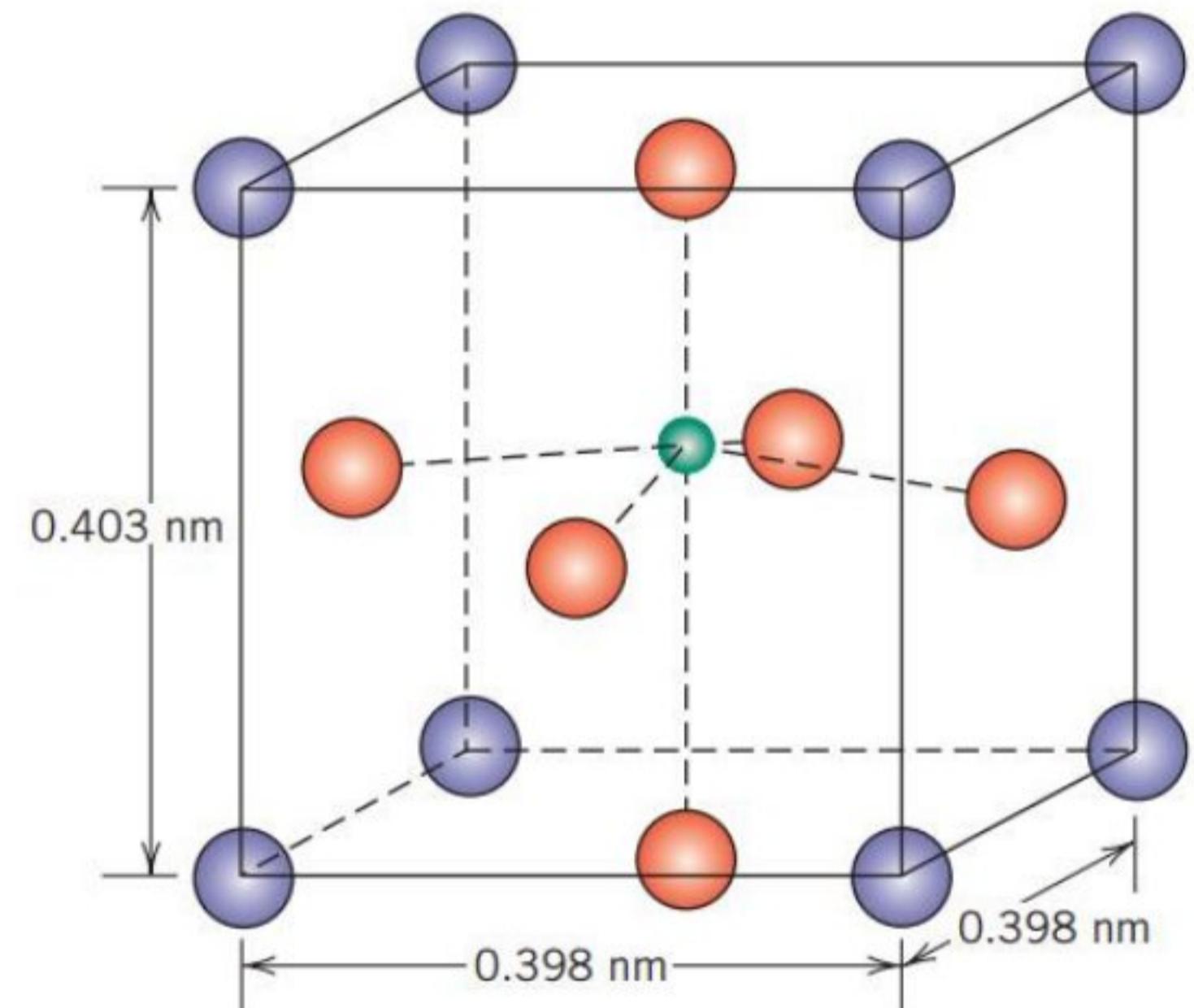
Perovskite is a family name of a group of materials having the mineral name of calcium titanate (CaTiO_3) exhibiting a structure of the type ABO_3 . Many piezoelectrics including FE ceramics such as

- Barium titanate (BaTiO_3)
- Strontium titanate (STO) (SrTiO_3)
- Barium strontium titanate (BST)
- Lead titanate (PbTiO_3), *Lead Zirconate Titanate (PZT)*
- Lead Lanthanum Zirconate Titanate (PLZT)
- *Lead Magnesium Niobate (PMN)*
- Potassium niobate (KN) (KNbO_3),
- Potassium sodium niobate ($\text{K}_x\text{Na}_{1-x}\text{NbO}_3$),
- and Potassium tantalate niobate ($\text{KTa}_x\text{Nb}_{1-x}\text{O}_3$)

have a perovskite-type structure.

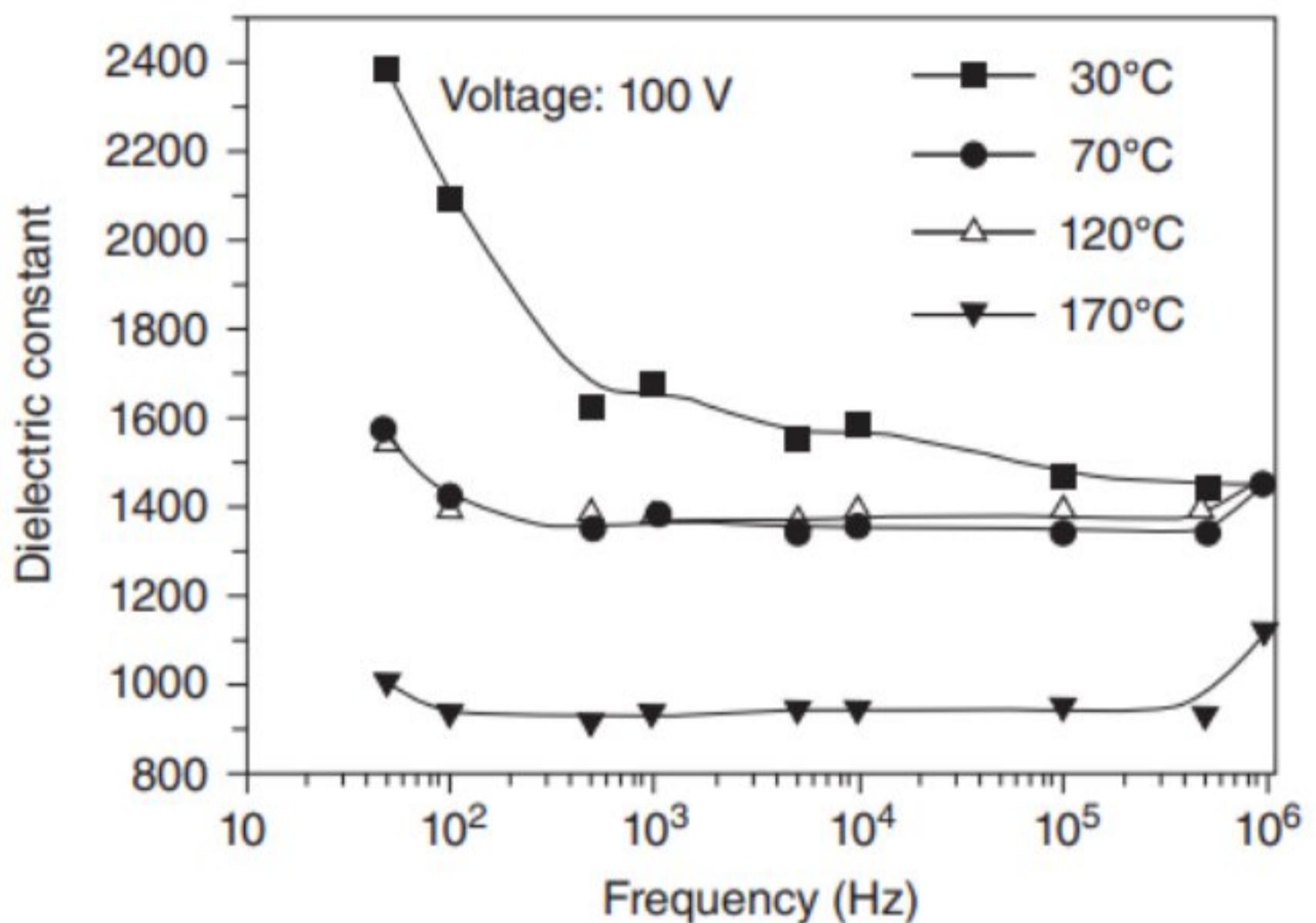


Barium titanate (BaTiO_3)

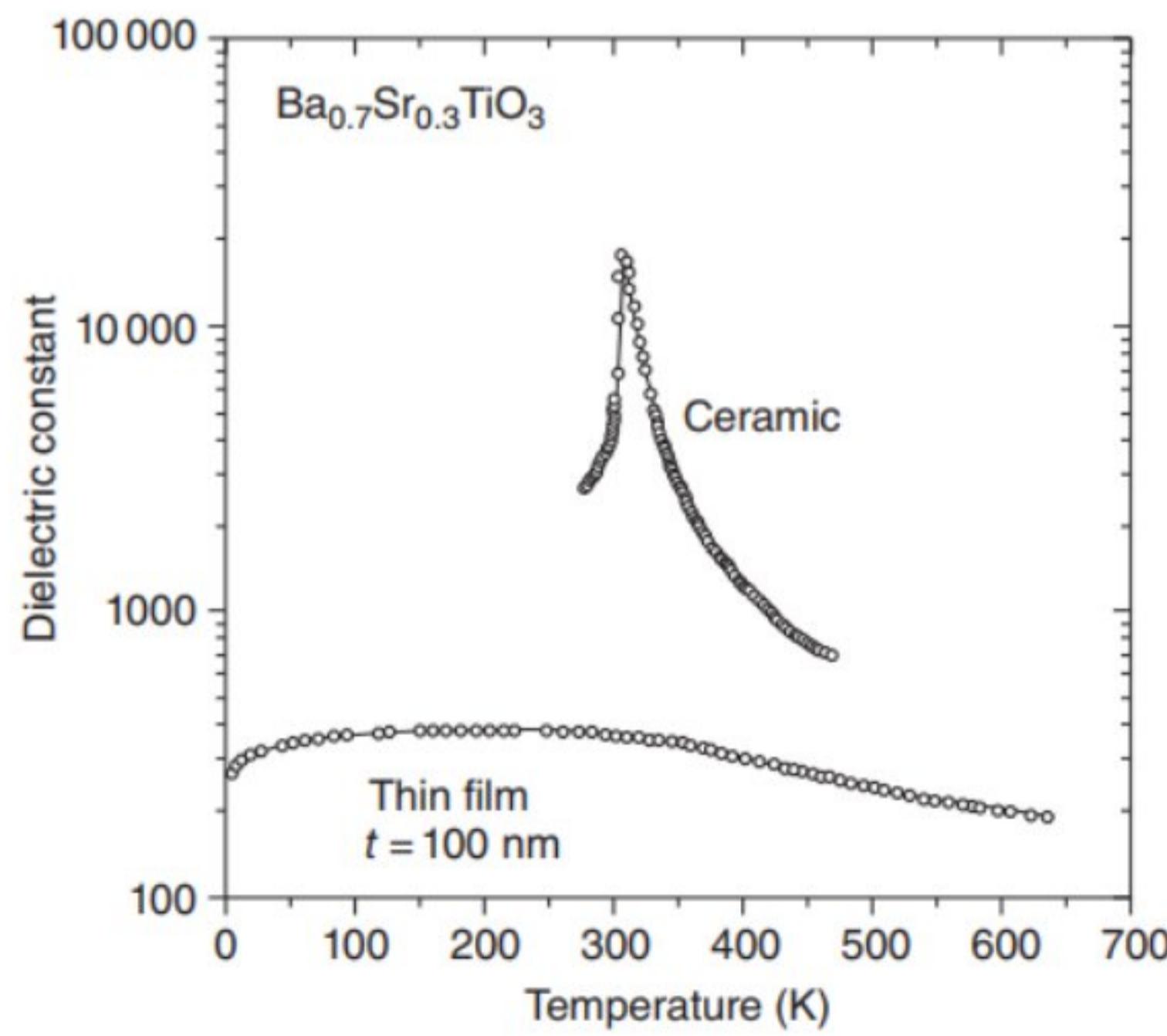
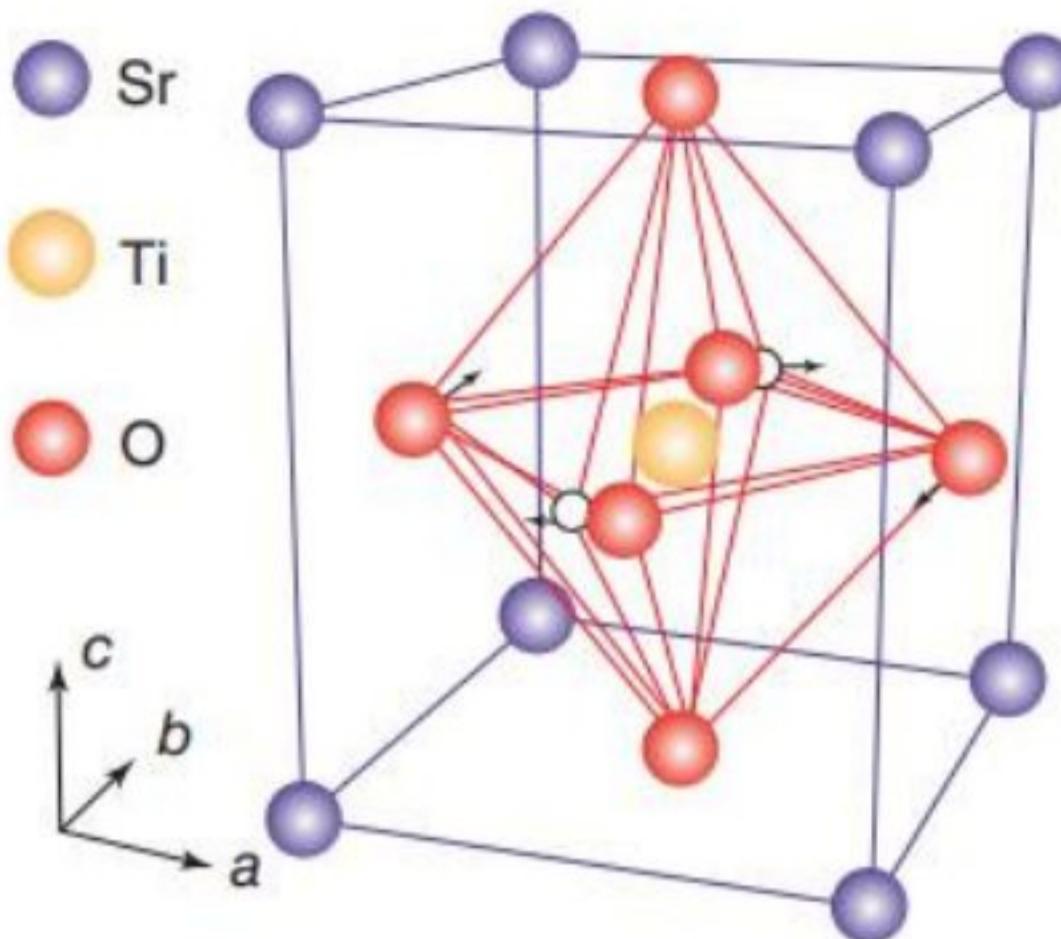


■ Ti^{4+} ■ Ba^{2+} ■ O^{2-}

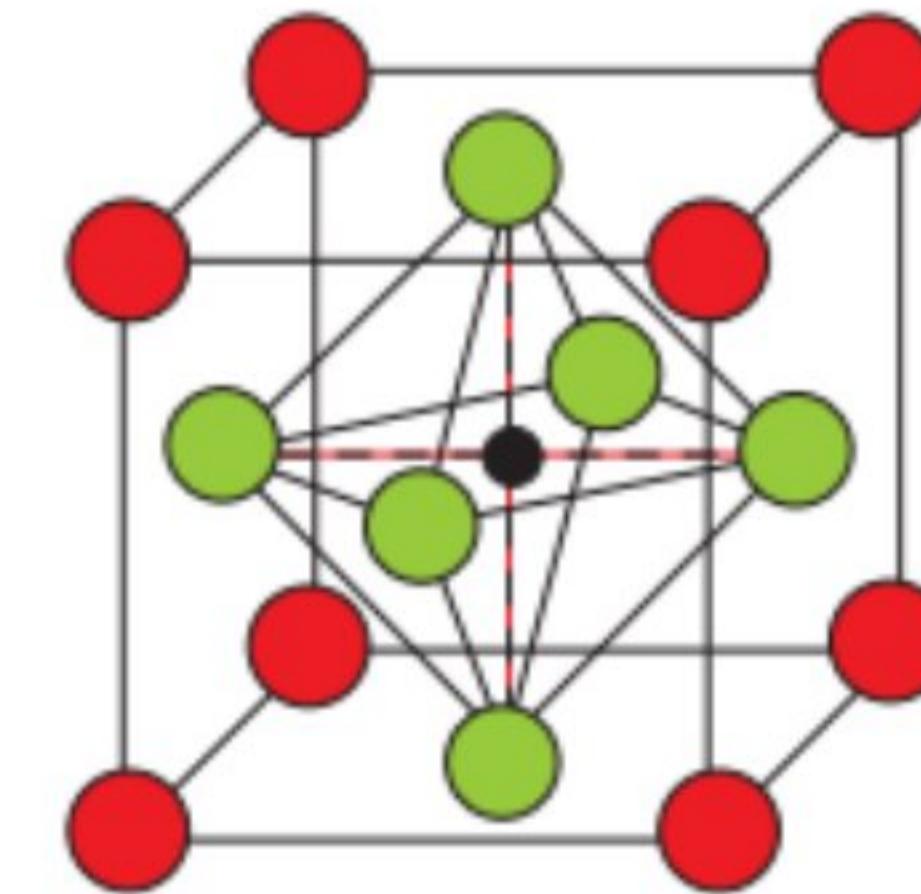
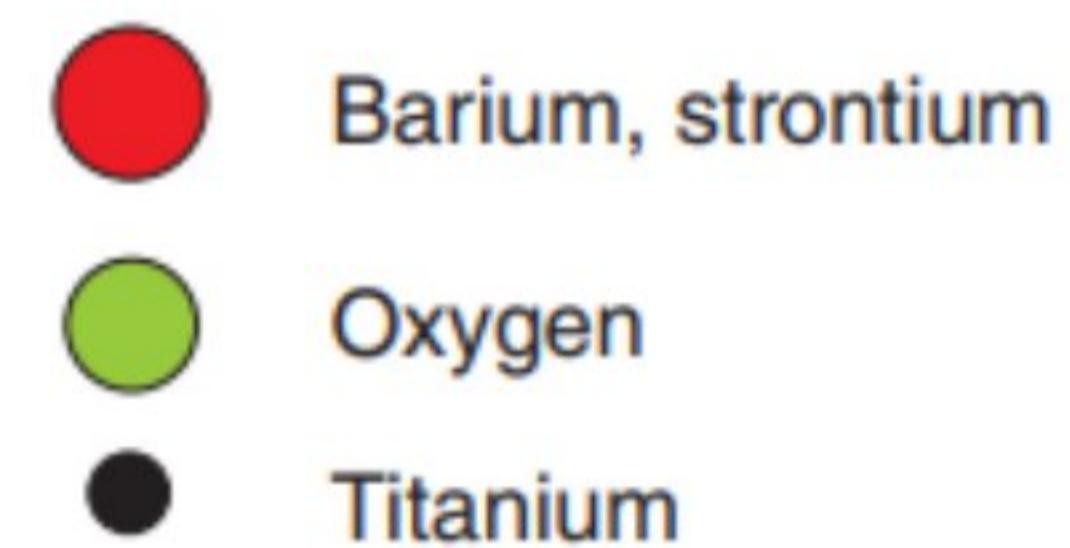
(a)



Strontium Titanate (SrTiO_3)

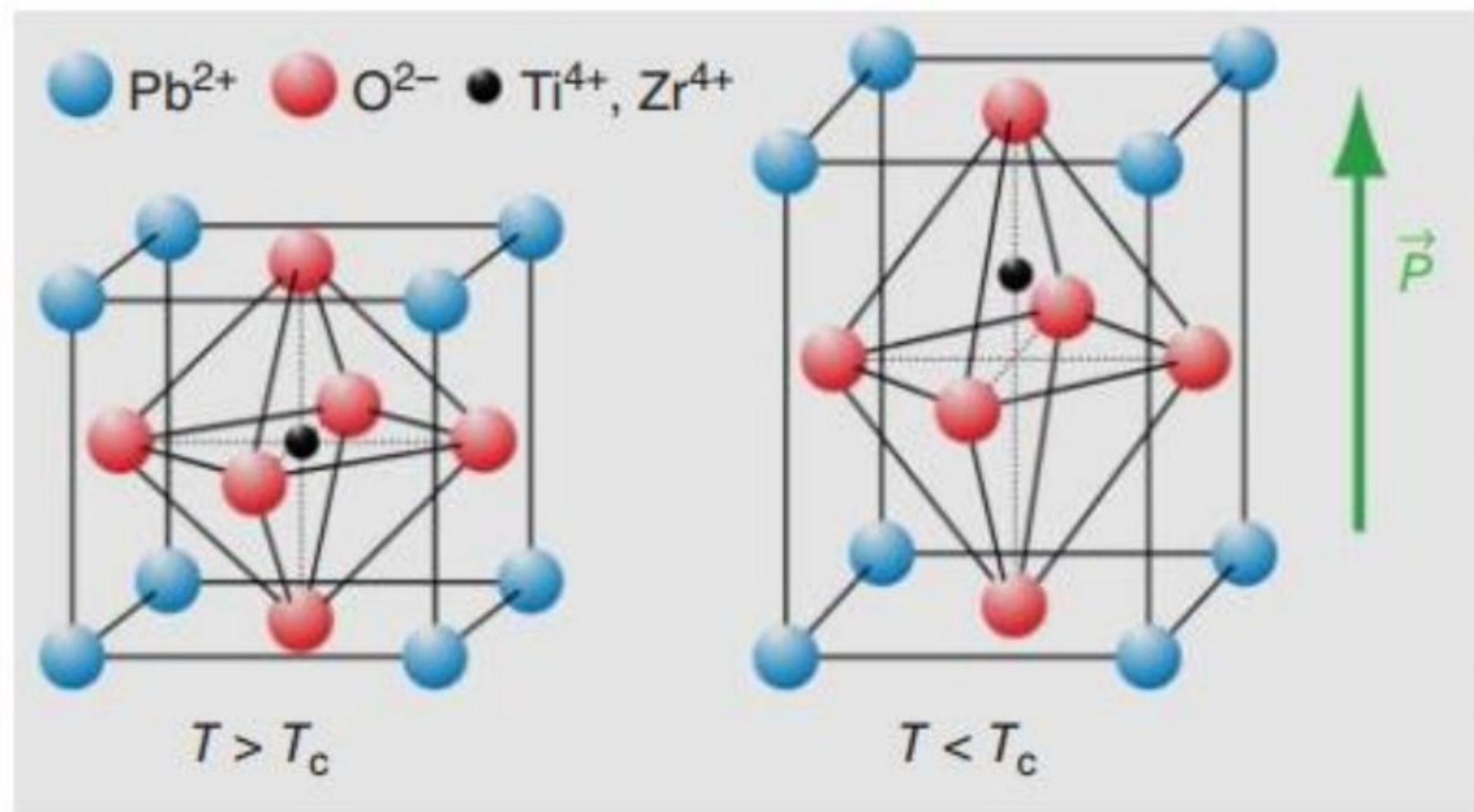


Barium Strontium Titanate (BST)

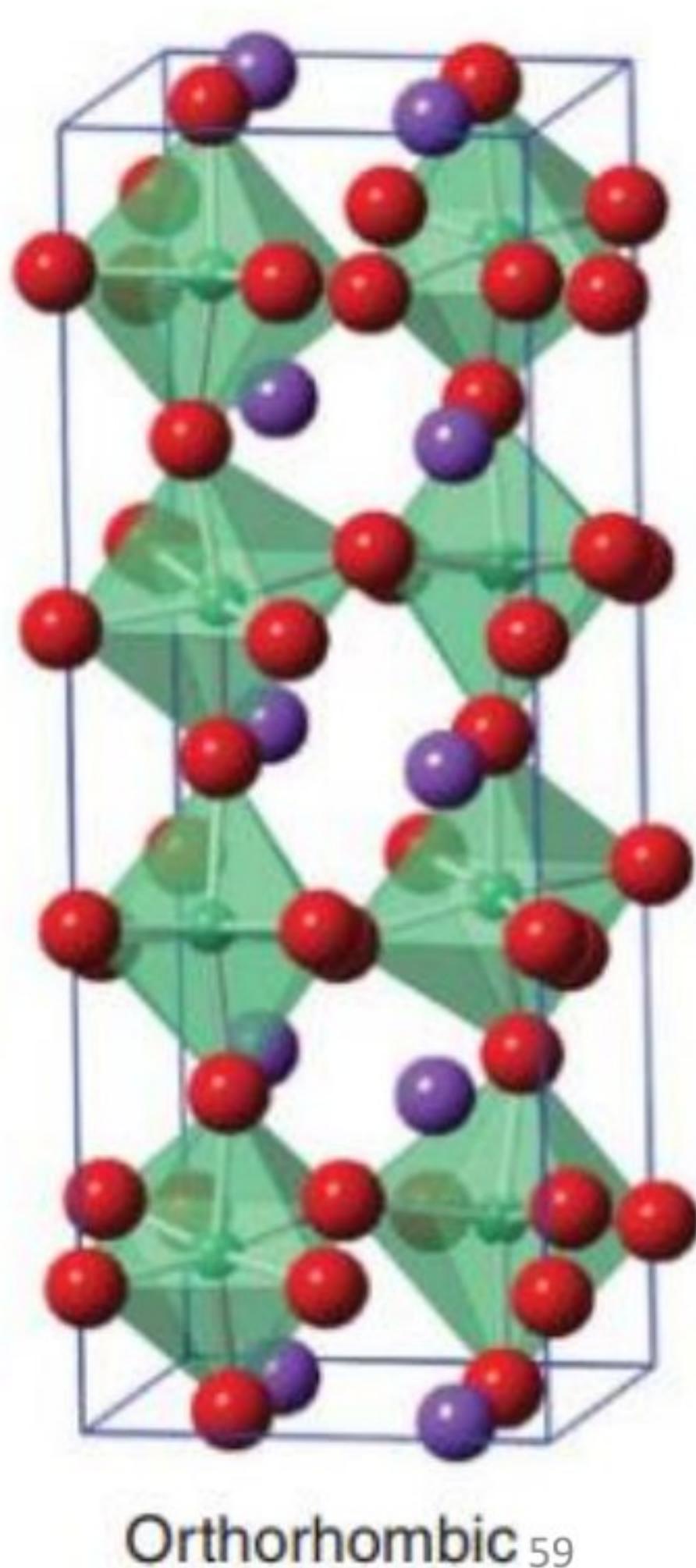
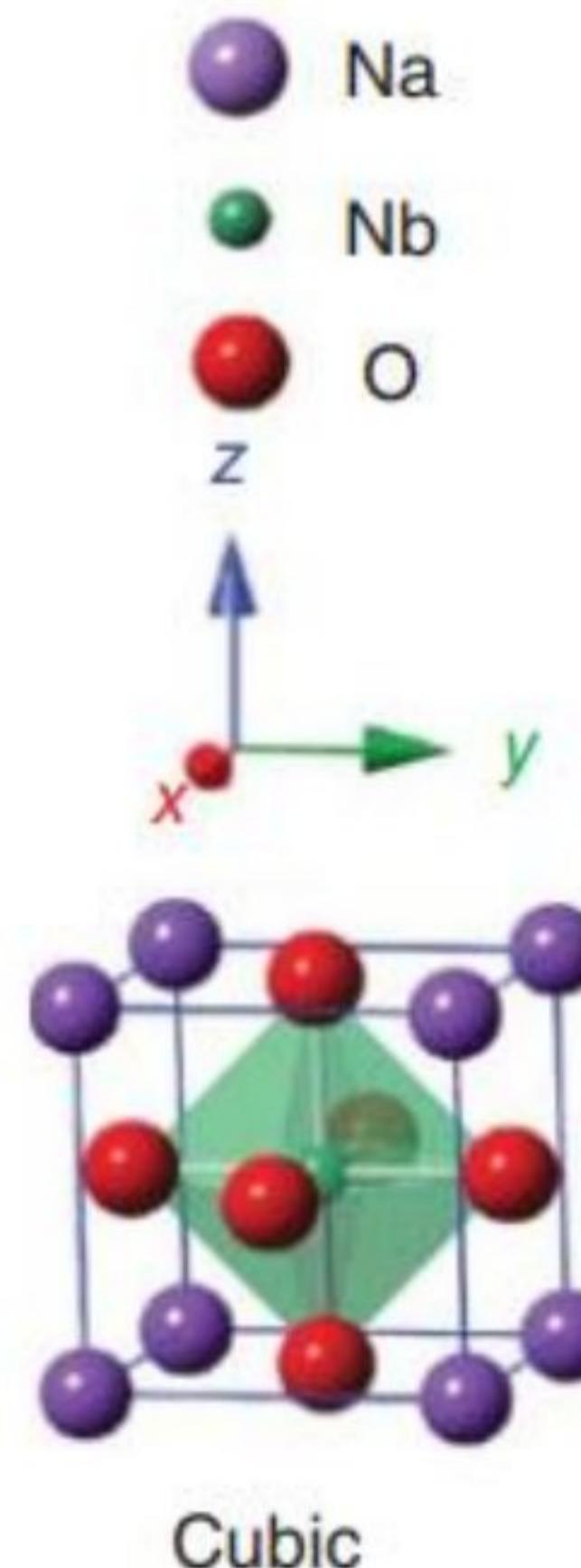


Lead Titanate ($PbTiO_3$)

Lead Zirconate Titanate (PZT)



Sodium Niobate ($NaNbO_3$)



Cubic

Orthorhombic 59

Polymers based Piezoelectrics

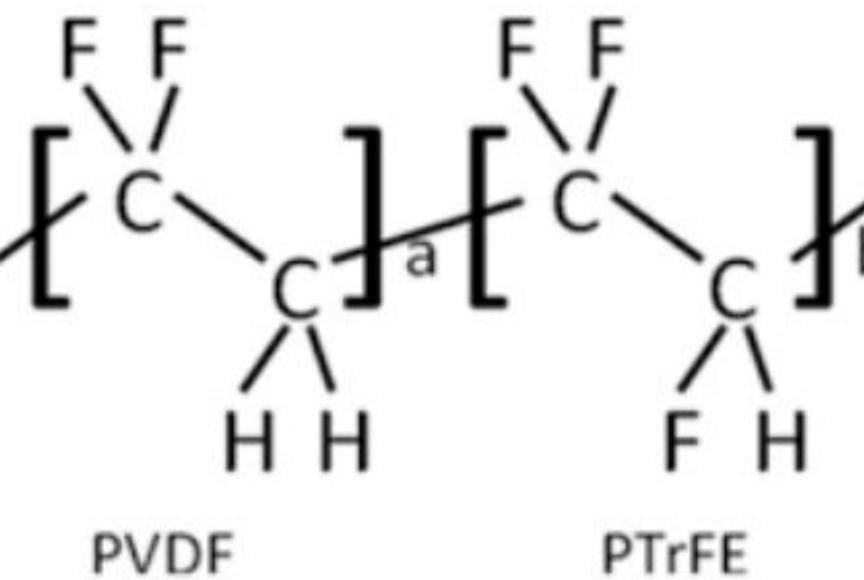
Organic Polymers

Molecular structure of ferroelectric polymer

(a) Polyvinylidene fluoride or Polyvinylidene difluoride (PVDF) and

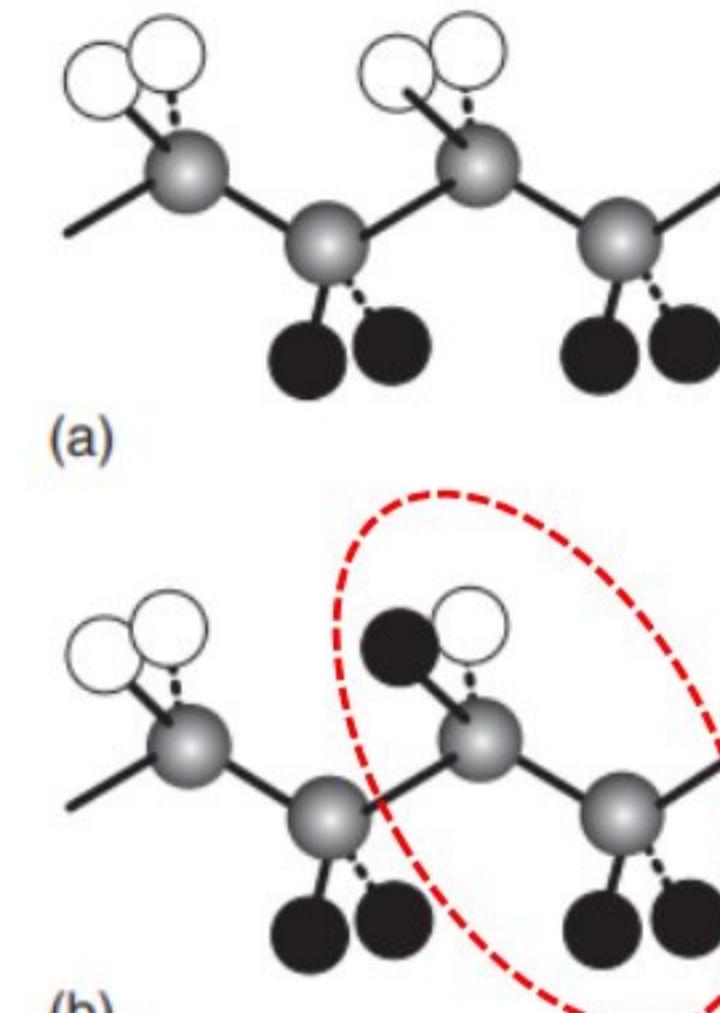
(b) Polyvinylidene fluoride-trifluoroethylene P(VDF-TrFE)

P(VDF-TrFE) copolymer



(a)

(b)



Ceramic Polymer Composites

- Ceramic polymer materials are **inorganic–organic composites consisting of ceramic fillers and a matrix of organic polymers**. The formation of ceramic polymer is based on thermal curing of functionalized resins being able to form ceramic-like structures as a result of heat treatment above 200 deg.C.
- Processed by a broad variety of plastic-forming techniques such as high-pressure injection molding or extrusion.
- Ceramic Polymer composites are characterized by **high thermal stability** (possible service temperatures above 600 deg. C), **low shrinkage**, **high stability of shape**, and **high dimensional accuracy**.
- Relevant usage properties (e.g., electrical conductivity, thermal conductivity) and processing parameters can be adjusted by the choice of appropriate functional fillers, binder systems, and plasticizing additives.
- The application of ceramic polymer materials could pay off if a cost-efficient, easy processing of the material including plastic-forming techniques in order to realize complex shaped parts is required and the thermal stability of standard materials such as plastics does not suffice.

Electrets

- An electret can be considered a piece of dielectric material with the presence of **quasi-permanent real charges** on the surface or in the bulk of the material, or frozen-in aligned dipoles in the bulk. An electret behaves like a battery or acts as an electrical counterpart of a permanent magnet. A piece of poled ferroelectric material can also be an electret.
- The term ***quasi-permanent*** implies that the amount of charges stored in the material does not remain the same permanently, but decays very slowly depending on the situation, and the decay time is normally much longer than the time period over which the electret is in use.
- Historically, electrets were made by first melting a suitable dielectric material such as a polymer or wax that contains polar molecules and then allowing it to resolidify in a powerful electrostatic field.
- The polar molecules of the dielectric align themselves to the direction of the electrostatic field, producing a dipole electret with a permanent electrostatic “bias.”

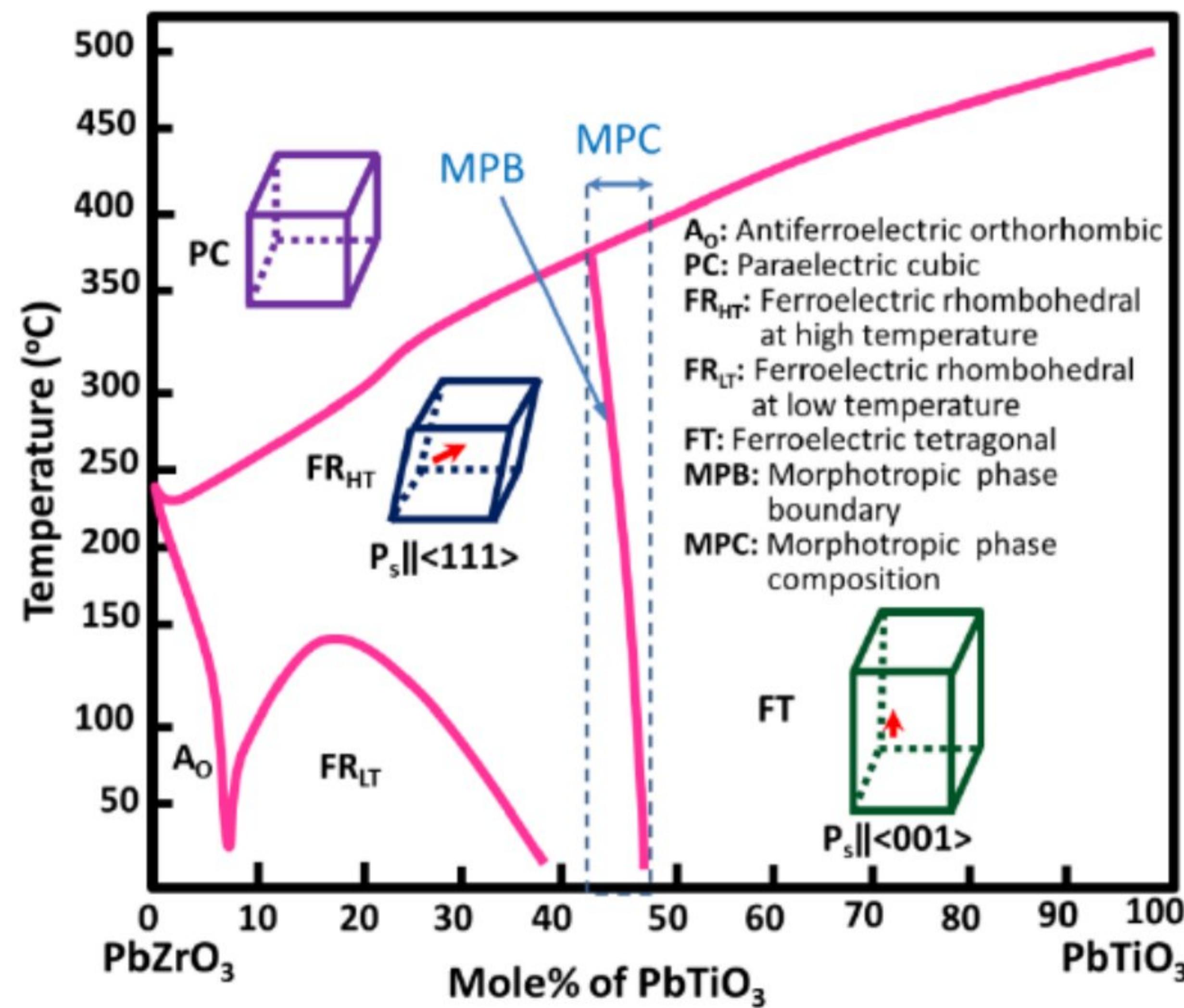
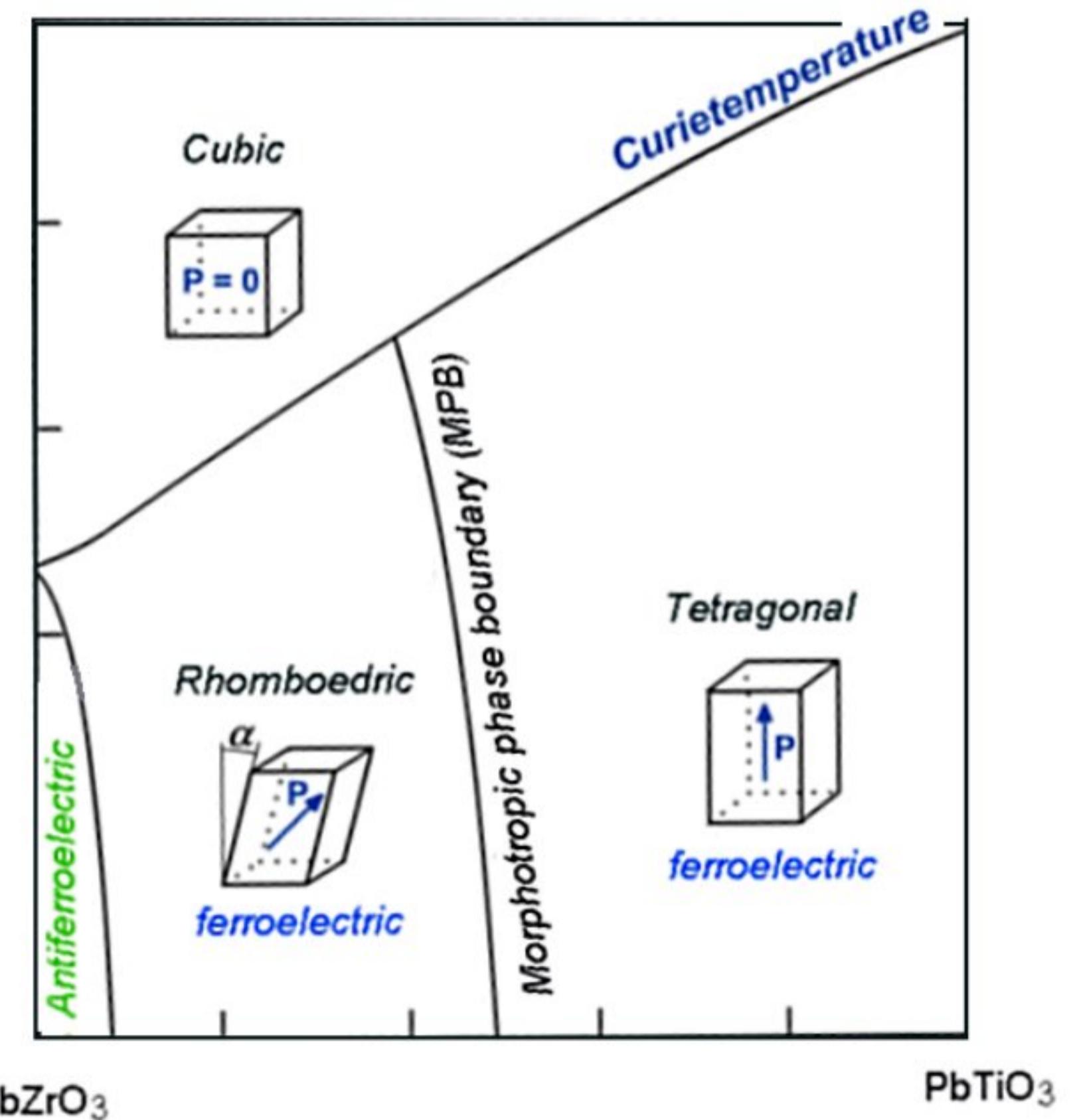
Applications:

- Electret materials were proposed as **condenser microphone elements** several times, but they were considered impractical until the foil electret type was invented at Bell Laboratories in 1962 by Gerhard Sessler and Jim West using a thin metallized Teflon foil.
- This became the most common type used in many applications from **high-quality recording to built-in microphones in small sound recording devices and telephones**.
- Electret materials have found commercial and technical interest. For example, they are used in electret microphones and in copy machines.
- They are also used in some types of **air filters, for electrostatic collection of dust particles**, in electret ion chambers for measuring ionizing radiation or radon, and in vibration energy harvesting.

Phase Diagram

MPB: Coexistence of Rhombohedral and Tetragonal Phases

Good Piezoelectric properties due to the coexistence of two phases.



Phase Changes in PZT

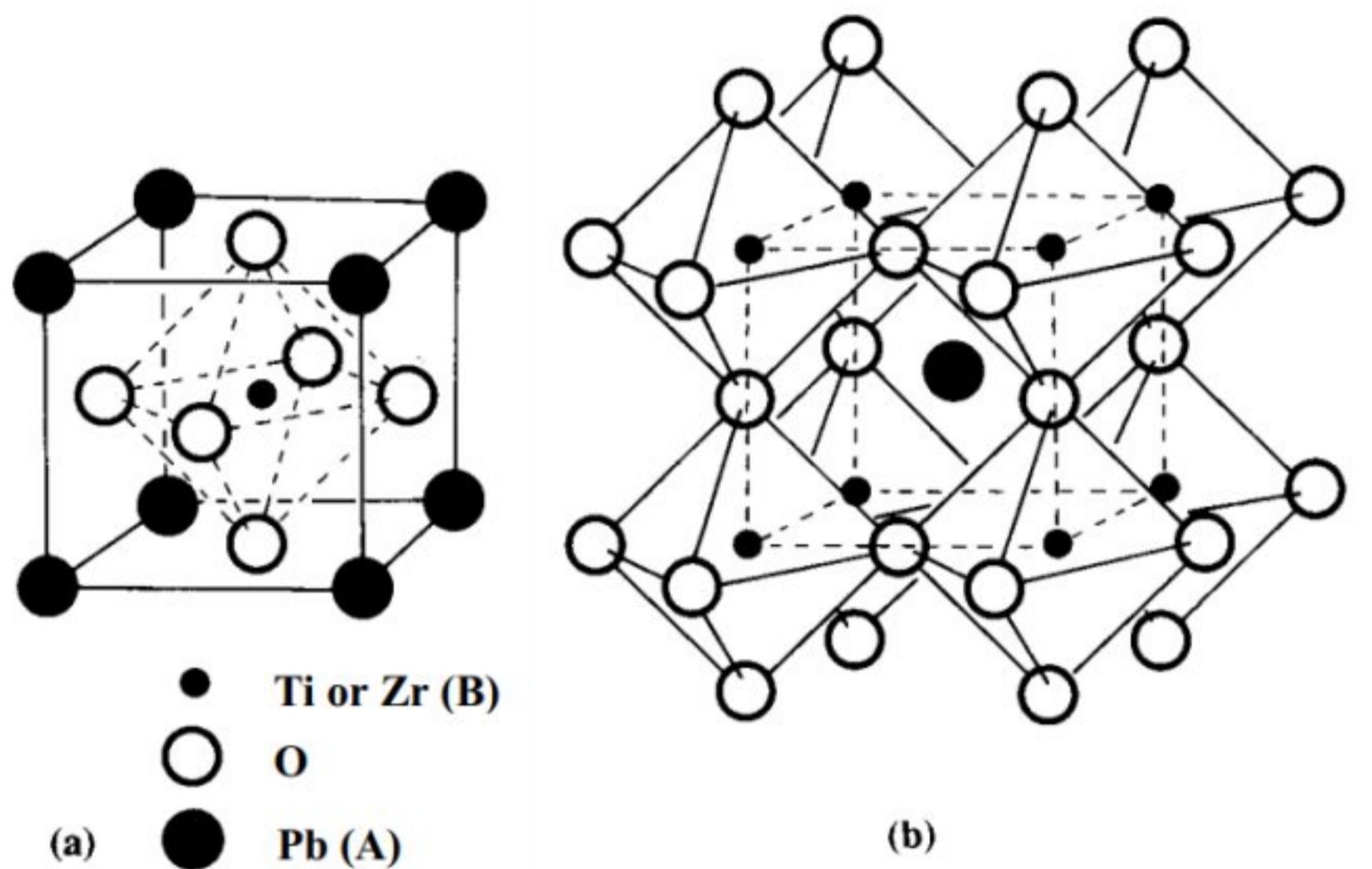
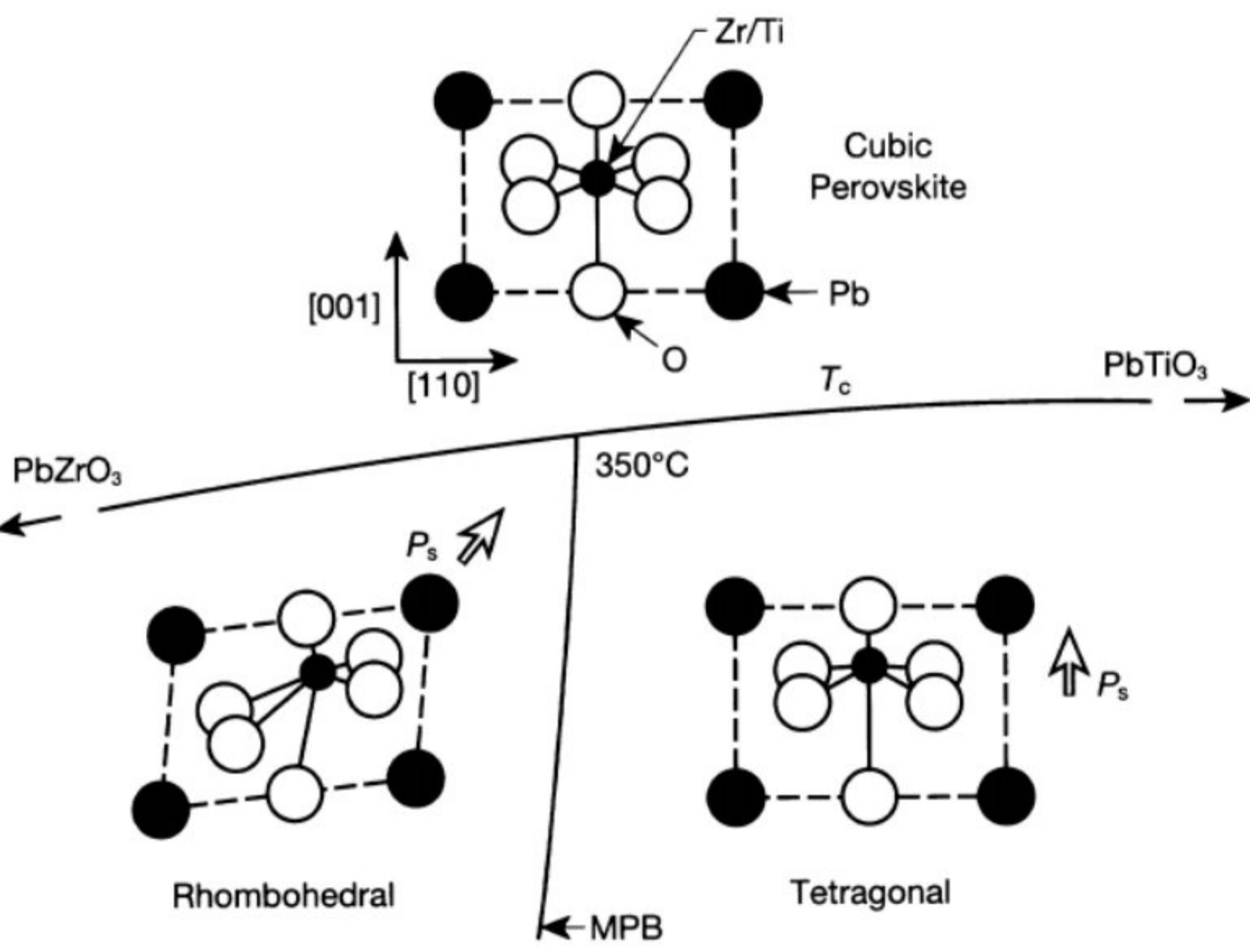
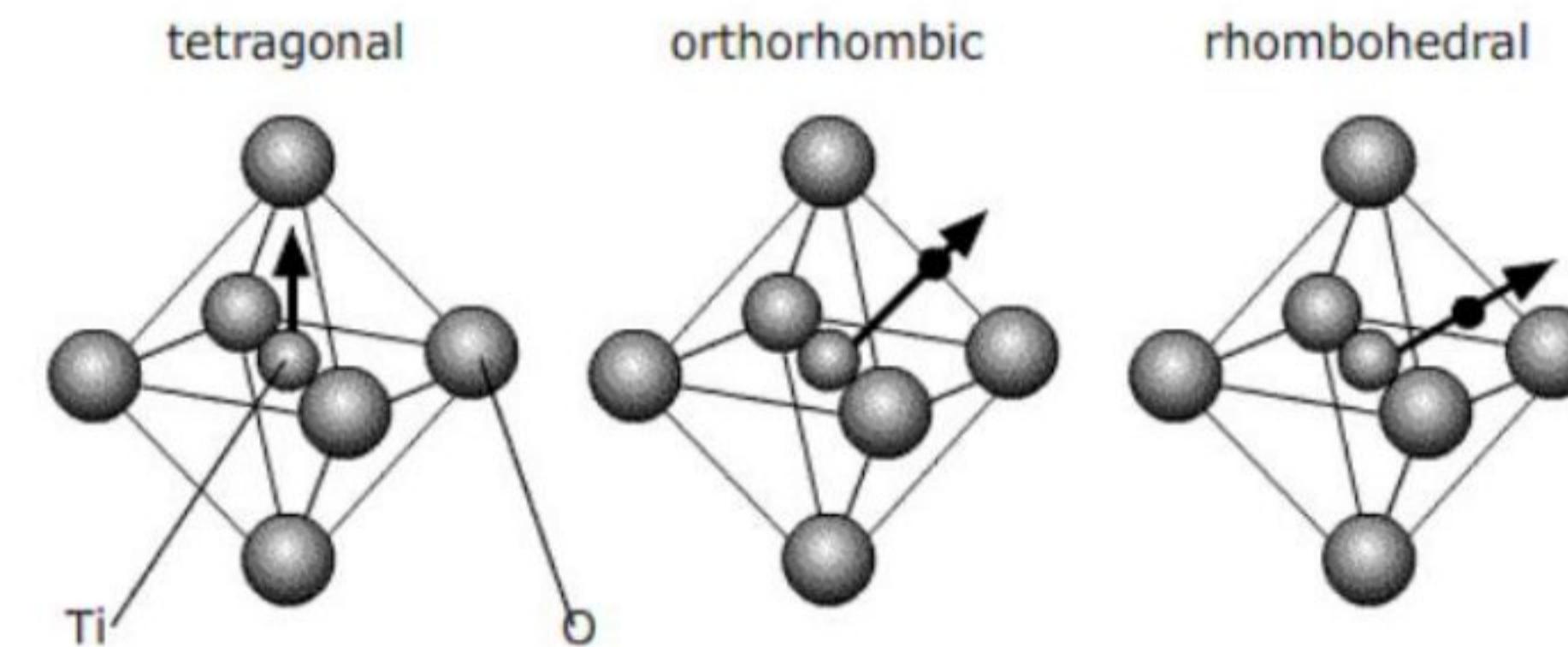
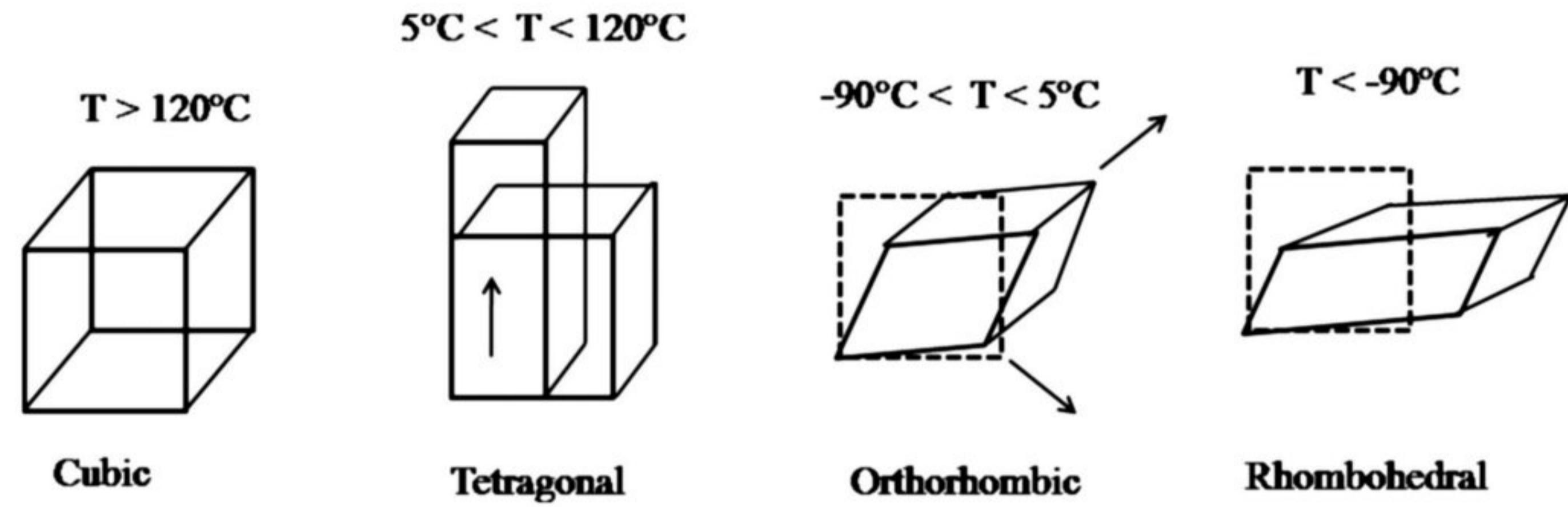
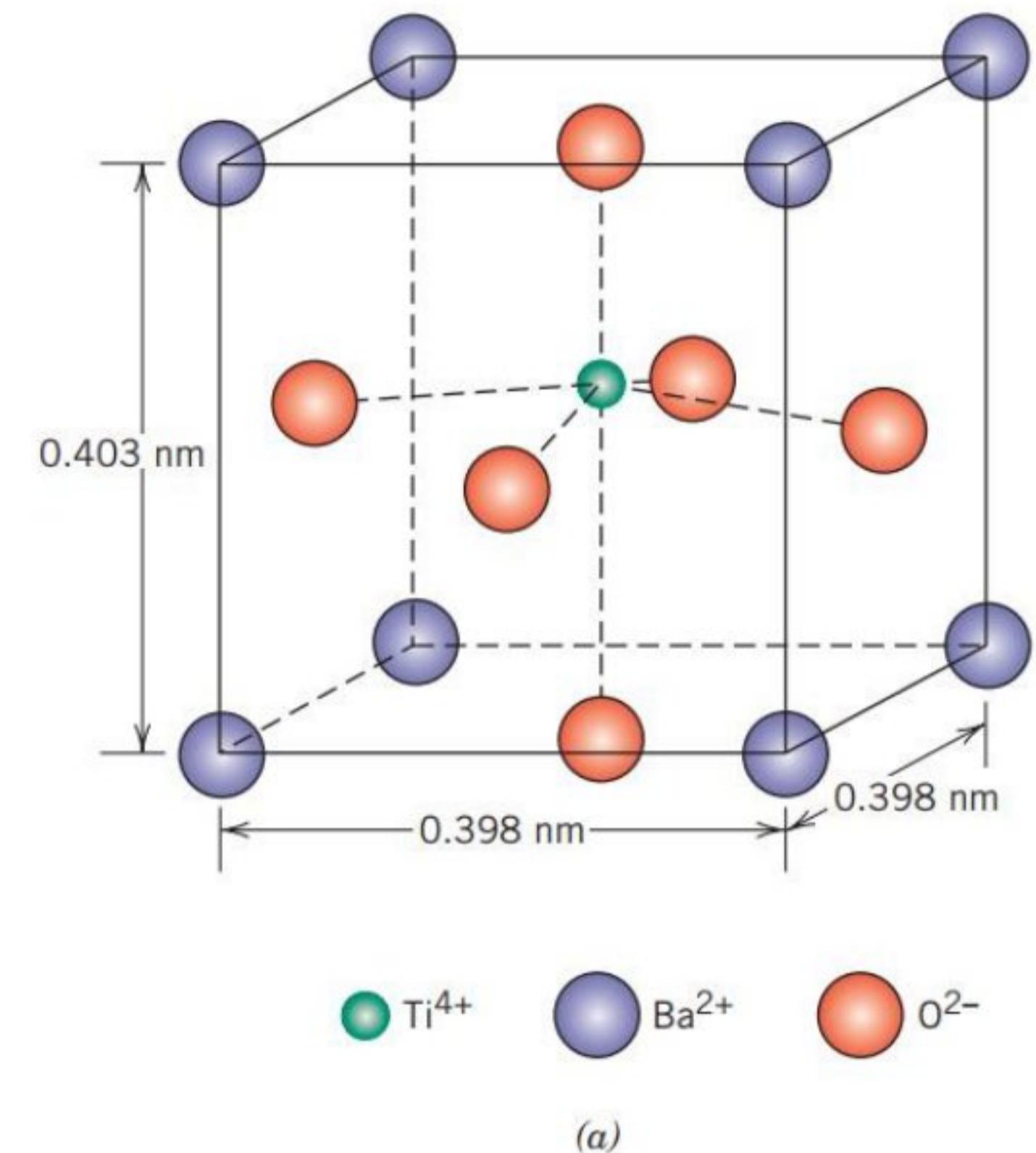


Fig. 2.4. Basic structural unit of perovskite PZT. The basic structural unit is a cube (a). Titanium or zirconium atoms (B) lie at the centre; eight lead atoms (A) occupy the corners and six oxygen atoms (O) are at the surface centres.



Phase Changes in BaTiO₃



No. of Favorable
Polarization
directions = 6

No. of Favorable
Polarization
directions = 8

Doping

Ceramic ferroelectrics properties can be modified by adjusting the composition and the ceramic microstructure.

Additions and the substitution of alternative cations can have the following effects:

- 1. Shift the Curie point and other transition temperatures;**

Changing the Curie point enables the peak permittivity to be put in a temperature range in which it can be exploited. The substitution of Sr^{2+} form Ba^{2+} in BaTiO_3 lowers T_c whilst the substitution of Pb^{2+} increases it.

- 2. Restrict domain wall motion;**

number of transition ions (Fe^{3+} , Ni^{2+} , Co^{3+}) that can occupy Ti^{4+} sites reduce that part of the dissipation factor due to domain wall motion

4. Control crystallite size;

Cations that have a higher valency than those they replace, when present at levels exceeding about 0.5 cation percent, e.g. La^{3+} in place of Ba^{2+} or Nb^{5+} in place of Ti^{4+} , generally inhibit crystal growth.

Crystal size is also controlled by sintering conditions. It has important effects on the electro-optical behaviour.

5. Control the oxygen content and the valency of the Ti ion.

Higher-valency substituents at low concentrations in BaTiO_3 lead to low resistivity.

However, lower-valency substituents, such as Mn^{3+} on Ti^{4+} sites, act as acceptors and enable high-resistivity dielectrics to be sintered in atmospheres with low oxygen contents

Type of Dopants

Donor Dopants

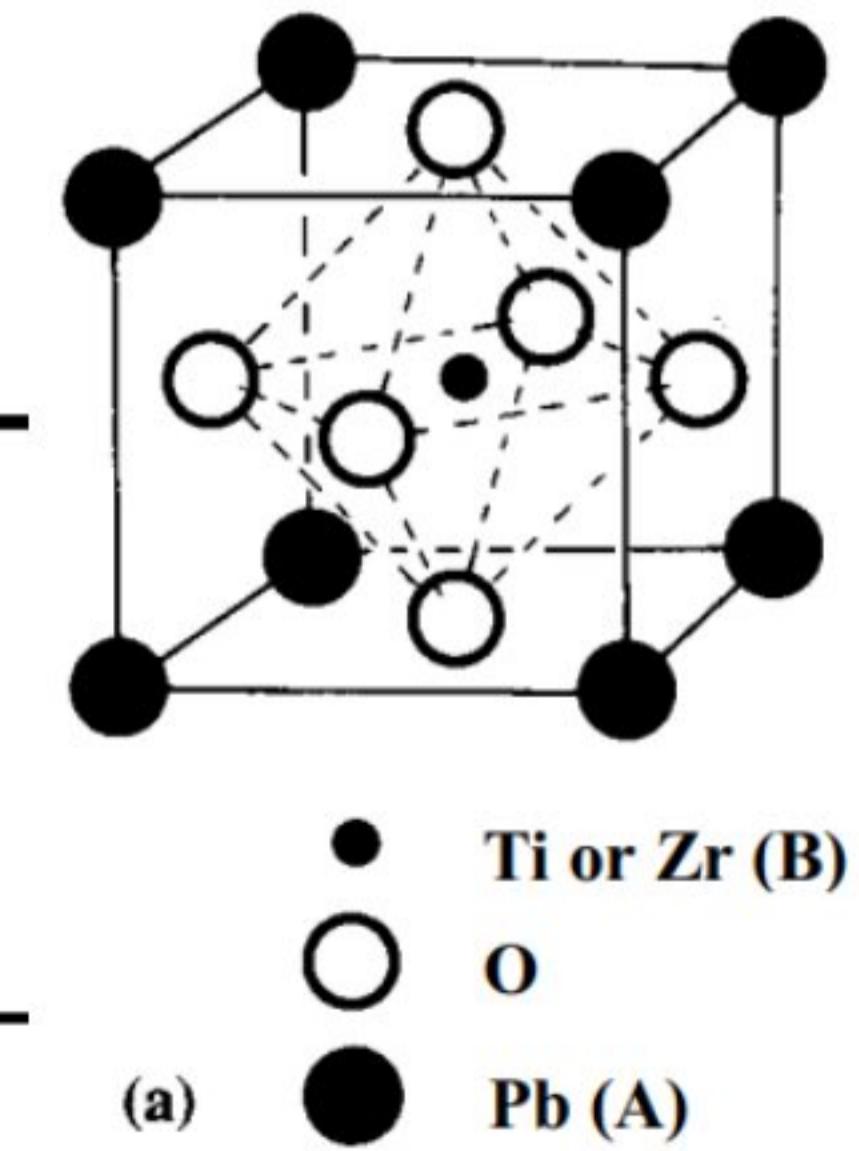
- Donor dopants, i.e. higher charge than that of the ions they replace, are compensated by cation vacancies
- Acceptors, i.e. dopants of lower charge than that of the replaced ions, are compensated by oxygen vacancies
- Significant difference between oxygen vacancies and cation vacancies in perovskite-type structures is the higher mobility of the former
- Cations and cation vacancies tend to be separated by oxygen ions so that there is a considerable energy barrier to be overcome before the ion and its vacancy can be interchanged.
- Oxygen ions, however, form a continuous lattice structure so that oxygen vacancies have oxygen ion neighbors with which they can easily exchange.

Acceptor Dopants

- Donor–cation vacancy combinations can be assumed to have a stable orientation so that their initially random state is unaffected by spontaneous polarization or applied fields.
- Acceptor–oxygen vacancy combinations are likely to be less stable and thermally activated reorientation may take place in the presence of local or applied fields.
- The dipoles, once oriented in a common direction, will provide a field stabilizing the domain structure.

Inhibition of wall movement : A reduction in permittivity, dielectric and mechanical loss and an increase in the coercive field.

A-site donors	La^{3+} , Bi^{3+} , Nd^{3+}
B-site donors	Nb^{5+} , Ta^{5+} , Sb^{5+}
A-site acceptors	K^+ , Rb^+
B-site acceptors	Co^{3+} , Fe^{3+} , Sc^{3+} , Ga^{3+} , Cr^{3+} , Mn^{3+} , Mn^{2+} , Mg^{2+} , Cu^{2+}



Dopants which gives rise to soft and hard PZT properties

Additives	Major Effects
<u>Isovalent additives</u> Ba ²⁺ (0.134) or Sr ²⁺ (0.112) for Pb ²⁺ (0.132) Sn ⁴⁺ (0.071) for Zr ⁴⁺ (0.068) or Ti ⁴⁺ (0.079)	Lower Curie point Higher permittivity
<u>Soft dopants</u> La ³⁺ (0.122), Nd ³⁺ (0.115), Sb ³⁺ (0.090), Bi ³⁺ (0.114) or Th ⁴⁺ (0.110) for Pb ²⁺ (0.132) Nb ⁵⁺ (0.069), Ta ⁵⁺ (0.068), Sb ⁵⁺ (0.063) or W ⁶⁺ (0.065) for Ti ⁴⁺ (0.068) or Zr ⁴⁺ (0.079)	Higher permittivity Higher K _p Much lower Q _m Resistivity about 10 ³ higher
<u>Hard dopants</u> K ⁺ (0.133) or Na ⁺ (0.094) for Pb ²⁺ (0.132) Fe ³⁺ (0.067), Al ³⁺ (0.057), Sc ³⁺ (0.083), In ³⁺ (0.092) or Cr ³⁺ (0.064) for Ti ⁴⁺ (0.068) or Zr ⁴⁺ (0.079)	Lower permittivity Lower dielectric loss Lower K _p Much higher Q _m

Doping in PZT

Donor doping in PZT would be expected to reduce the concentration of oxygen vacancies, leading to a reduction in the concentration of domain-stabilizing defect pairs and so to lower ageing rates.

The resulting increase in wall mobility causes the observed increases in permittivity, dielectric losses, elastic

compliance and coupling coefficients, and reductions in mechanical Q and coercivity.

e.g. Soft and Hard PZT

Characteristic	Soft Ceramic	Hard Ceramic
Piezoelectric Constants	larger	smaller
Permittivity	higher	lower
Dielectric Constants	larger	smaller
Dielectric Losses	higher	lower
Electromechanical Coupling Factors	larger	smaller
Electrical Resistance	very high	lower
Mechanical Quality Factors	low	high
Coercive Field	low	higher
Linearity	poor	better
Polarization / Depolarization	easier	more difficult

Piezoelectric Constants one needs to know

◆ Piezoelectric constants

- d [C/N] = (charge developed)/(applied stress)
- g [V-m/N] = (Electric field developed)/(applied stress)

Charge Constant

Voltage Constant

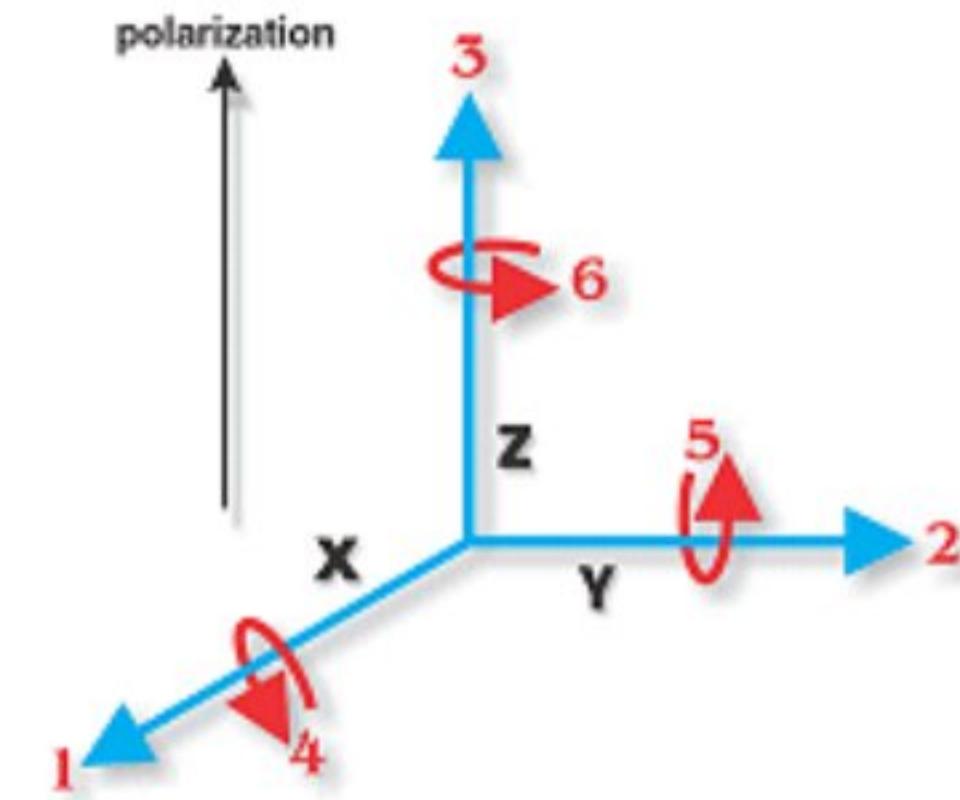
◆ Electromechanical coupling coefficient (k)

- Parameter used to compare different piezoelectric materials
- A measure of the interchange of electrical & mechanical energy

Piezoelectric Charge Constant

Figure 1.6 Directions of forces affecting a piezoelectric element

- d_{33} induced polarization in direction 3 (parallel to direction in which ceramic element is polarized) per unit stress applied in direction 3
or
induced strain in direction 3 per unit electric field applied in direction 3
- d_{31} induced polarization in direction 3 (parallel to direction in which ceramic element is polarized) per unit stress applied in direction 1 (perpendicular to direction in which ceramic element is polarized)
or
induced strain in direction 1 per unit electric field applied in direction 3
- d_{15} induced polarization in direction 1 (perpendicular to direction in which ceramic element is polarized) per unit shear stress applied about direction 2 (direction 2 perpendicular to direction in which ceramic element is polarized)
or
induced shear strain about direction 2 per unit electric field applied in direction 1



$$d = \frac{\text{Polarization}}{\text{Mechanical Stress}}$$

Piezoelectric Voltage Constant

- §33 induced electric field in direction 3 (parallel to direction in which ceramic element is polarized) per unit stress applied in direction 3
or
induced strain in direction 3 per unit electric displacement applied in direction 3
- §31 induced electric field in direction 3 (parallel to direction in which ceramic element is polarized) per unit stress applied in direction 1 (perpendicular to direction in which ceramic element is polarized)
or
induced strain in direction 1 per unit electric displacement applied in direction 3
- §15 induced electric field in direction 1 (perpendicular to direction in which ceramic element is polarized) per unit shear stress applied about direction 2 (direction 2 perpendicular to direction in which ceramic element is polarized)
or
induced shear strain about direction 2 per unit electric displacement applied in direction 1

$$d = \frac{\text{Electric Field}}{\text{Mechanical Stress}}$$

Permittivity Constant

The *permittivity*, or *dielectric constant*, ϵ , for a piezoelectric ceramic material is the dielectric displacement per unit electric field. ϵ^T is the permittivity at constant stress, ϵ^S is the permittivity at constant strain. The first subscript to ϵ indicates the direction of the dielectric displacement; the second is the direction of the electric field.

The relative dielectric constant, K, is the ratio of , the amount of charge that an element constructed from the ceramic material can store, relative to the absolute dielectric constant, 0 , the charge that can be stored by the same electrodes when separated by a vacuum, at equal voltage ($0 = 8.85 \times 10^{-12}$ farad / meter).

ϵ_{11}^T permittivity for dielectric displacement and electric field in direction 1 (perpendicular to direction in which ceramic element is polarized), under constant stress

ϵ_{33}^S permittivity for dielectric displacement and electric field in direction 3 (parallel to direction in which ceramic element is polarized), under constant strain

$$\epsilon = \frac{\text{Dielectric Displacement}}{\text{Electric Field}}$$

Elastic and Compliance

Inverse of Modulus of Elasticity

Elastic compliance, s , is the strain produced in a piezoelectric material per unit of stress applied and, for the 11 and 33 directions, is the reciprocal of the modulus of elasticity (Young's modulus, Y). s^D is the compliance under a constant electric displacement; s^E is the compliance under a constant electric field. The first subscript indicates the direction of strain, the second is the direction of stress.

$$S = \frac{\text{Mechanical Strain}}{\text{Mechanical Stress}}$$

s^E_{11} elastic compliance for stress in direction 1 (perpendicular to direction in which ceramic element is polarized) and accompanying strain in direction 1, under constant electric field (short circuit)

s^D_{33} elastic compliance for stress in direction 3 (parallel to direction in which ceramic element is polarized) and accompanying strain in direction 3, under constant electric displacement (open circuit)

Young's Modulus

Young's modulus, Y , is an indicator of the stiffness (elasticity) of a ceramic material. Y is determined from the value for the stress applied to the material divided by the value for the resulting strain in the same direction.

Electromechanical Coupling Factor

The *electromechanical coupling factor*, k , is an indicator of the effectiveness with which a piezoelectric material converts electrical energy into mechanical energy, or converts mechanical energy into electrical energy. The first subscript to k denotes the direction along which the electrodes are applied; the second denotes the direction along which the mechanical energy is applied, or developed.

- k_{33} factor for electric field in direction 3 (parallel to direction in which ceramic element is polarized) and longitudinal vibrations in direction 3
(ceramic rod, length >10x diameter)
- k_t factor for electric field in direction 3 and vibrations in direction 3
(thin disc, surface dimensions large relative to thickness; $k_t < k_{33}$)
- k_{31} factor for electric field in direction 3 (parallel to direction in which ceramic element is polarized) and longitudinal vibrations in direction 1 (perpendicular to direction in which ceramic element is polarized)
(ceramic rod)
- k_p factor for electric field in direction 3 (parallel to direction in which ceramic element is polarized) and radial vibrations in direction 1 and direction 2 (both perpendicular to direction in which ceramic element is polarized)
(thin disc)

$$k = \frac{\text{Electrical Energy}}{\text{Mechanical Energy}} \quad \text{OR} \quad \frac{\text{Mechanical Energy}}{\text{Mechanical Energy}}$$

Constitutive Equation of Piezoelectricity

- For mechanical problems, a **constitutive equation** describes how a material strains when it is stressed, or vice-versa.
- Constitutive equations exist also for electrical problems; they describe how charge moves in a (dielectric) material when it is subjected to a voltage, or vice-versa.
- Engineers are already familiar with the most common mechanical constitutive equation that applies for everyday metals and plastics. This equation is known as Hooke's Law and is written as:

$$\mathbf{S} = \mathbf{s} \cdot \mathbf{T}$$

In words, this equation states: **Strain = Compliance × Stress**.

- However, since piezoelectric materials are concerned with electrical properties too, we must also consider the constitutive equation for common dielectrics:

$$\mathbf{D} = \mathbf{\epsilon} \cdot \mathbf{E}$$

In words, this equation states: **Charge Density = Permittivity × ElectricField**.

Constitutive Equation of Piezoelectricity

$$\begin{aligned} S &= s T + d^t E \\ D &= d T + \epsilon E \end{aligned}$$

Diagram illustrating the Constitutive Equations of Piezoelectricity:

- Strain (S):** Indicated by a blue arrow pointing to the left term in the first equation.
- Stress (T):** Indicated by a blue arrow pointing to the right term in the first equation.
- Electric field (E):** Indicated by a blue arrow pointing to the right term in the second equation.
- Permittivity (ϵ):** Indicated by a blue arrow pointing to the right term in the second equation.
- matrix for the direct piezoelectric effect (d):** Indicated by a blue arrow pointing to the left term in the second equation.
- Electric charge density displacement (D):** Indicated by a blue arrow pointing to the left term in the second equation.

Effect of Grain Size

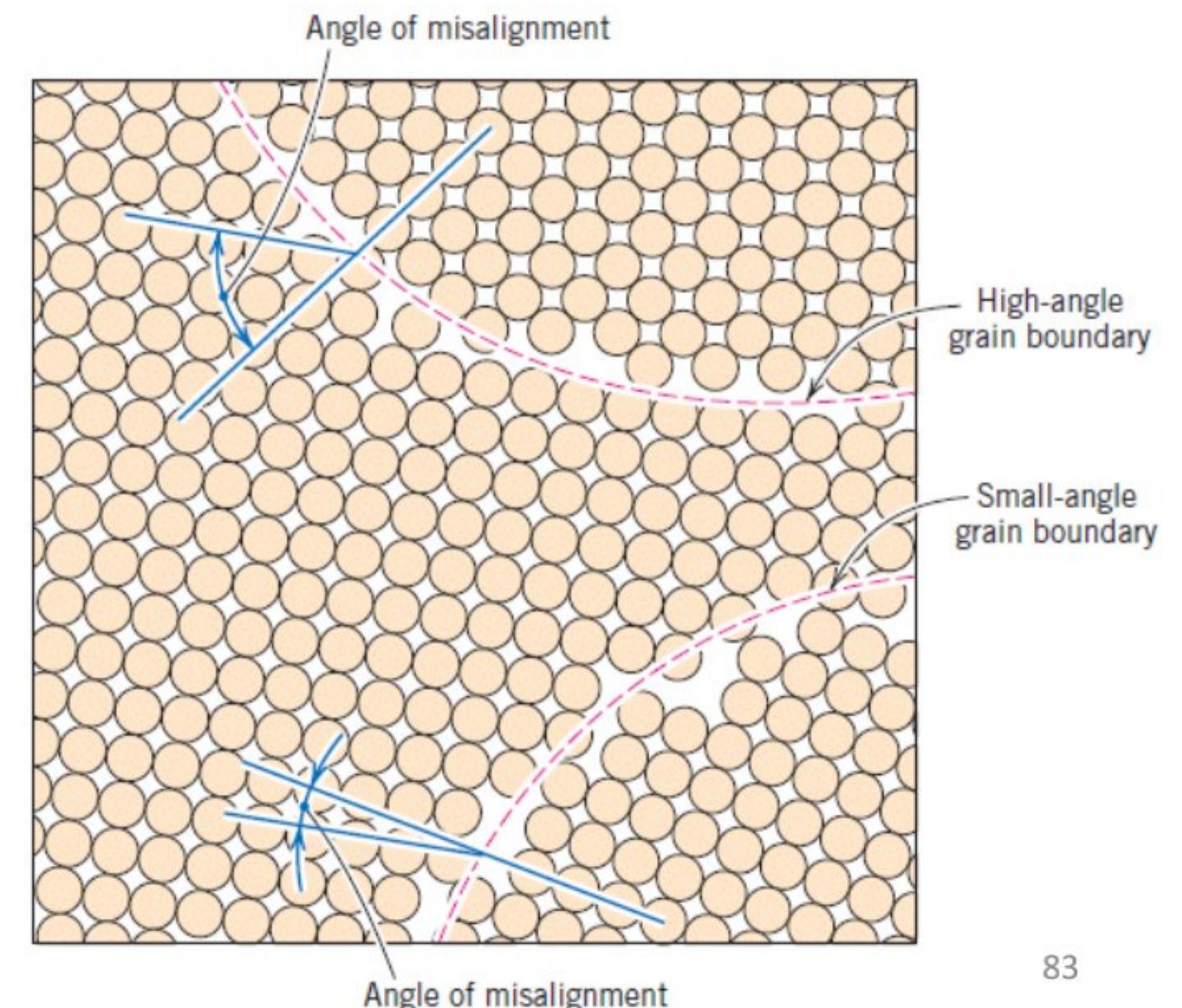
- The grain size of PZT ceramics depends on the compositions and sintering conditions.
- In general, the grain size of PZT ceramics increases with the increasing sintering temperatures and sintering time, from submicron to about $10\text{ }\mu\text{m}$.
- Metal oxide dopants will affect the grain growth during sintering process. Some metal oxide may restrain the grain growth in the ceramics.
- The deterioration of the piezoelectric properties with decreasing grain size is probably related to fewer domains and less mobile domain walls [Martirena & Burfoot, 1974].
- Below a critical size, the formation of ferroelectric domains is not energetically favourable [Mishra and Pandey, 1995] .

- It has been confirmed that the undoped PZT ceramics possess p-type conductivity (hole-type semiconductor) due to the lead oxide evaporation from the PZT sample during the sintering process, which creates Pb vacancies in the sintered PZT ceramic [Gerson, 1960] .
- Therefore, in a PZT ceramic with hard doping ions, space charge, i.e. both centres of negative charges and hole-carriers, increase dramatically; which cause an internal field E_s inside the grains of PZT, and this field E_s may inhibit domain motion.
- The inhibition of domain motion reduces the dielectric loss (including the energy loss in domain vibration hysteresis).

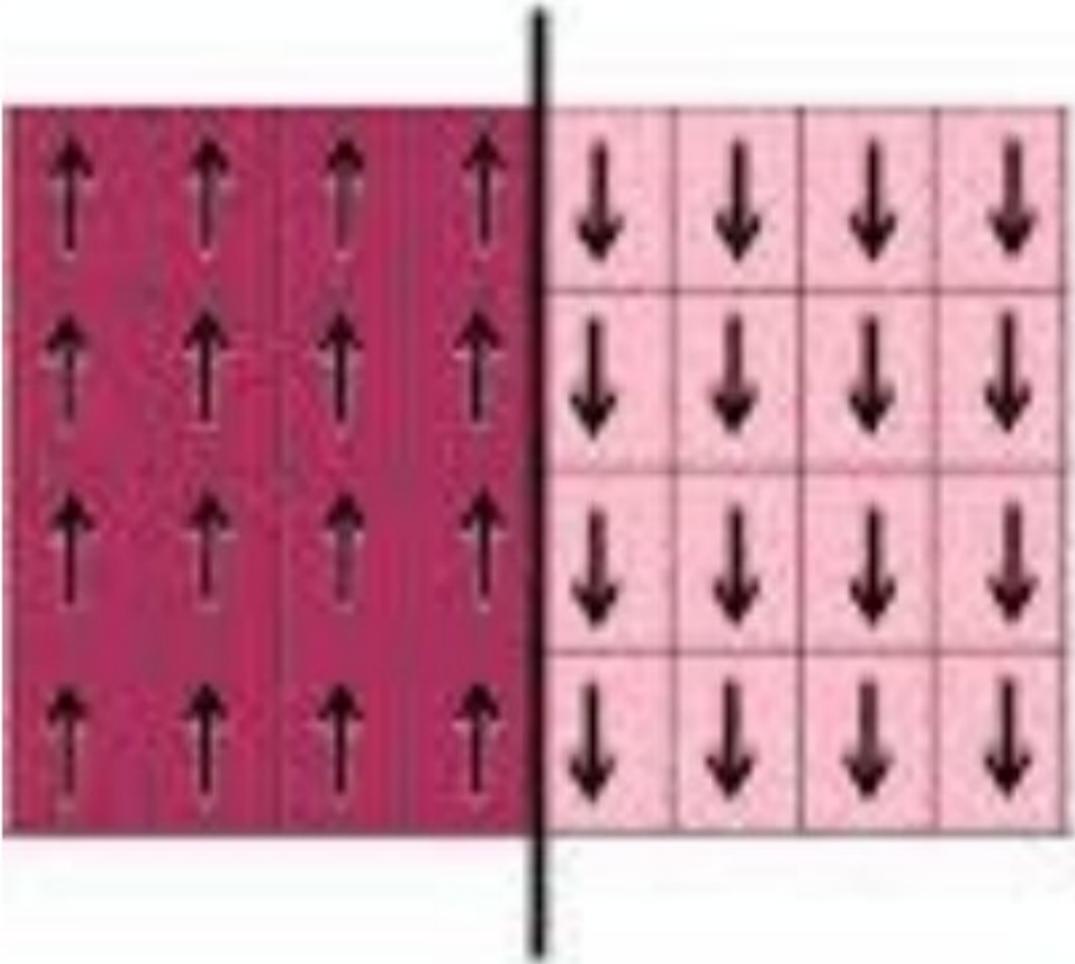
High Angle and Low Angle grain boundaries

Generally, it is assumed that **low-angle grain boundaries** (LAGBs) are those with a misorientation less than about 5 degrees.

In contrast, the misorientation of **high-angle grain boundaries** (HAGBs) is greater than about 5 degrees.

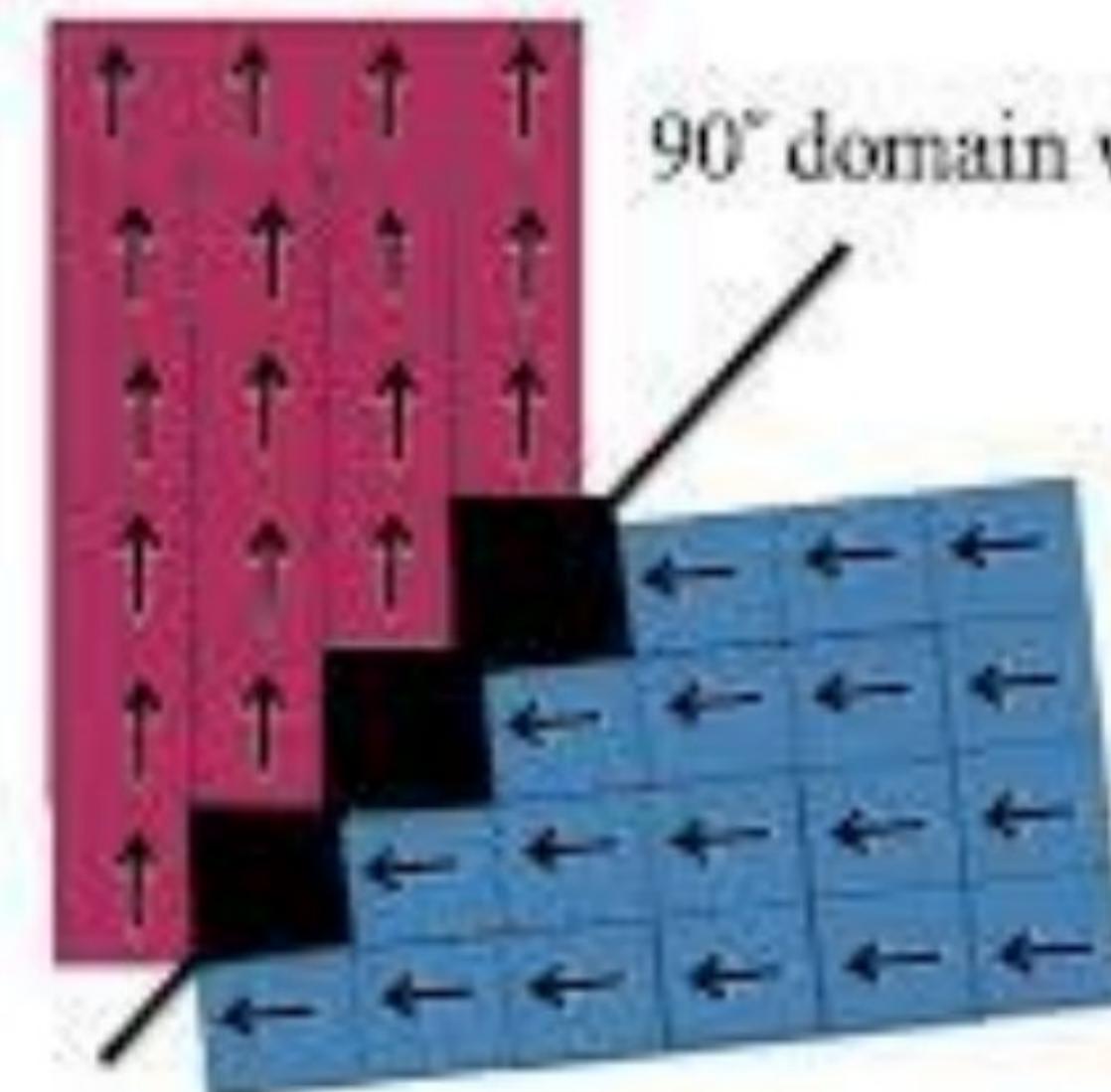


180° domain wall



(a)

90° domain wall



(b)

Applications of Ferroelectric Materials

Applications

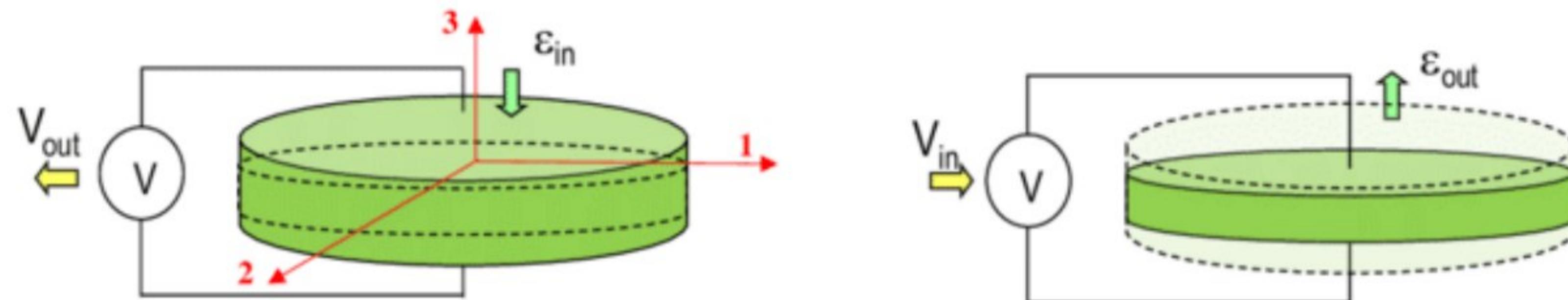
Use in Camera Flash

Ferroelectrics are very useful for devices and are used in many different ways today. If a ferroelectric is used in its linear region, above T_C it makes a very good capacitor, as its dielectric constant can be very high indeed. These are often used in cameras as a way of powering a flash.

A battery slowly stores a charge on a capacitor, which when connected to a bulb, releases a burst of high current, creating the flash.

First, the battery charges the ferroelectric capacitor and then, once fully charged, the ferroelectric is connected to the bulb and causes it to flash.

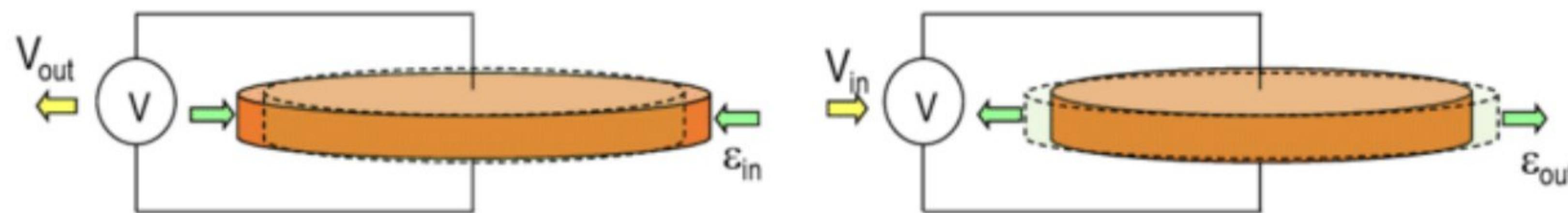
Sensors and Actuators



Direct Effect - Sensor

Deformation \rightarrow Charge and Voltage

(a) Longitudinal (d_{33}) sensor and actuator



Direct Effect - Sensor

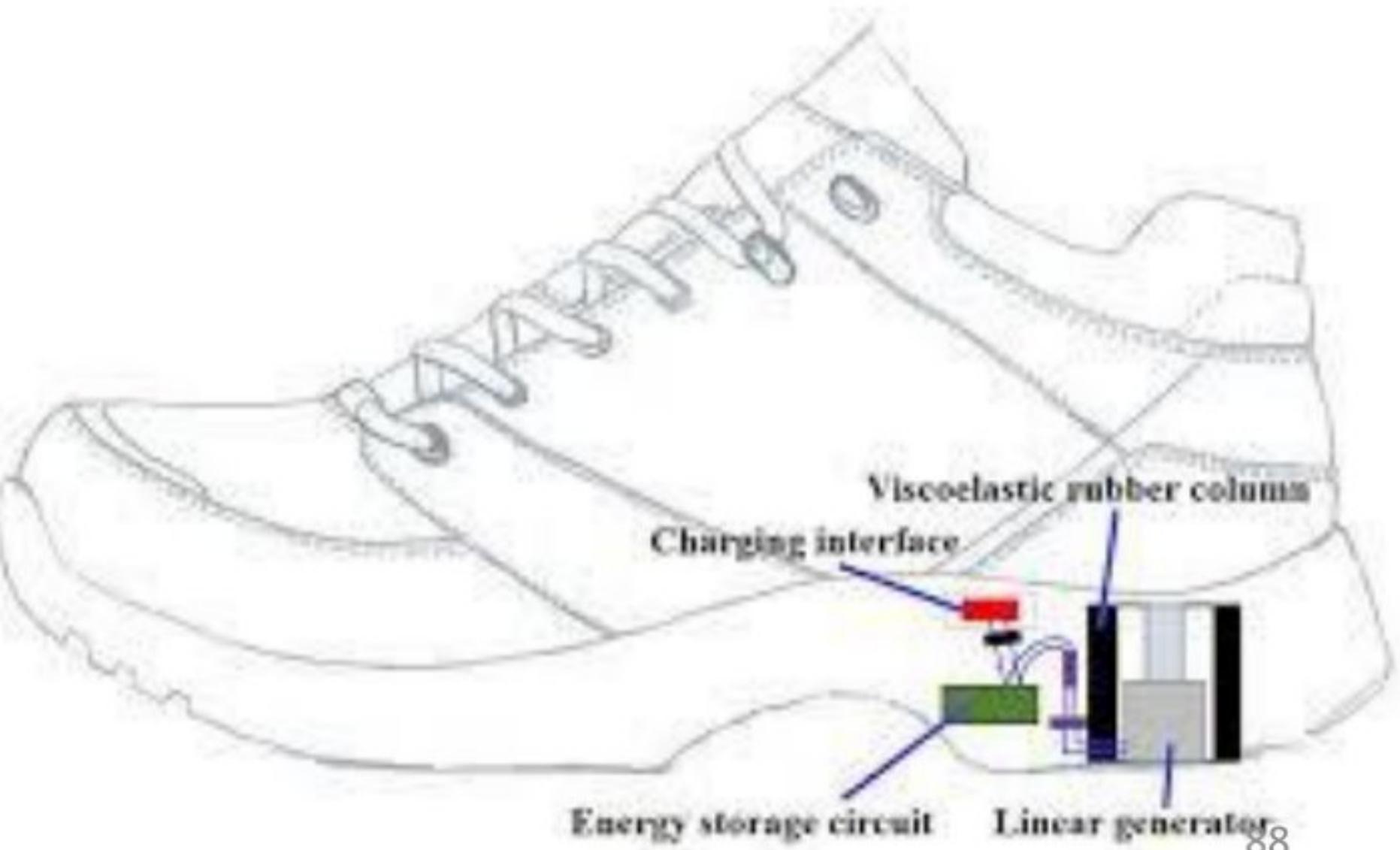
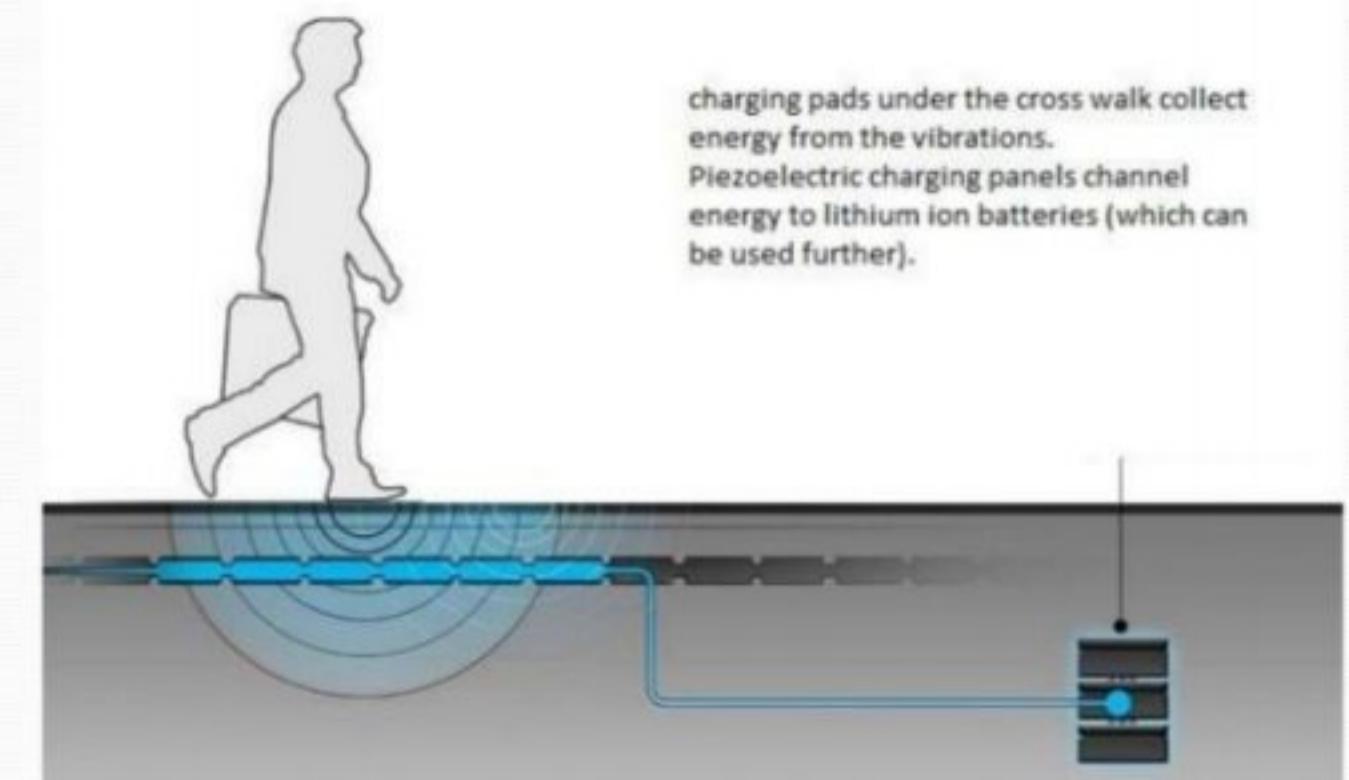
Deformation \rightarrow Charge and Voltage

(b) Transverse (d_{31}) sensor and actuator

Energy Harvesting

- Sidewalks
- Shoes
- Gyms and Work Places
- Piezoelectric Tiles, Floor mats and Carpets
- Mobile Keypads and Keyboards

POWER GENERATING SIDEWALK



Other Applications

1. As sensing elements

Detection of pressure variations in the form of sound is the most common sensor application, e.g. piezoelectric microphones. Sound waves bend the piezoelectric material, creating a changing voltage.

2. Ultrasound imaging

Piezoelectric sensors are used with high frequency sound in ultrasonic transducers for medical imaging . For many sensing techniques, the sensor can act as both a sensor and an actuator. Ultrasonic transducers, for example, can inject ultrasound waves into the body, receive the returned wave, and convert it to an electrical signal (a voltage).

3. Sonar sensors

Piezoelectric elements are also used in the detection and generation of sonar waves. Applications include power monitoring in high power applications such as medical treatment, sonochemistry and industrial processing etc.

4. As chemical and biological sensors

Piezoelectric microbalances are used as very sensitive chemical and biological sensors. Piezo are also used as strain gauges.

5. In Music instruments

Piezoelectric transducers are used in electronic drum pads to detect the impact of the drummer's sticks.

6. Automotive application

Automotive engine management systems use a piezoelectric transducer to detect detonation by sampling the vibrations of the engine block. Ultrasonic piezosensors are used in the detection of acoustic emissions in acoustic emission testing.

7. Piezoresistive silicon devices

The Piezoresistive effect of semiconductors has been used for sensor devices employing all kinds of semiconductor materials such as germanium, polycrystalline silicon, amorphous silicon, and single crystal silicon. Since silicon is today the material of choice for integrated digital and analog circuits the use of Piezoresistive silicon devices has been of great interest. It enables the easy integration of stress sensors with Bipolar and CMOS circuits.

8. Piezoresistors

Piezoresistors are resistors made from a Piezoresistive material and are usually used for measurement of mechanical stress. They are the simplest form of Piezoresistive device.

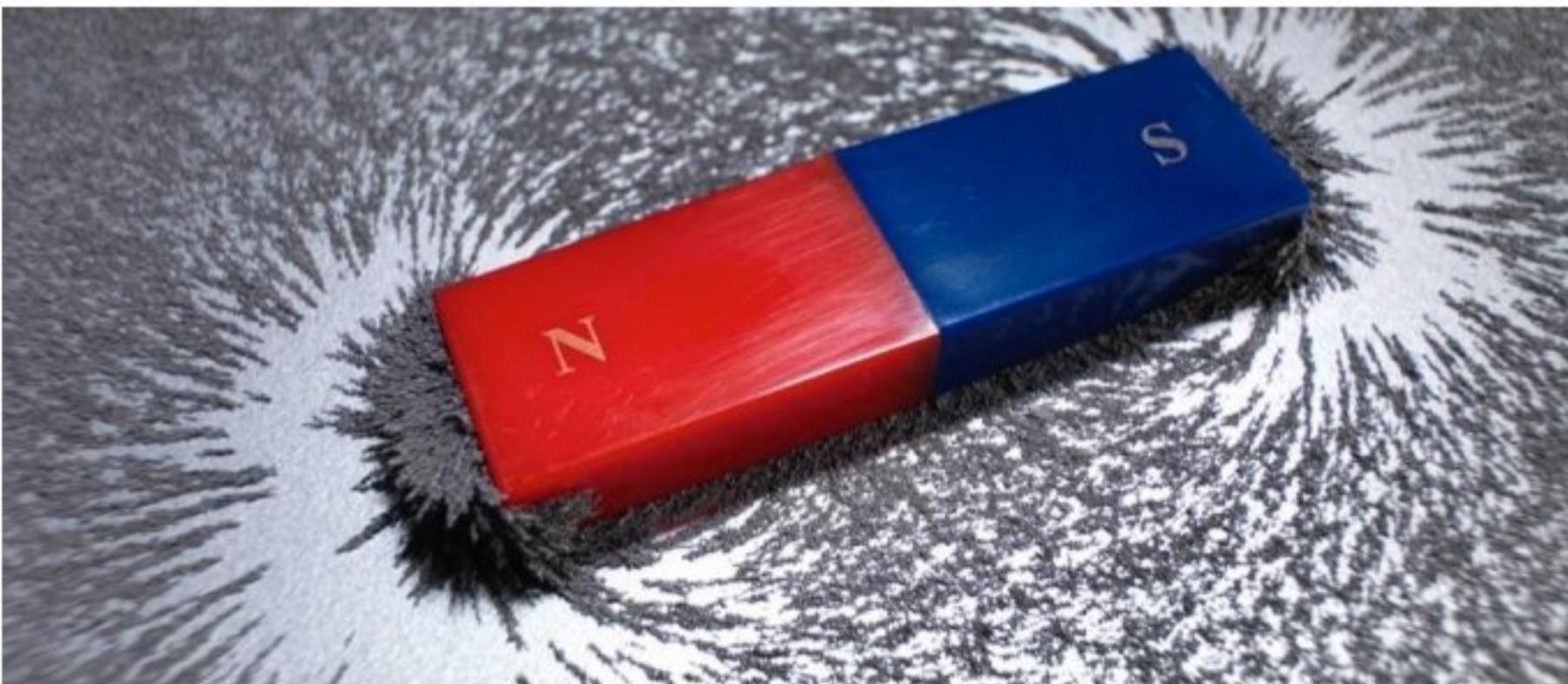
Application of a Pyroelectric-Infrared detection

Refer to the link : <https://www.doitpoms.ac.uk/tplib/pyroelectricity/infrared.php>

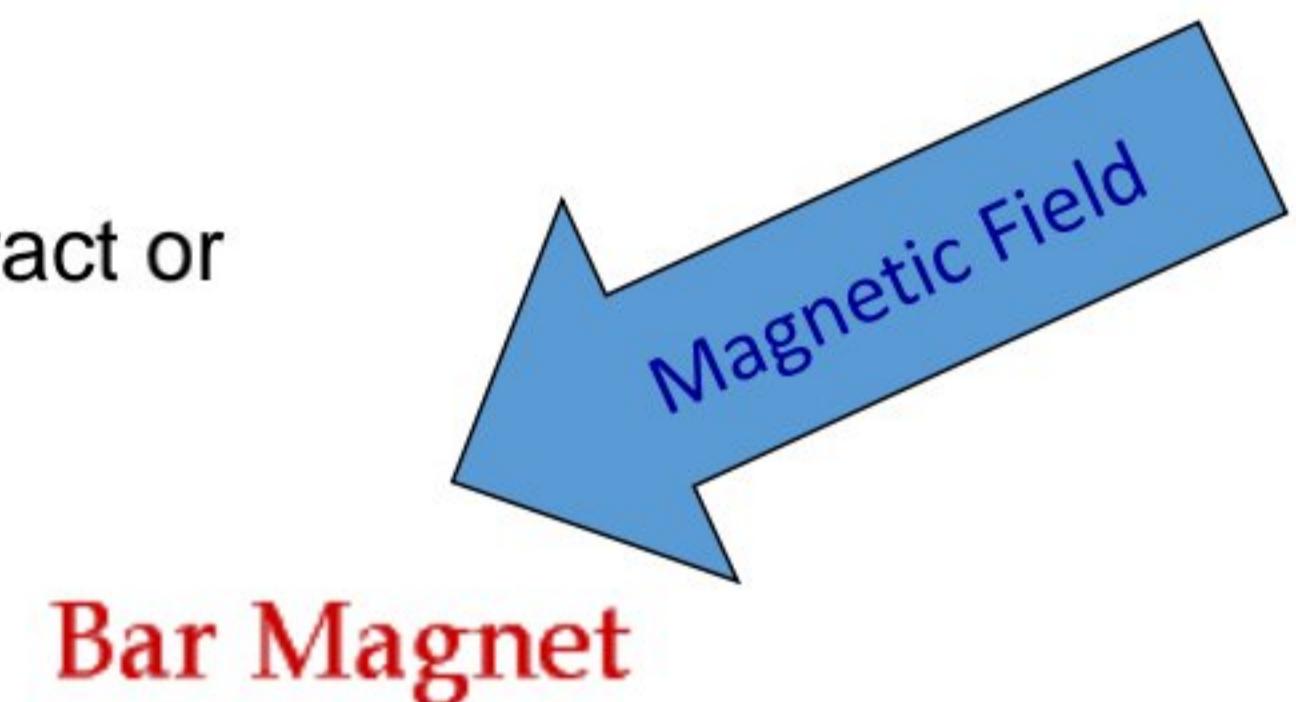
Pollutant Control

Refer to the link: <https://www.doitpoms.ac.uk/tplib/pyroelectricity/pollution.php>

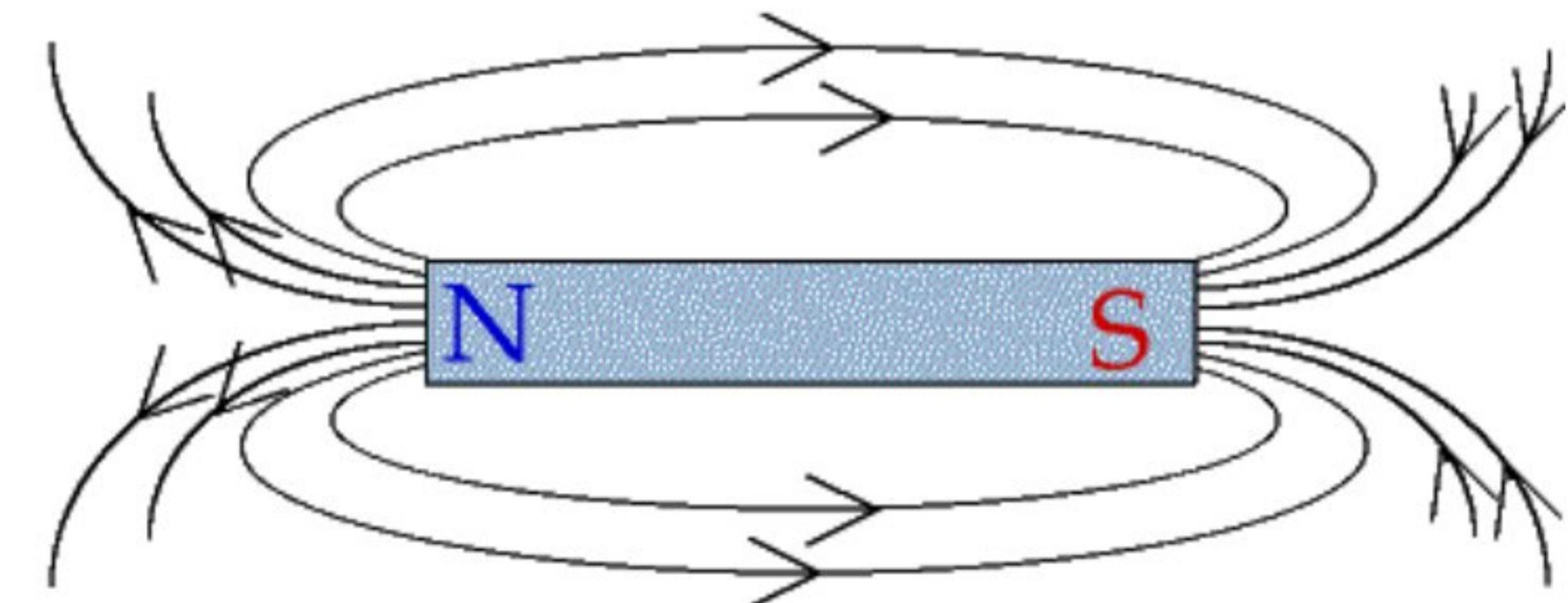
Magnetism



- The earliest experiences with magnetism involved **magnetite**, the only material that occurs naturally in a magnetic state.
- This mineral was also known as **lodestone**, after its property of aligning itself in certain directions if allowed to rotate freely, thus being able to indicate the positions of north and south, and to some extent also latitude.
"course stone" or "leading stone"
- The other well-known property of lodestone is that two pieces of it can attract or even repel each other



Magnetic Dipoles



Cutting a bar magnet in half produces TWO bar magnets, each with N and S poles.

Day to day applications

Many of our modern technological devices rely on magnetism and magnetic materials; these include **electrical power generators and transformers, electric motors, radio, television, telephones, computers, and components of sound and video reproduction systems**



Loud Speaker



Printer



Medical Equipment



Magnetic Levitation



Motor



Sensor



Mobile Cover



Gift Box Packing



Magnetic Toy



Car holder



Wind Turbine



VCM

Origin of Magnetism

Macroscopic
(*Charge currents*)

Microscopic
(*Atomic scale*)

- If a loop of area A is carrying a current I, the **intrinsic intensity of the magnetic field** is given by the magnetic moment vector (**m** or **μ**) directed from the north pole to the south pole; such that the magnitude of **m** is given by: $m = IA$ (units: [Am^2]).
- The magnetic moment is the **measure of the strength of the magnet** and is the ability to *produce (and be affected by)* a magnetic field.

Important quantities in magnetism

- **Magnetic Moment Vector (m or μ).** $|\mathbf{m}| = IA$, Units: [Am^2] or equivalently [Joule/Tesla].

Measure of the strength of the magnet.

- **Magnetic field strength/Magnetizing force (H).** Units: [A/m]

Measure of the strength of the externally applied field.

Magnetic induction, or **Magnetic flux density**, denoted by B , represents the magnitude of the internal field strength within a substance that is subjected to an H field.

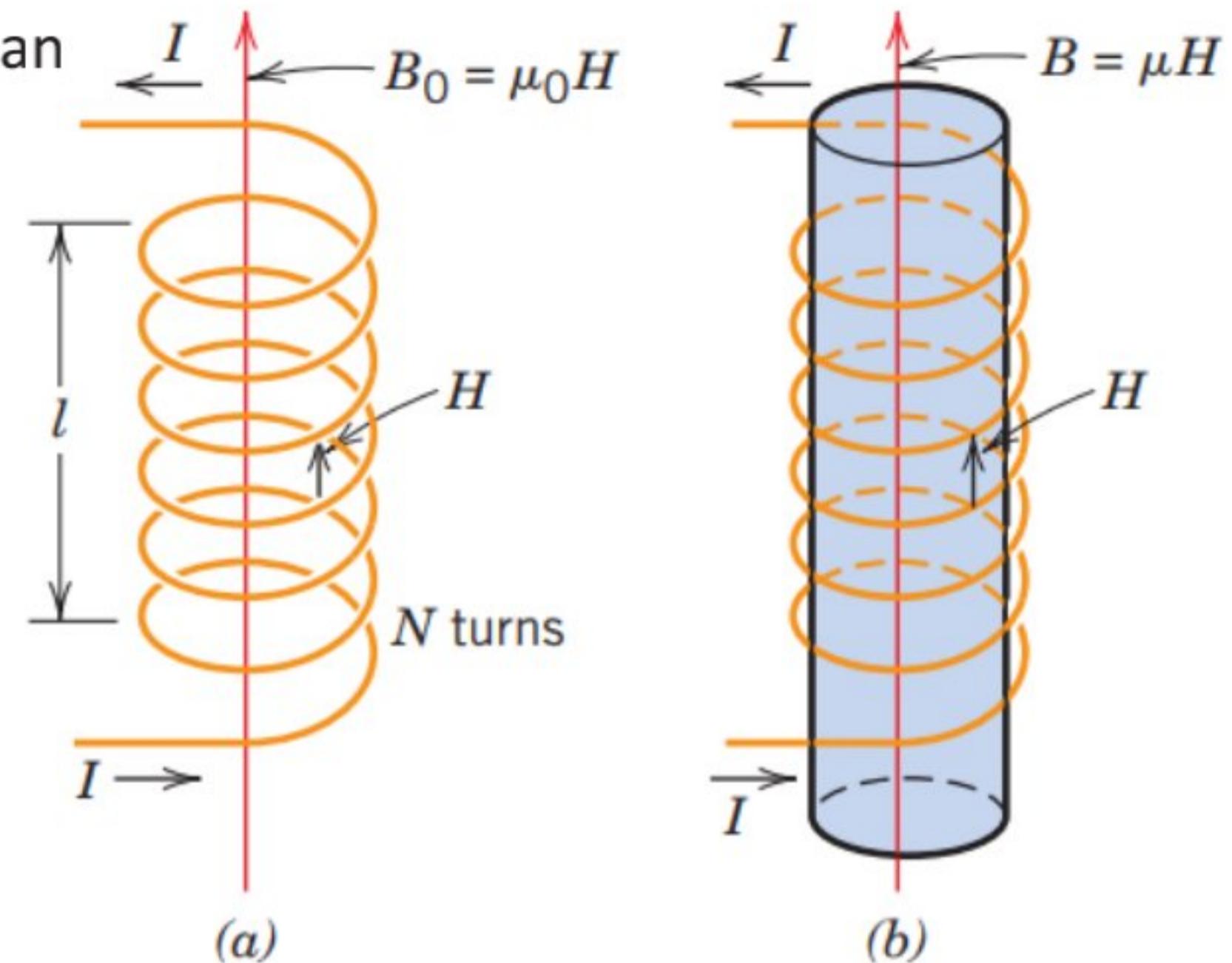
$$B = \mu H$$

M , called the **magnetization** of the solid

$$B = \mu_0 H + \mu_0 M$$

In the presence of an H field, the magnetic moments within a material tend to become aligned with the field and to reinforce it by virtue of their magnetic fields; is given by the term $\mu_0 M$

B and **H** are analogous to **D** and **E** discussed in Ferroelectrics



Quantity	Symbol
Magnetic induction (flux density)	B
Magnetic field strength	H
Magnetization	M (SI) I (cgs-emu)
Permeability of a vacuum	μ_0
Relative permeability	μ_r (SI) μ' (cgs-emu)
Susceptibility	χ_m (SI) χ'_m (cgs-emu)

- Magnetization (**M**) = magnetic moment (**m**) per unit volume (**V**). Units: [A/m]

$$M = \frac{m}{V}$$

M measures the materials response to the applied field **H** (of course we know from our experience with permanent magnets that **M** can exist even if **H** is removed). **M** is the magnetization induced by the applied external field **H**.

➤ **σ** = magnetic moment per unit mass = m/mass. Units: [Am²/kg]

- Magnetic induction/Magnetic flux density (**B**) = Magnetic flux per unit area. Units: [Tesla = Weber/m² = Vs/m² = Kg/s²/A]

B is the magnetic flux density inside the material.

➤ **B** = $\mu_0 (\mathbf{H} + \mathbf{M})$ (μ_0 is the magnetic permeability of vacuum
 $= H/m = Wb/A/m = mKg/s^2 A^2$)

- **Permeability (μ)**. Units: [dimensionless]

$$\mu = \frac{\mathbf{B}}{\mathbf{H}}$$

- **Magnetic susceptibility (χ)**. (volume susceptibility) Units: [dimensionless]

$\chi = \frac{\mathbf{M}}{\mathbf{H}}$ (the symbol χ_v is also used to emphasize that the quantity is per unit volume).

- **Magnetic anisotropy**

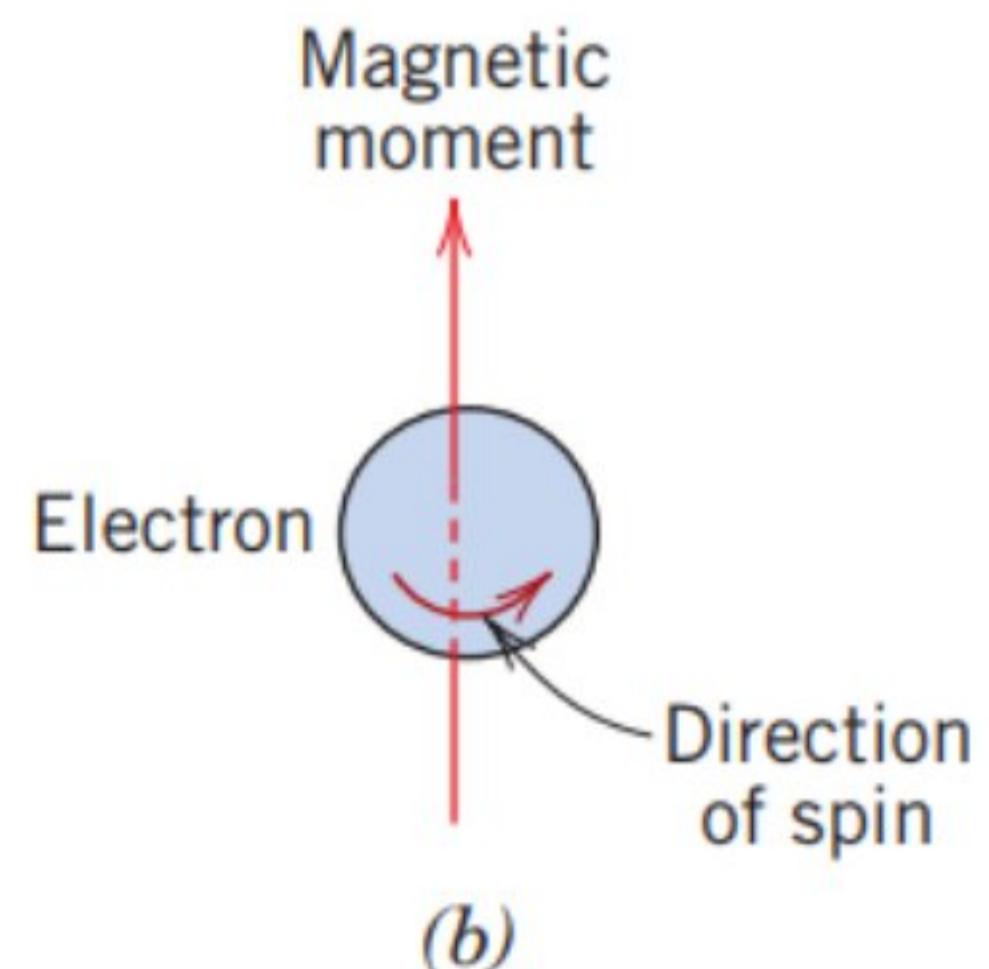
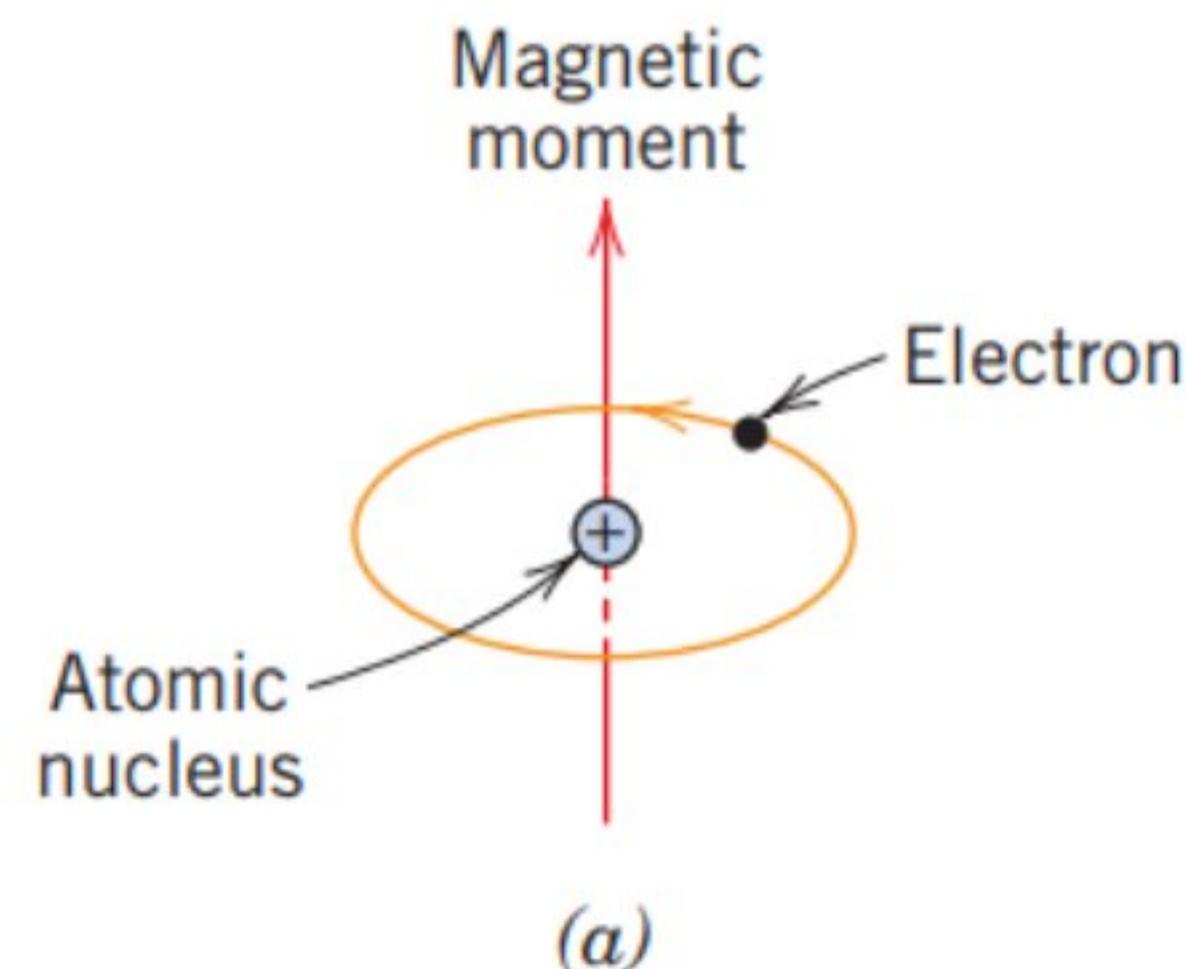
Anisotropy means that various directions in the crystals are non-equivalent with respect magnetization (\mathbf{M}) and this implies that \mathbf{M} may not be in the same direction of the applied field. There are many contributions to this anisotropy as we shall see later, crystalline (magneto-crystalline) anisotropy being the prominent one.

Origin of Magnetic Moments

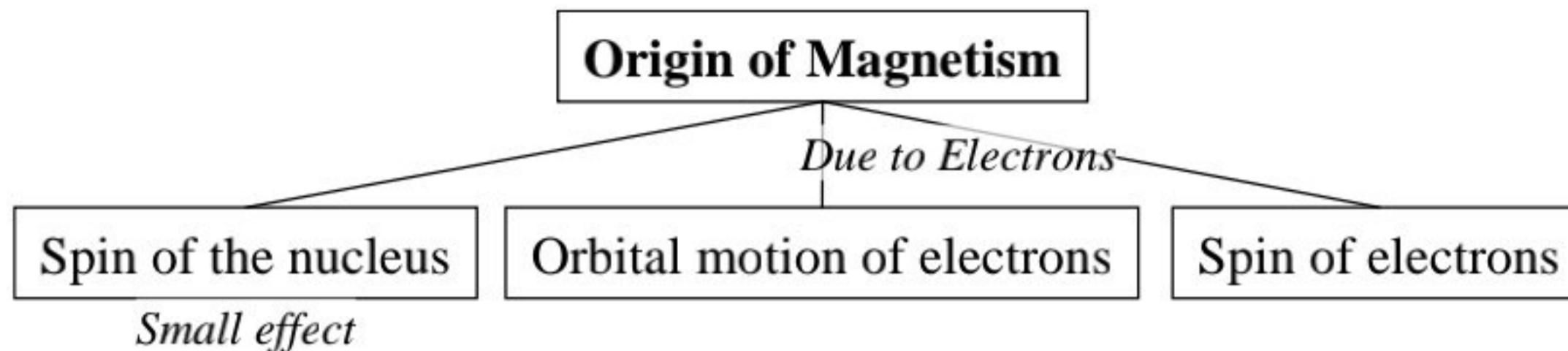
- In each individual atom, orbital moments of some electron pairs cancel each other; this also holds for the spin moments.
- For an atom having completely filled electron shells or subshells, when all electrons are considered, there is total cancellation of both orbital and spin moments.
- Thus materials composed of atoms having completely filled electron shells are not capable of being permanently magnetized. This category includes the inert gases (He, Ne, Ar, etc.) as well as some ionic materials.

Most free atoms possess net angular momentum and therefore have magnetic moments, but when atoms combine to form molecules or solids, the electrons interact so that the resultant angular momentum is nearly always zero.

Exceptions are atoms of the elements of the three transition series which, because of their incomplete inner electron shells, have a resultant magnetic moment.



Atomic origin of magnetic moments



This is classical way of looking at a quantum effect !

- i) Nuclear spin (which is slow and has a small contribution to the overall magnetic effect)

Note: at very low temperatures magnetism due to nuclear spin may become important

- ii) Spin of electrons
- iii) Orbital motion of electrons around the nucleus

The magnetic moment due to spin is equal to the magnetic moment due to orbital motion (in the first Bohr orbit) and is approximately expressed in terms of the **Bohr magneton** (μ_B):

$$m_B = \mu_B = \frac{e\hbar}{4\pi m} = 9.27 \times 10^{-24} \text{ Am}^2$$

Magnetic Moment of a Single Unpaired Atomic Electron

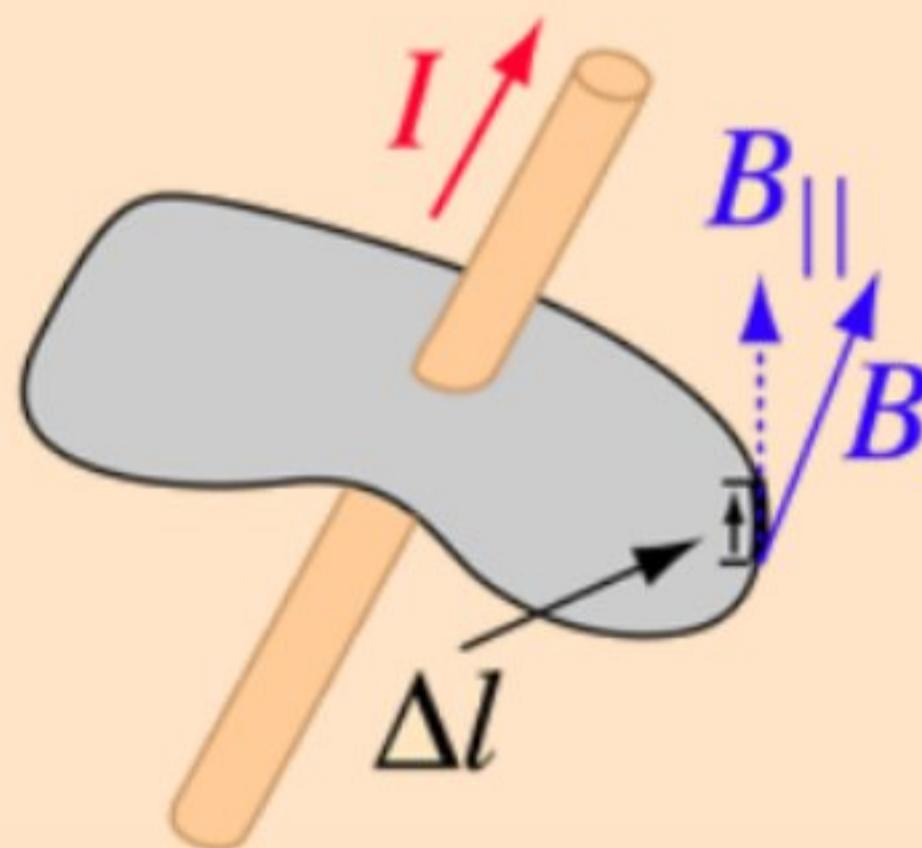
Each electron spinning on its own axis behaves as a magnetic dipole and has a dipole moment called the **Bohr magneton** μ_B . This dipole moment has a value of

$$\mu_B = \frac{e\hbar}{4\pi m}$$

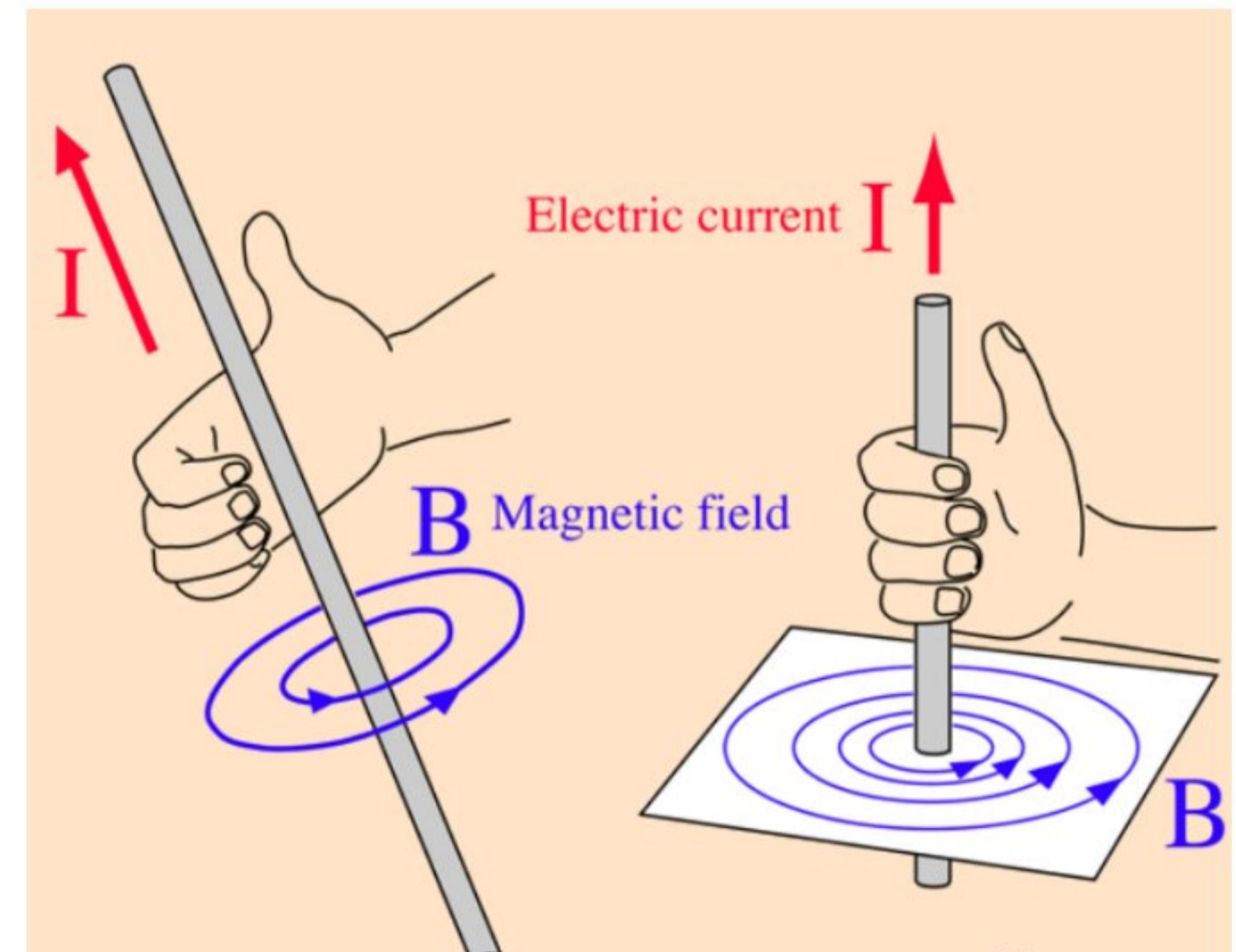
where e = electronic charge, h = Planck's constant, and m = electron mass. In SI units, $\mu_B = 9.27 \times 10^{-24} \text{ A} \cdot \text{m}^2$. In most cases, electrons in atoms are paired, and so the positive and negative magnetic moments cancel. However, unpaired electrons in inner electron shells can have small positive dipole moments, as is the case for the $3d$ electrons of Fe, Co, and Ni.

Ampere's Law

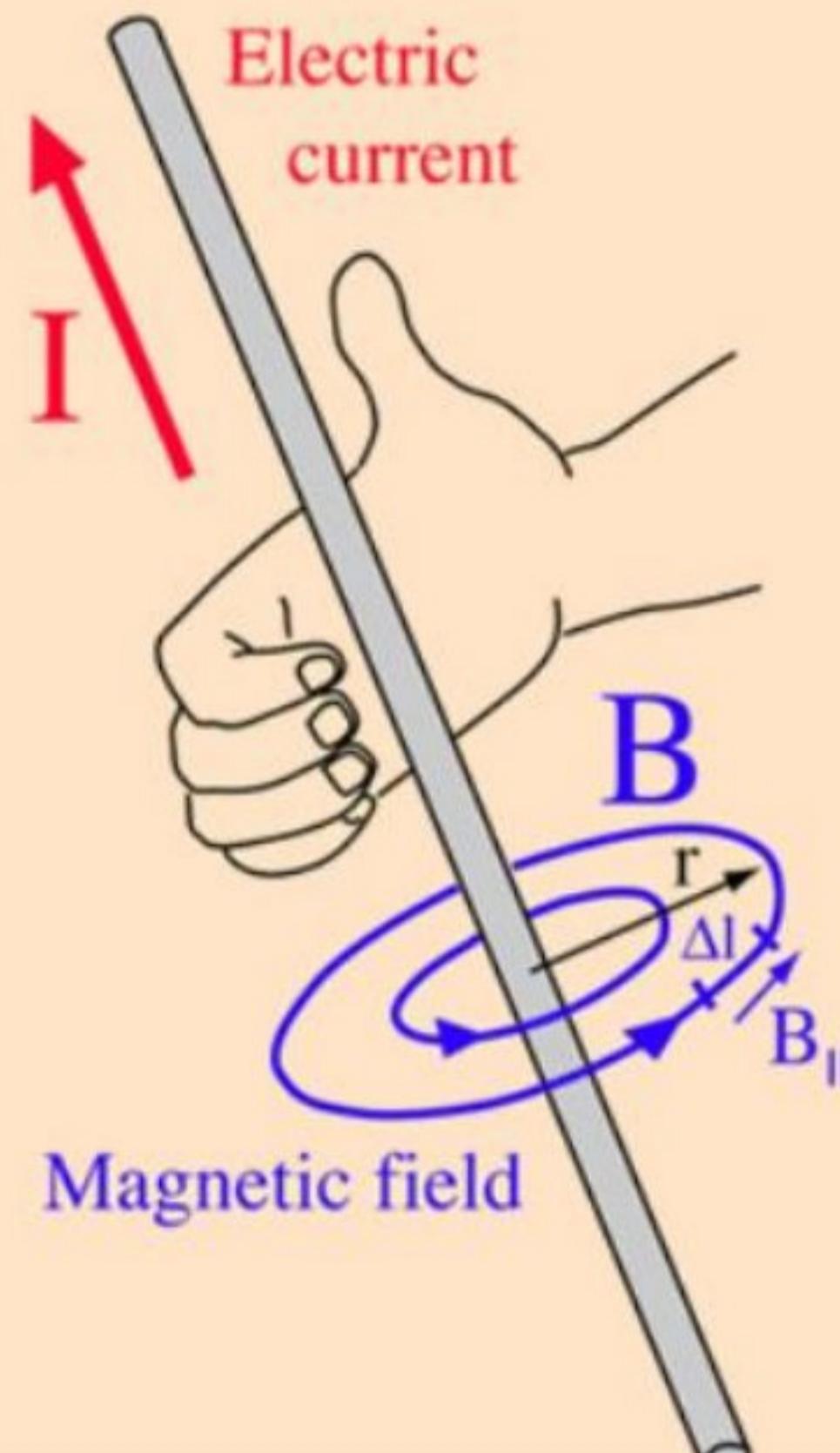
The magnetic field in space around an electric current is proportional to the electric current which serves as its source, just as the electric field in space is proportional to the charge which serves as its source. Ampere's Law states that for any closed loop path, the sum of the length elements times the magnetic field in the direction of the length element is equal to the permeability times the electric current enclosed in the loop.



$$\sum B_{||} \Delta l = \mu_0 I$$



Magnetic Field of Current



The magnetic field of an infinitely long straight wire can be obtained by applying Ampere's law. Ampere's law takes the form

$$\sum B_{||} \Delta l = \mu_0 I$$

and for a circular path centered on the wire, the magnetic field is everywhere parallel to the path. The summation then becomes just

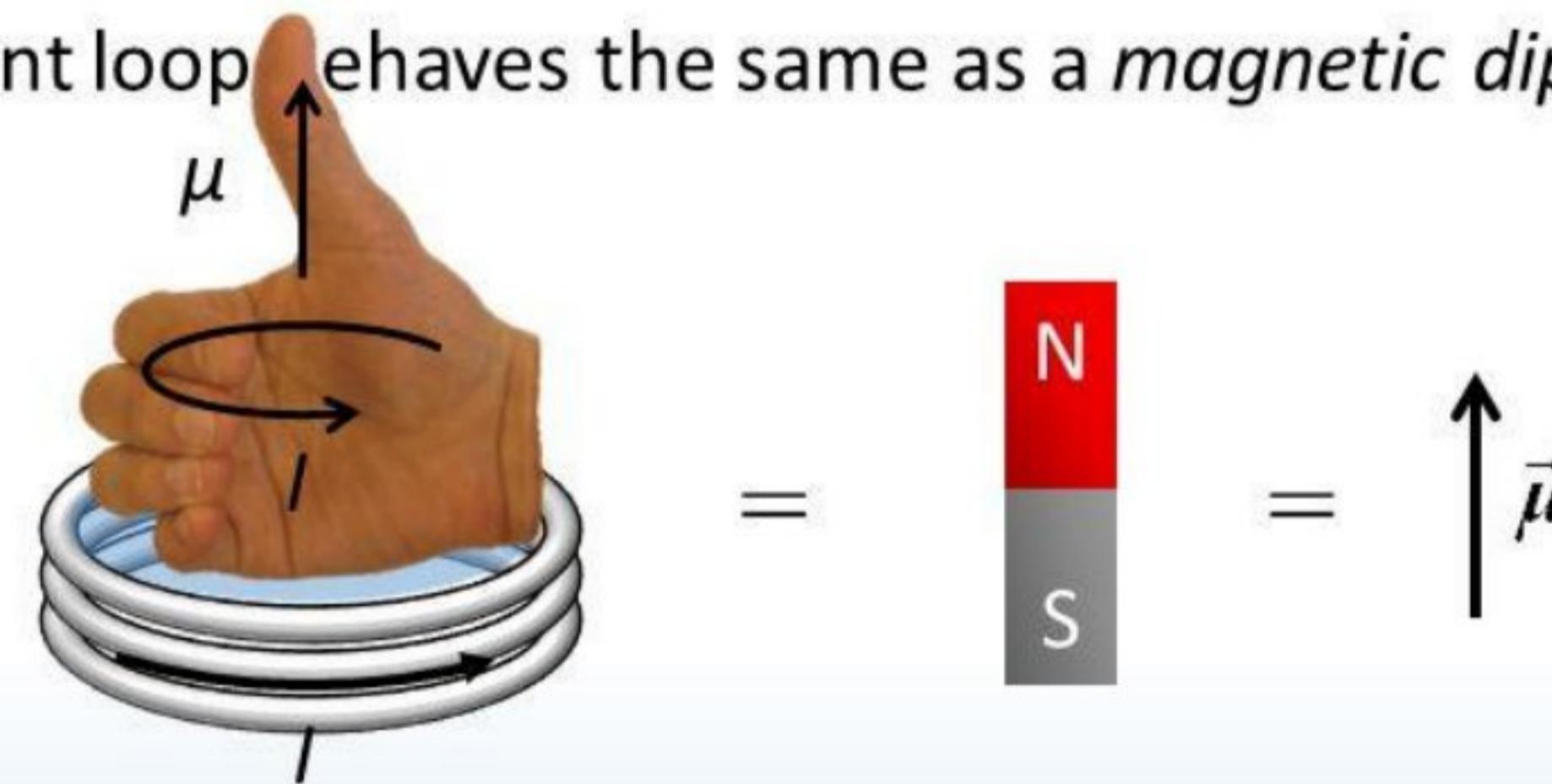
$$\sum B_{||} \Delta l = B 2\pi r$$

$$B = \frac{\mu_0 I}{2\pi r}$$

The constant μ_0 is the permeability of free space.

Magnetic dipole & current loop

A current loop behaves the same as a *magnetic dipole*



Equivalent magnetic dipole moment:

Magnitude
$$\mu = NIA \quad \text{True for flat loop of any shape}$$

For a loop with N turns of wire

Direction Another “right hand rule”: Curl fingers along I
Another “right hand rule”: Curl fingers along I
 $\vec{\mu}$ along thumb

Magnetic permeability (μ)

is the ability of a magnetic material **to support magnetic field development**. In other words, magnetic permeability is the constant in the proportionality between magnetic induction and magnetic field intensity.

The **greater the magnetic permeability of the material, the greater the conductivity for magnetic lines of force**, and vice versa.

The magnetic permeability of a material indicates the ease with which an external magnetic field can create a higher magnetic force of attraction in the material.

$$B = \mu H$$

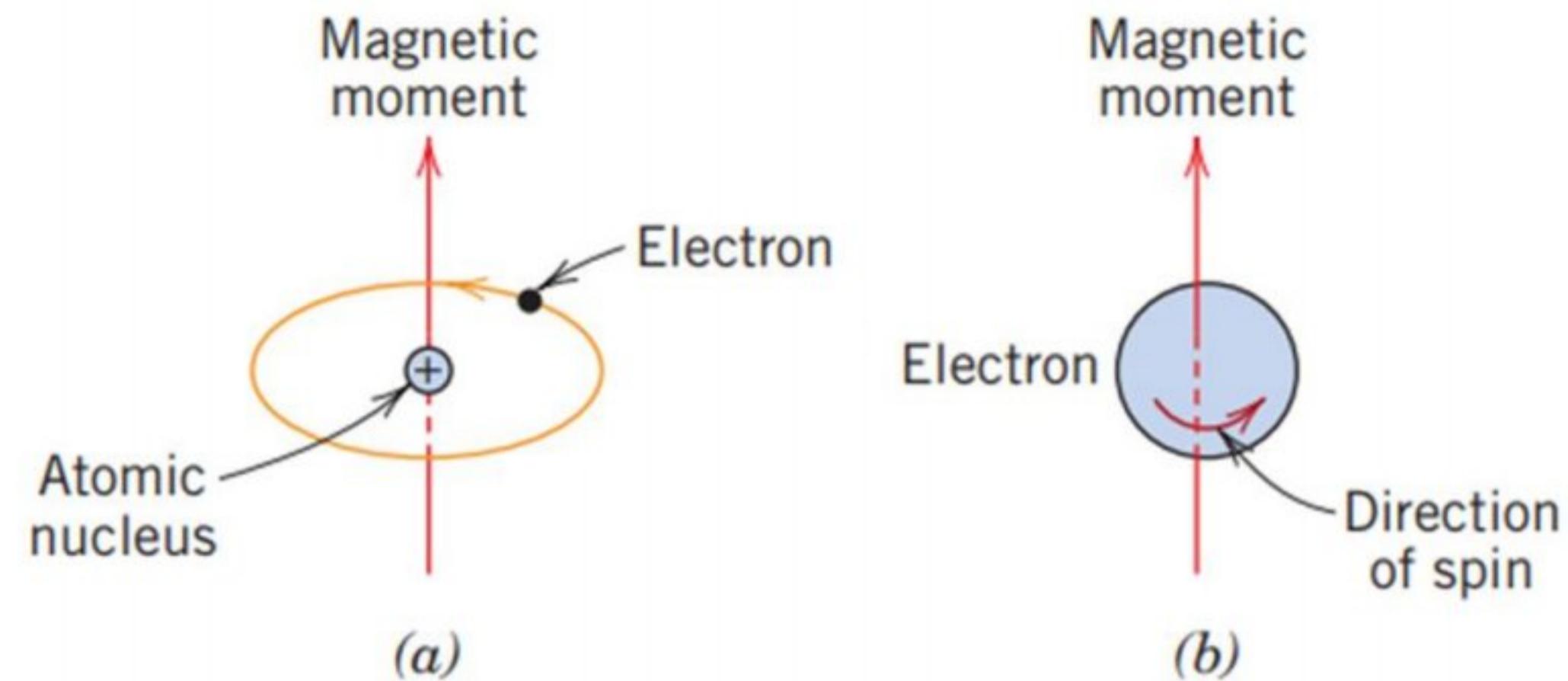
Magnetic susceptibility (χ)

is a measure of **how much a material will become magnetized in an applied magnetic field**. It is the ratio of magnetization M (magnetic moment per unit volume) to the applied magnetizing field intensity H .

$$\chi_m = \frac{M}{H}$$

The Bohr magneton μ_B

is a physical constant and the natural unit for expressing the magnetic moment of an electron caused by either its orbital or spin angular momentum.



Value of Bohr Magneton

$$\mu_B = \frac{e\hbar}{2m} = 9.27 \times 10^{-21}$$

Diamagnetism

- An external magnetic field acting on the atoms of a material slightly unbalances their orbiting electrons and creates small magnetic dipoles within the atoms that oppose the applied field.
- This action produces a negative magnetic effect known as **diamagnetism**.
- The diamagnetic effect produces a very small negative magnetic susceptibility on the order of $\chi_m \approx -10^{-6}$.
- Diamagnetism occurs in all materials, but in many its negative magnetic effect is canceled by positive magnetic effects.
- Diamagnetic behavior has no significant engineering importance.

Paramagnetism

- Materials that exhibit a small positive magnetic susceptibility in the presence of a magnetic field.
- The paramagnetic effect in materials disappears when the applied magnetic field is removed.
- Paramagnetism is produced by the alignment of individual magnetic dipole moments of atoms or molecules in an applied magnetic field.
- Since thermal agitation randomizes the directions of the magnetic dipoles, an increase in temperature decreases the paramagnetic effect.
- The atoms of some transition and rare earth elements possess incompletely filled inner shells with unpaired electrons.
- These unpaired inner electrons in atoms, since they are not counterbalanced by other bonding electrons in solids, cause strong paramagnetic effects and in some cases produce very much stronger ferromagnetic and ferrimagnetic effects

DIAMAGNETISM AND PARAMAGNETISM

Non-Magnetic

Diamagnetism very weak, nonpermanent and persists only while an external field is being applied.

induced by a **change in the orbital motion of electrons due to an applied magnetic field**.

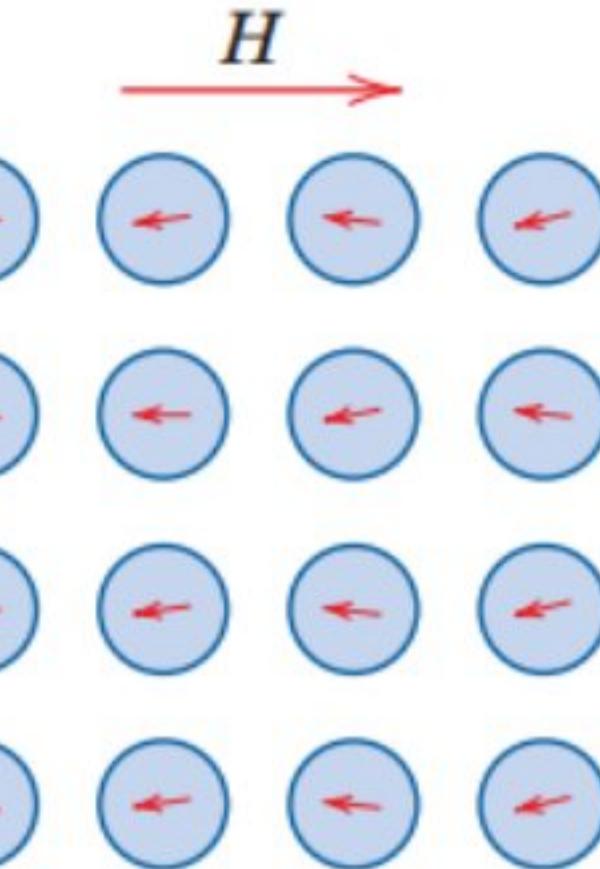
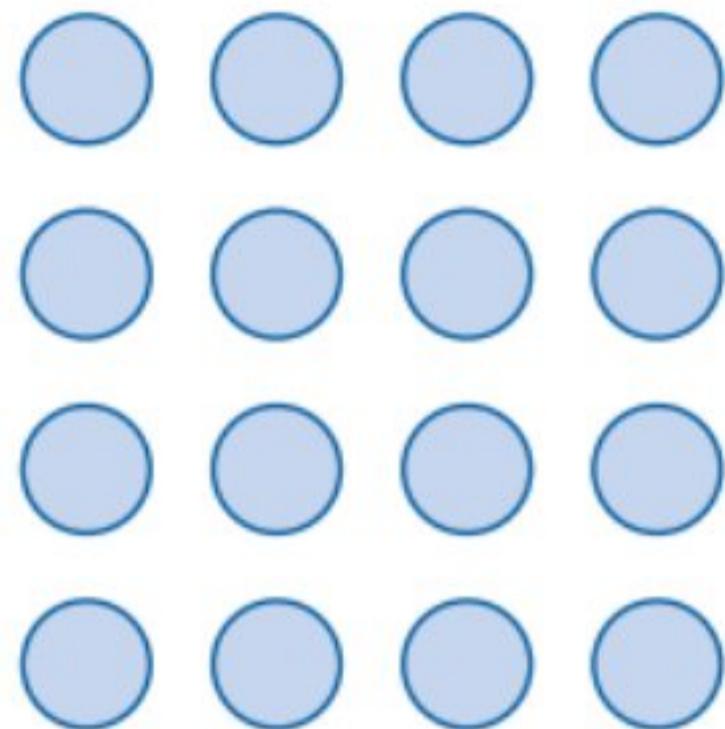
For some solid materials, each atom possesses a permanent dipole moment by virtue of incomplete cancellation of electron spin and/or orbital magnetic moments.

In the absence of an external magnetic field, the orientations of these atomic magnetic moments are random, such that a piece of material possesses no net macroscopic magnetization.

These atomic dipoles are free to rotate, and **paramagnetism** results when they preferentially align, by rotation, with an external field

Diamagnetism

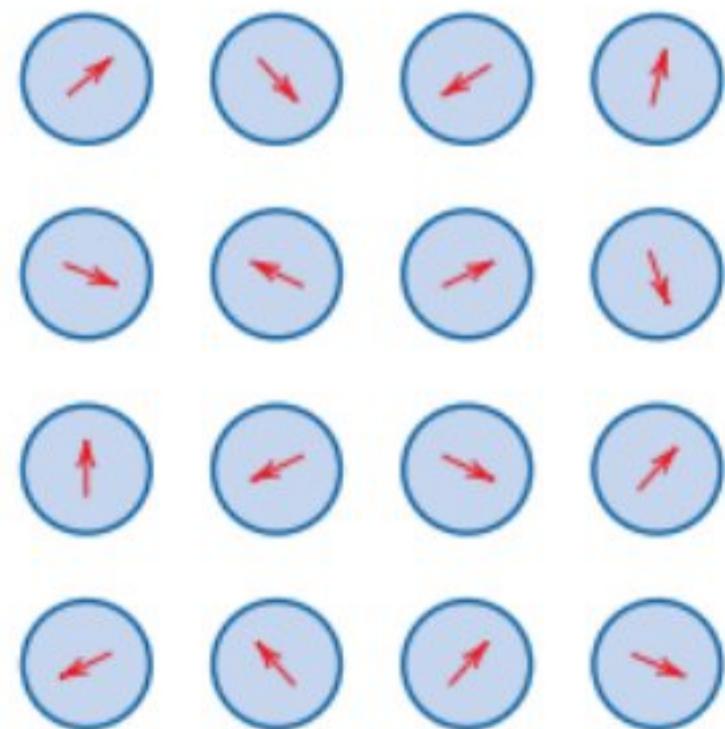
$$H = 0$$



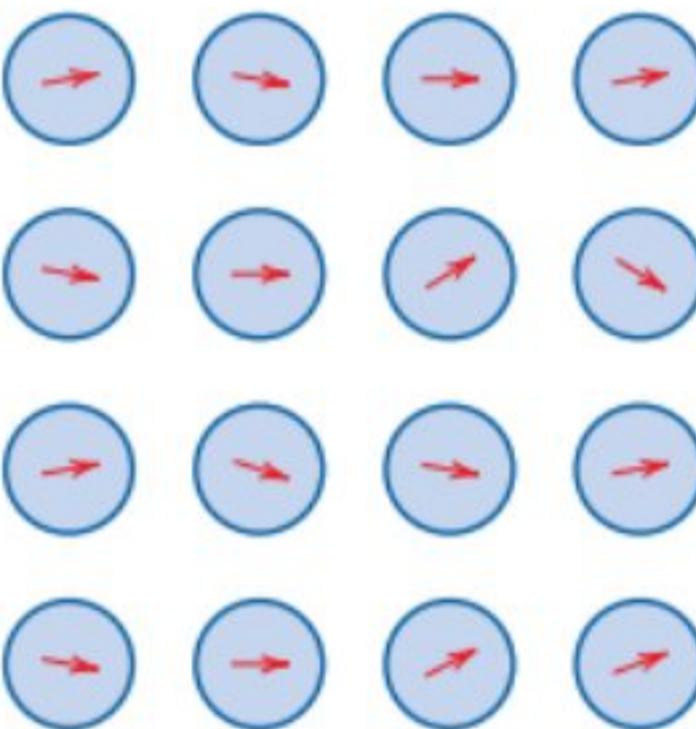
(a)

Paramagnetism

$$H = 0$$



$$H$$



(b)

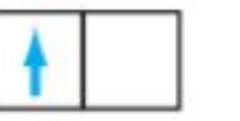
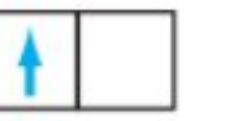
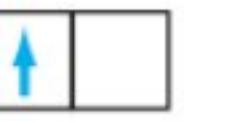
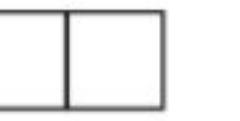
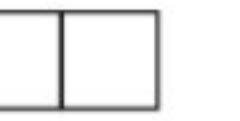
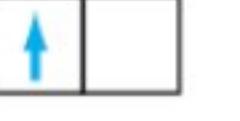
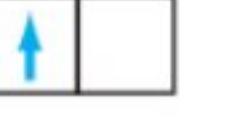
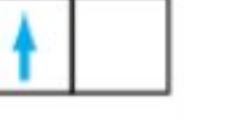
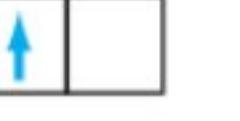
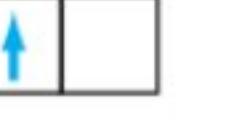
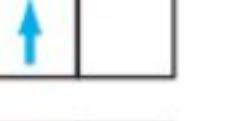
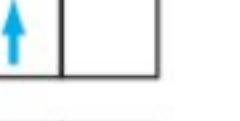
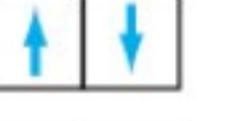
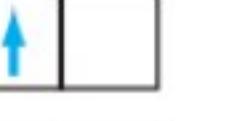
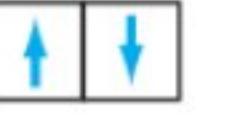
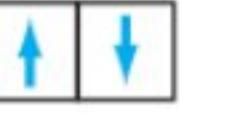
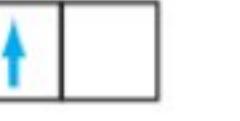
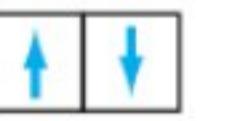
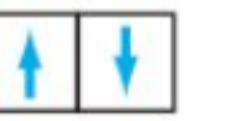
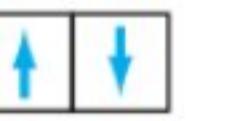
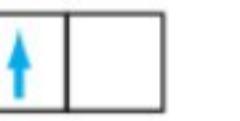
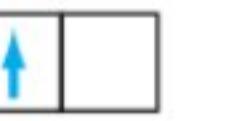
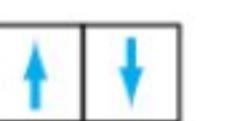
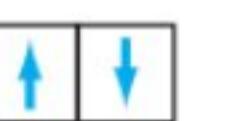
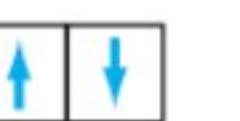
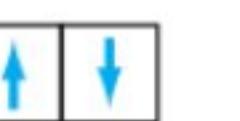
electron spin and/or orbital magnetic moments

Ferromagnetism

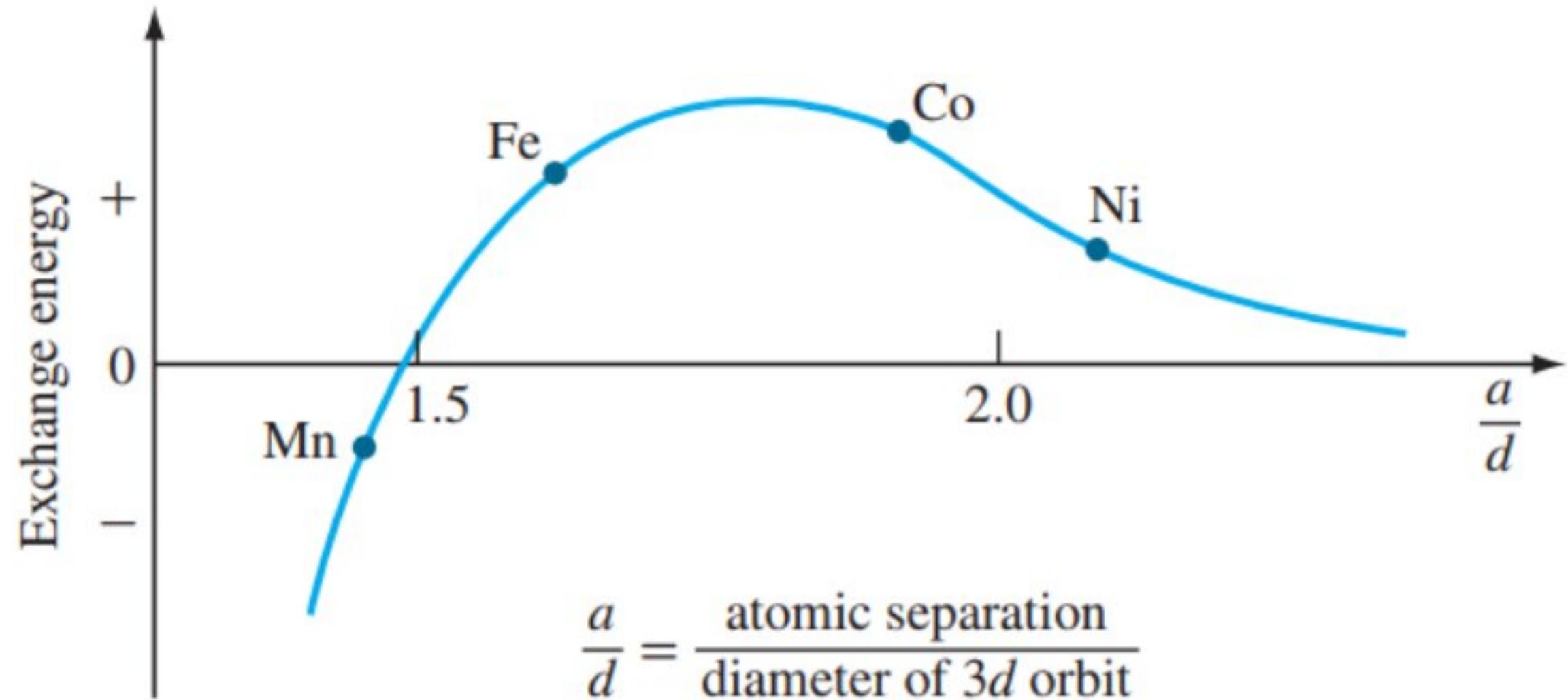
- **Ferromagnetism**, is of great engineering importance.
- Large magnetic fields that can be retained or eliminated as desired can be produced in ferromagnetic materials.
- The most important ferromagnetic elements from an industrial standpoint are iron (Fe), cobalt (Co), and nickel (Ni)
- Gadolinium (Gd), a rare earth element, is also ferromagnetic below 16°C but has little industrial application
- The ferromagnetic properties are due to the way the spins of the inner unpaired electrons are aligned in their crystal lattices.
- The inner shells of individual atoms are filled with pairs of electrons with opposed spins, and so they do not contribute to the resultant magnetic dipole moments.
- In solids, the outer valence electrons of atoms are combined with each other to form chemical bonds, and so there is no significant magnetic moment due to these electrons.

Unpaired 3d electrons	Atom	Number of electrons	Electronic configuration 3d orbitals					4s electrons
3	V	23						2
5	Cr	24						1
5	Mn	25						2
4	Fe	26						2
3	Co	27						2
2	Ni	28						2
0	Cu	29						1

In Fe, Co, and Ni, the unpaired inner 3d electrons are responsible for the ferromagnetism that these elements exhibit

Unpaired 3d electrons	Atom	Number of electrons	Electronic configuration 3d orbitals					4s electrons
3	V	23						2
5	Cr	24						1
5	Mn	25						2
4	Fe	26						2
3	Co	27						2
2	Ni	28						2
0	Cu	29						1

- In a solid sample of Fe, Co, or Ni at room temperature, the spins of the 3d electrons of adjacent atoms align in a parallel direction by a phenomenon called *spontaneous magnetization*. This parallel alignment of atomic magnetic dipoles occurs only in microscopic regions called **magnetic domains**.
- The parallel alignment of the magnetic dipoles of atoms of Fe, Co, and Ni is due to the creation of a positive exchange energy between them.
- For this parallel alignment to occur, the ratio of the atomic spacing to the diameter of the 3d orbit must be in the range from about 1.4 to 2.7. Thus Fe, Co, and Ni are ferromagnetic, but manganese (Mn) and chromium (Cr) are not.



Magnetic exchange interaction energy as a function of the ratio of atomic spacing to the diameter of the 3d orbit for some 3d transition elements. Those elements that have positive exchange energies are ferromagnetic; those with negative exchange energies are antiferromagnetic.

FERROMAGNETISM

Certain metallic materials possess a permanent magnetic moment in the absence of an external field, and manifest very large and permanent magnetizations.

These are the characteristics of **ferromagnetism**, and they are displayed by the transition metals iron (as BCC -ferrite), cobalt, nickel, and some of the rare earth metals such as gadolinium (Gd).

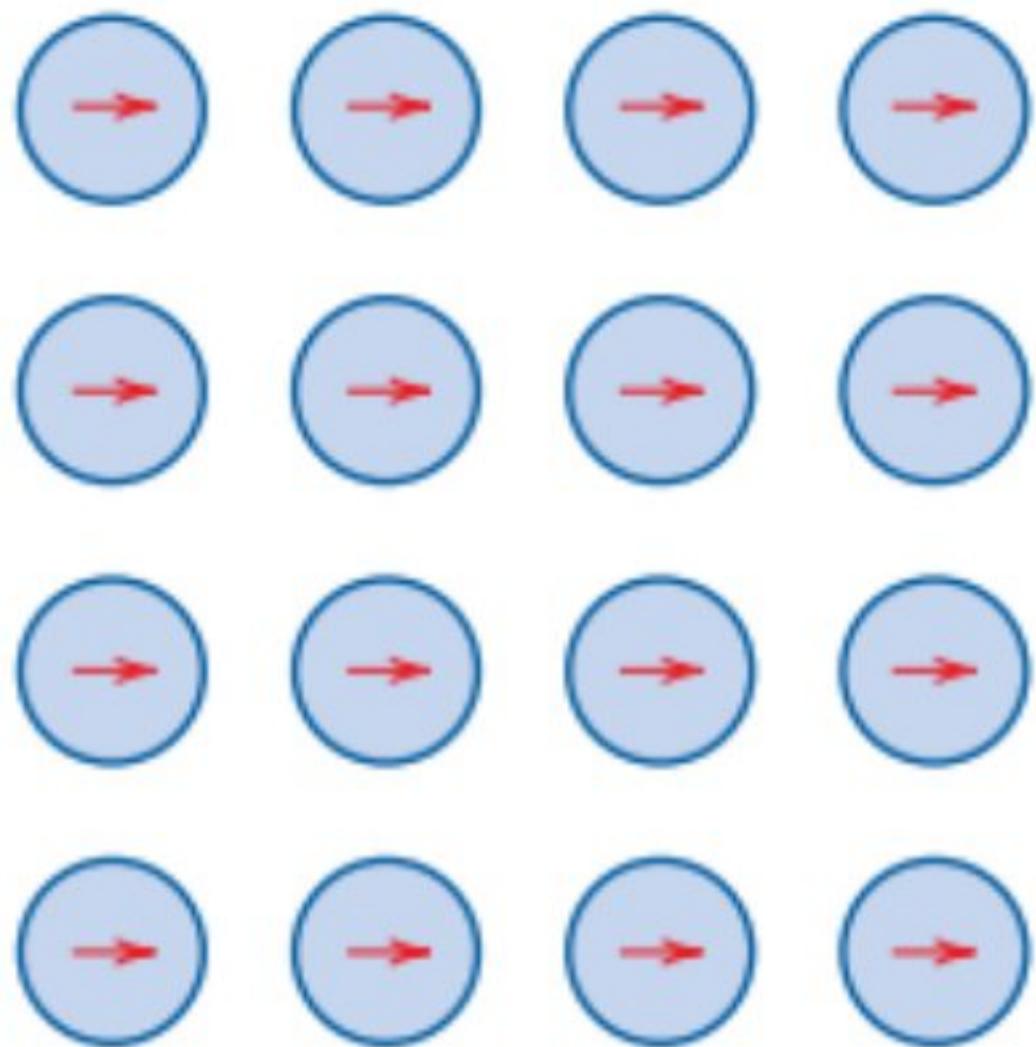
Due to uncancelled electron spins

Orbital magnetic moment contribution that is small in comparison to the spin moment

Coupling interactions cause net spin magnetic moments of adjacent atoms to align with one another, even in the absence of an external field

Mutual spin alignment exists over relatively large-volume regions of the crystal called **domains**

$$H = 0$$



Spin Coupling

ANTIFERROMAGNETISM

This phenomenon of magnetic moment coupling between adjacent atoms or ions occurs in materials other than those that are ferromagnetic.

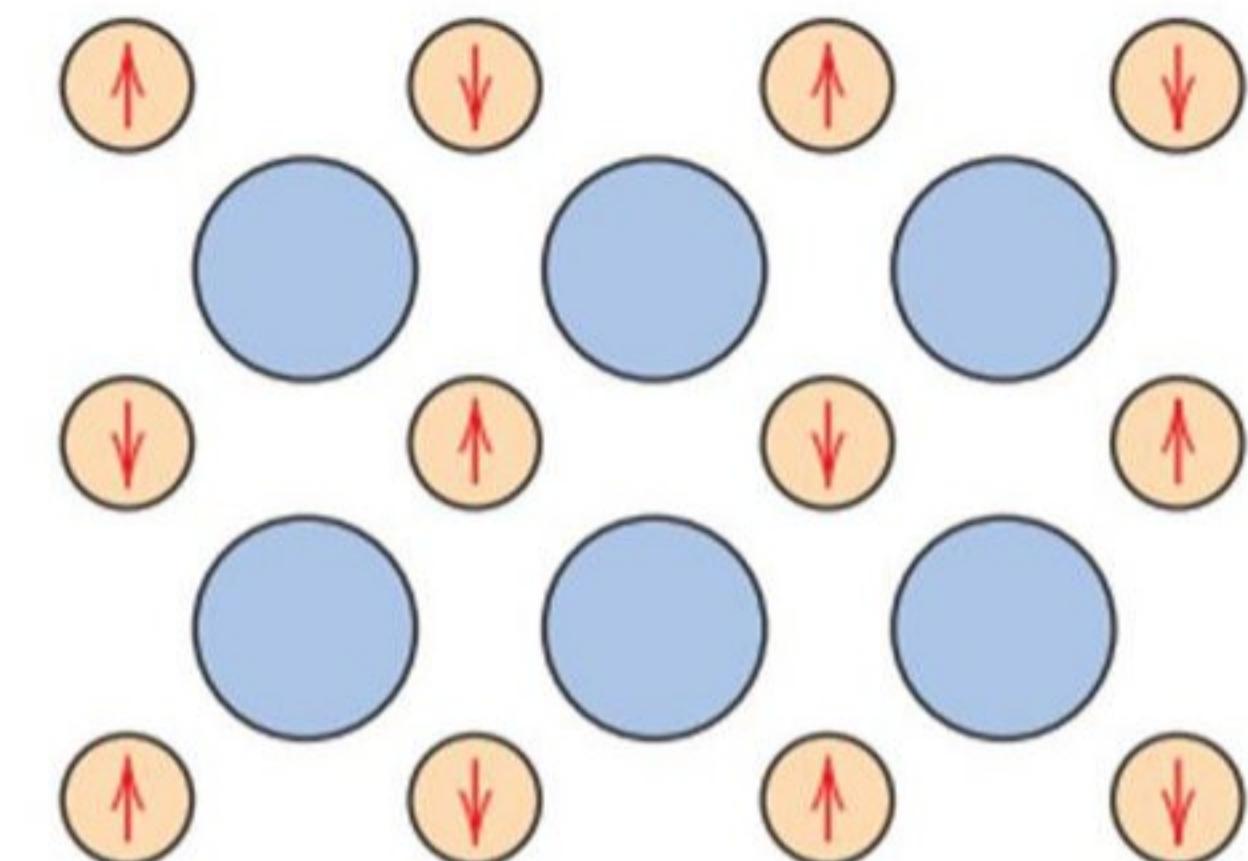
In one such group, this coupling results in an antiparallel alignment; the alignment of the spin moments of neighboring atoms or ions in exactly opposite directions is termed **antiferromagnetism**.

No net magnetic moment is associated with the O^{2-} ions, because there is a total cancellation of both spin and orbital moments.

Manganese oxide (MnO) is one material that displays this behavior. Manganese oxide is a ceramic material that is ionic in character, having both Mn^{2+} and O^{2-} ions.

No net magnetic moment is associated with the O^{2-} ions, because there is a total cancellation of both spin and orbital moments. However, the Mn^{2+} ions possess a net magnetic moment that is predominantly of spin origin.

These Mn^{2+} ions are arrayed in the crystal structure such that the moments of adjacent ions are antiparallel



**Antiferromagnetic
manganese oxide**

FERRIMAGNETISM

Some ceramics also exhibit a permanent magnetization, termed **ferrimagnetism**.

The macroscopic magnetic characteristics of ferromagnets and ferrimagnets are similar; the distinction lies in the source of the net magnetic moments.

However, the net ferromagnetic moment arises from the incomplete cancellation of spin moments

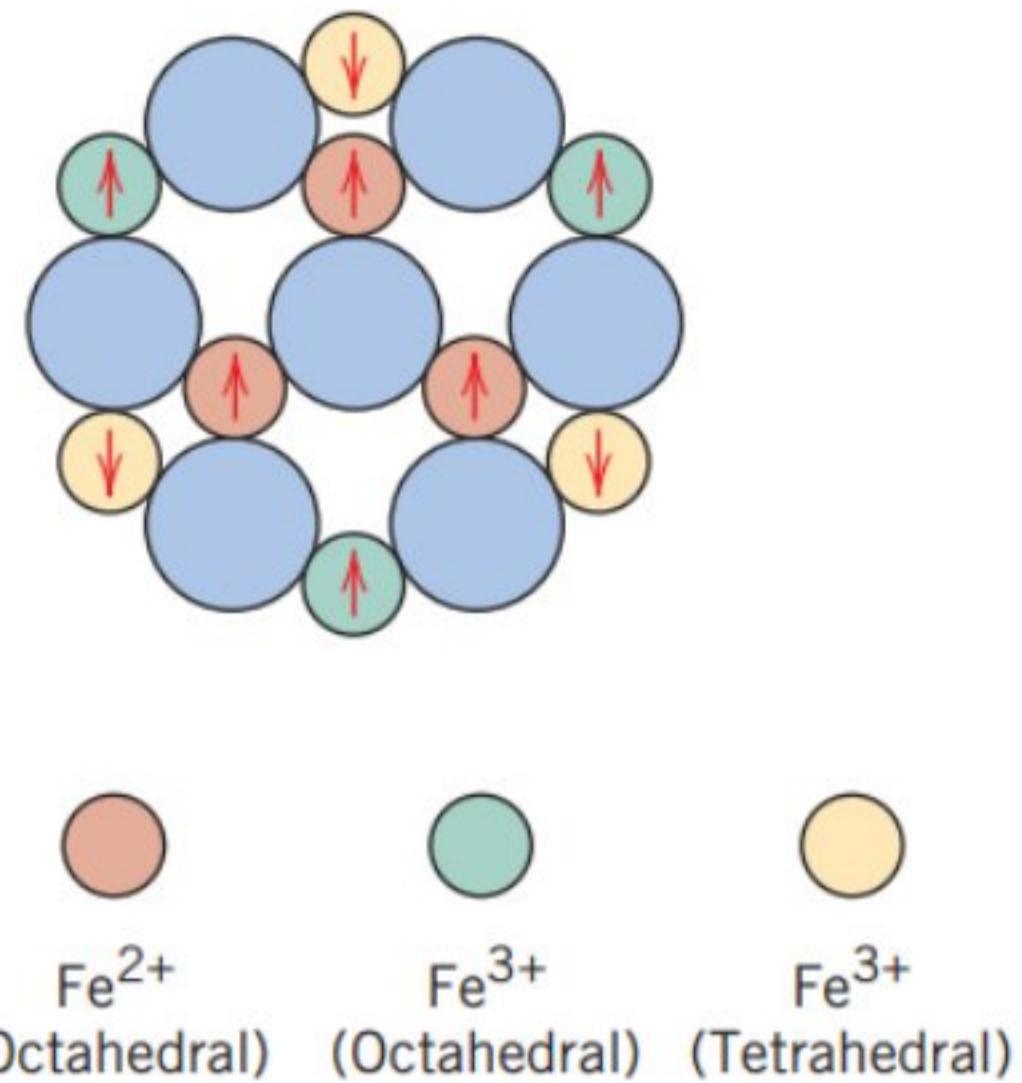
There are antiparallel **spin-coupling interactions** between the Fe ions, similar in character to antiferromagnetism.

The formula for Fe_3O_4 may be written as $\text{Fe}^{2+}\text{O}^{2-}-(\text{Fe}^{3+})_2(\text{O}^{2-})_3$, in which the Fe ions exist in both +2 and +3 valence states in the ratio of 1:2. A net spin magnetic moment exists for each Fe^{2+} and Fe^{3+} ion, which corresponds to 4 and 5 Bohr magnetons, respectively, for the two ion types.

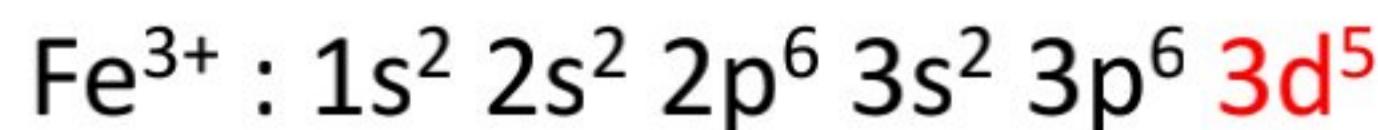
The spin moments of all the Fe^{3+} ions in the octahedral positions are aligned parallel to one another; however, they are directed oppositely to the Fe^{3+} ions disposed in the tetrahedral positions, which are also aligned.

This results from the antiparallel coupling of adjacent iron ions. Thus, the spin moments of all Fe^{3+} ions cancel one another and make no net contribution to the magnetization of the solid.

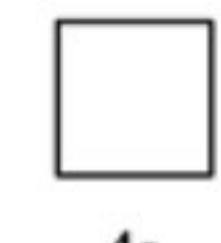
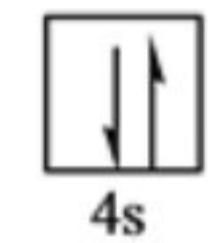
All the Fe^{2+} ions have their moments aligned in the same direction; this total moment is responsible for the net magnetization



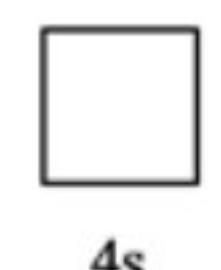
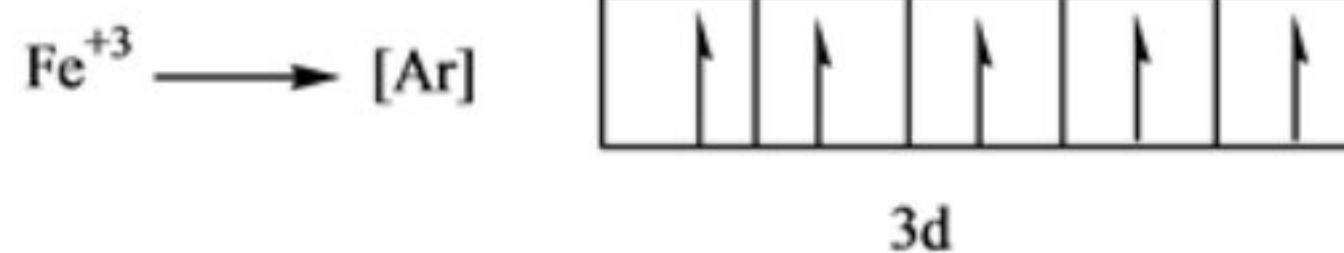
the net ferrimagnetic moment arises from the incomplete cancellation of spin moments.



This leaves 5 electrons that cannot all be paired off. It turns out that the magnetic moments arising from the orbital motion of these electrons do cancel out, but that the spin moments of all the electrons are parallel to one another. The ion therefore has a net magnetic moment.

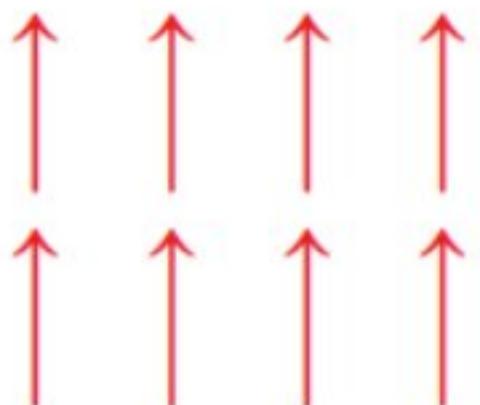
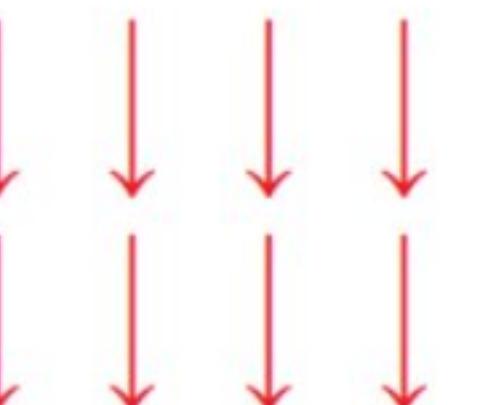
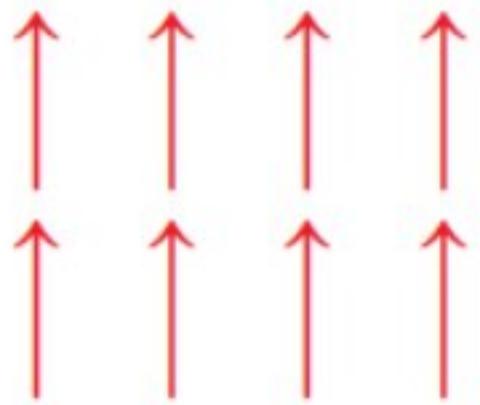
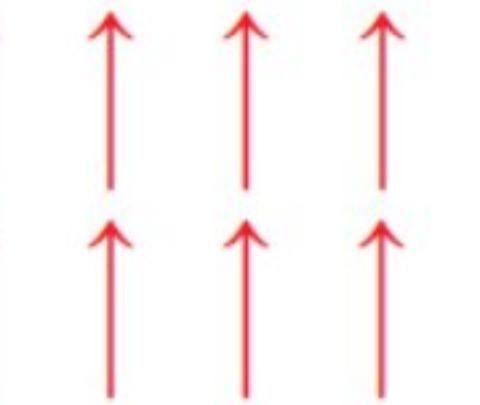


two electrons removed



three electrons removed

Order of Subshell filling							
1s	2	1s2	2s2	2p6	3s2	3p6	4s2
2s	2	2s	2p	6	3s	3p	10
3s	2	3s	3p	6	3d	10	3d10
4s	2	4s	4p	6	4d	10	4d10
5s	2	5s	5p	6	5d	10	5f14
6s	2	6s	6p	6	6d	10	6g
7s	2	7s	7p	6	7d	10	7?
8s	2	8s	8p	6	8d	10	8?
					8f	14	8g
							8?
							8?

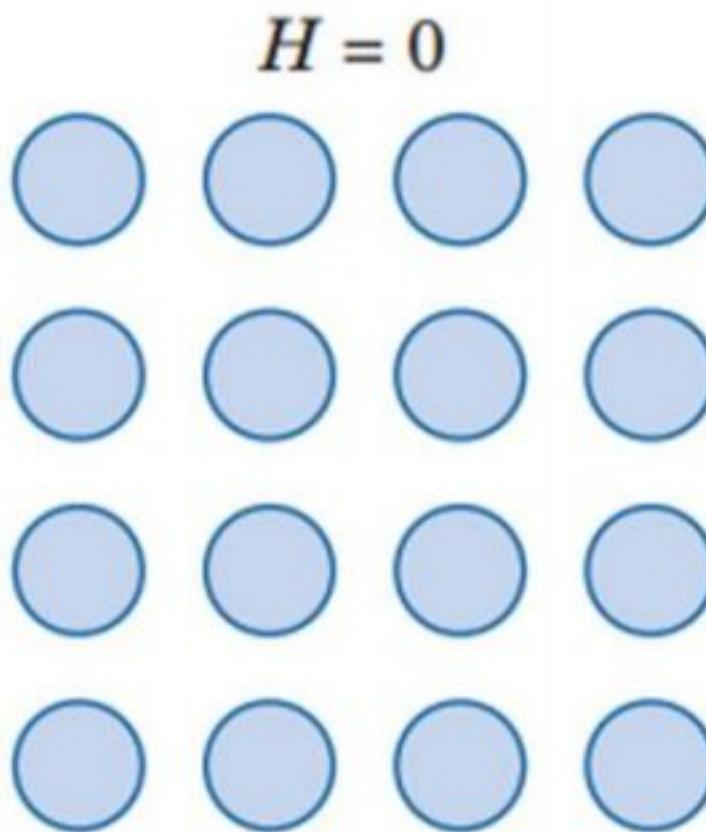
<i>Cation</i>	<i>Octahedral Lattice Site</i>	<i>Tetrahedral Lattice Site</i>	<i>Net Magnetic Moment</i>
Fe^{3+}			Complete cancellation
Fe^{2+}		—	

^a Each arrow represents the magnetic moment orientation for one of the

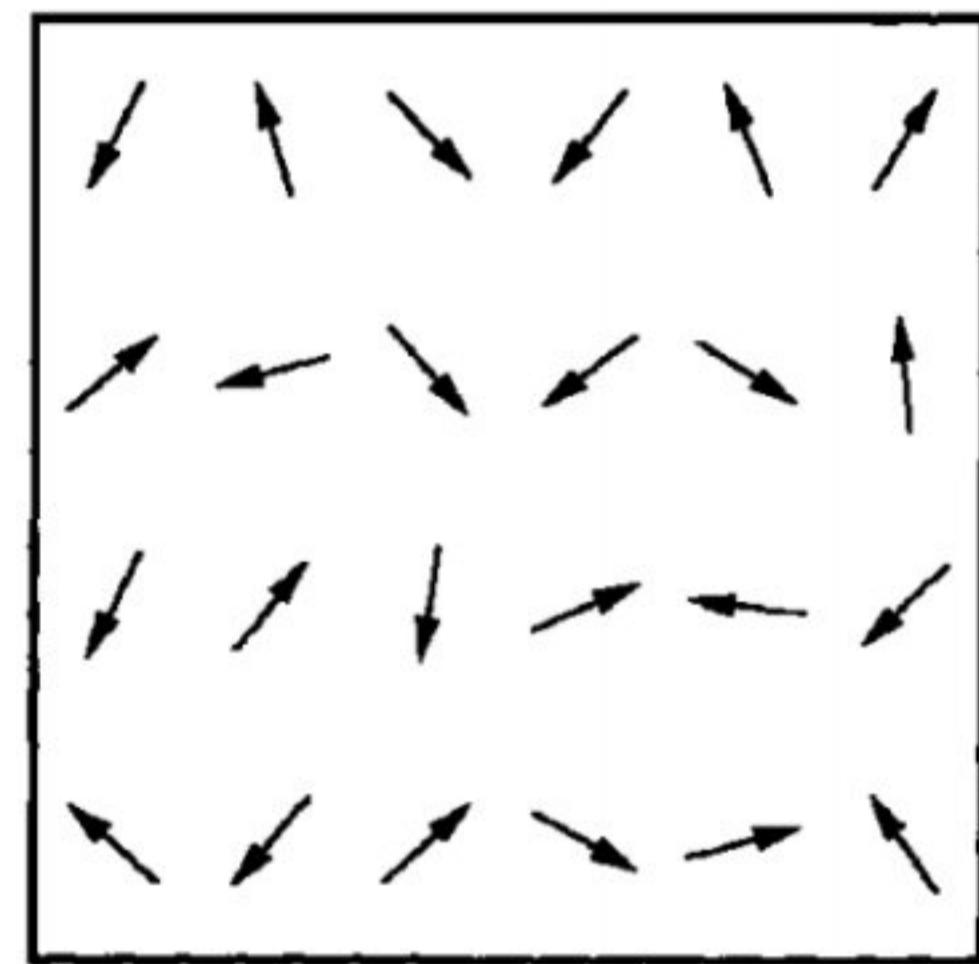
<i>Cation</i>	<i>Net Spin Magnetic Moment (Bohr magnetons)</i>
Fe^{3+}	5
Fe^{2+}	4
Mn^{2+}	5
Co^{2+}	3
Ni^{2+}	2
Cu^{2+}	1

Recap

Diamagnetic

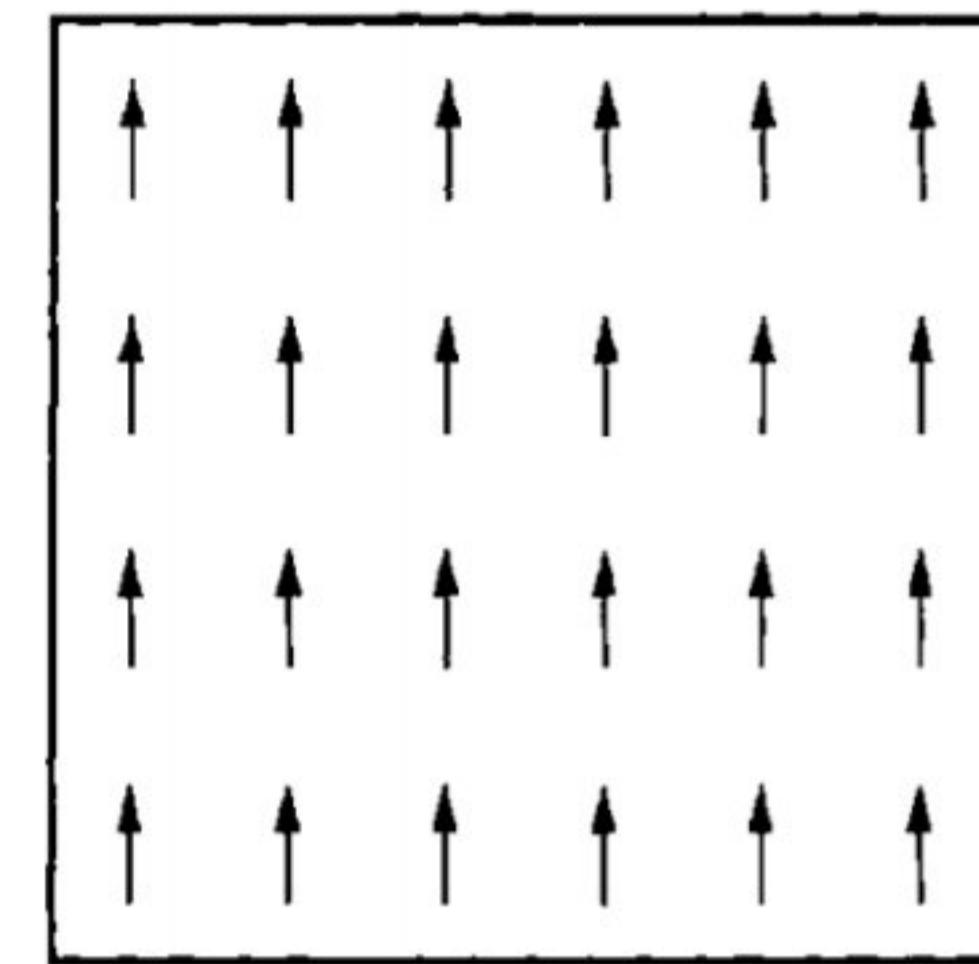


Paramagnetic



$H = 0$

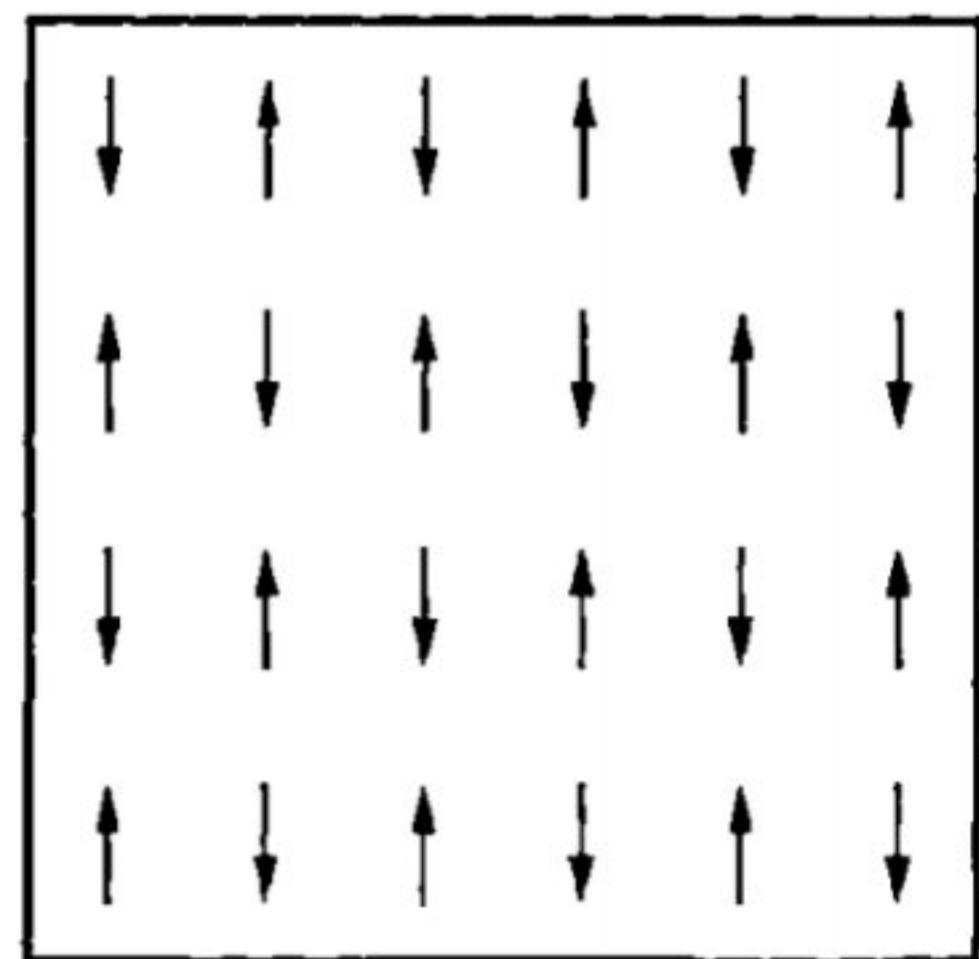
Ferromagnetic



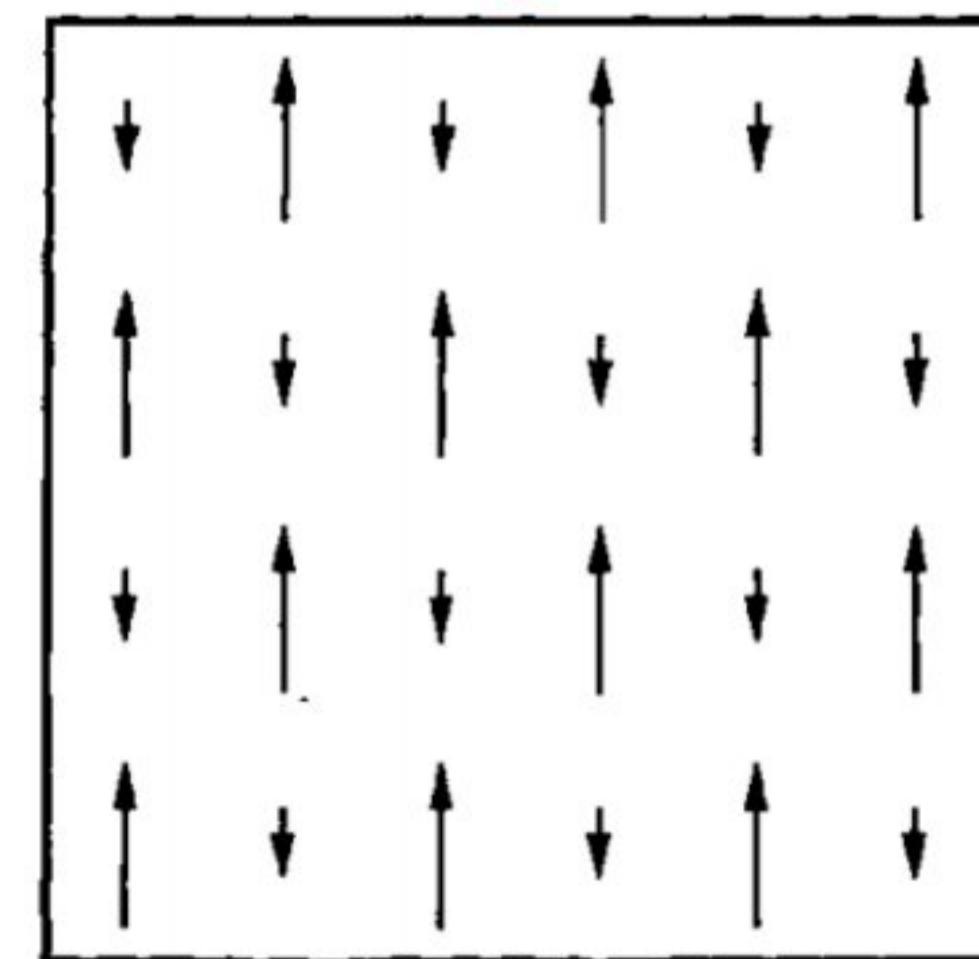
(a)

(b)

Antiferromagnetic



Ferrimagnetic



(No. or size in
one
direction
Is greater than
the other)

Domains in Magnetic Materials

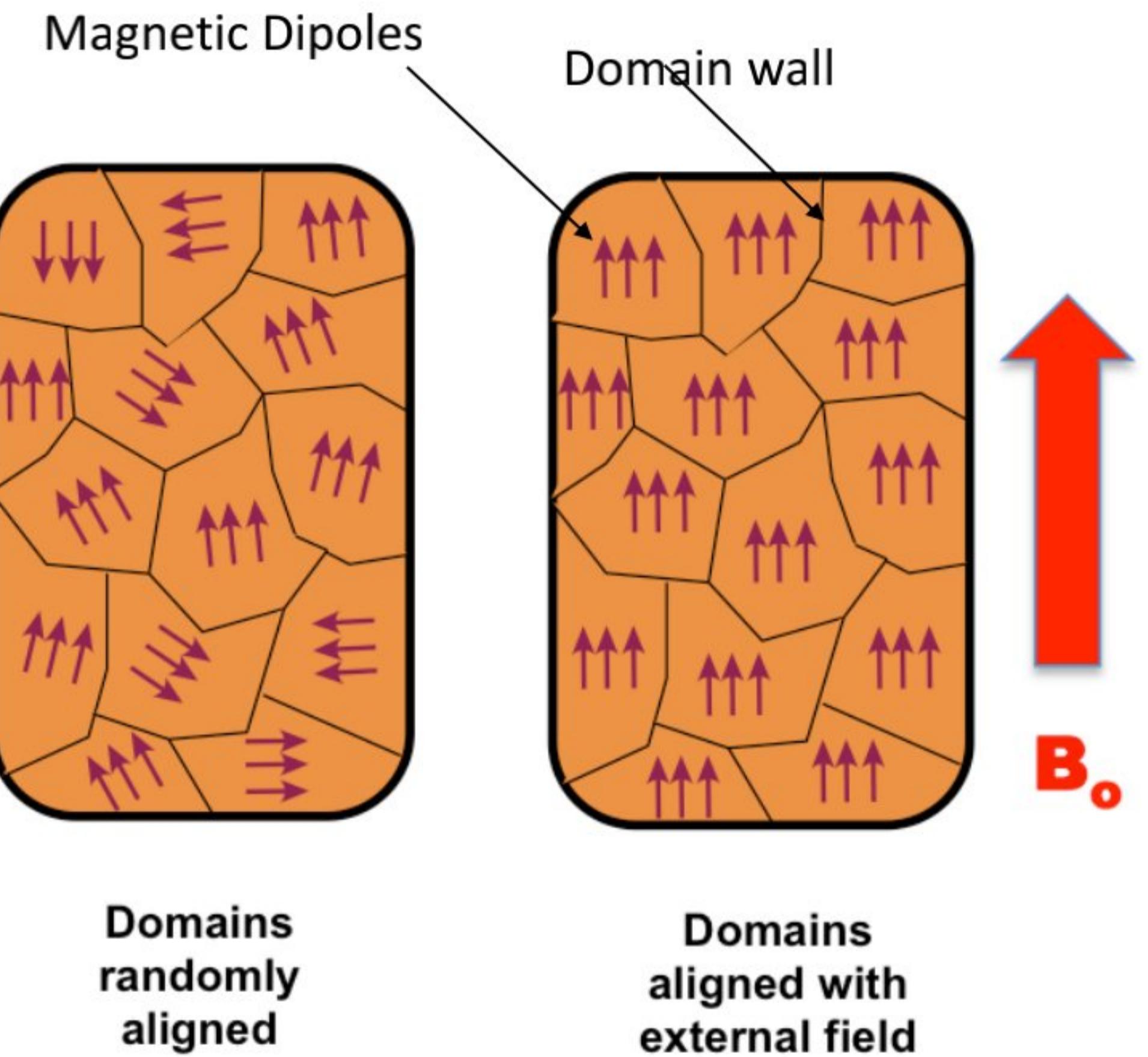
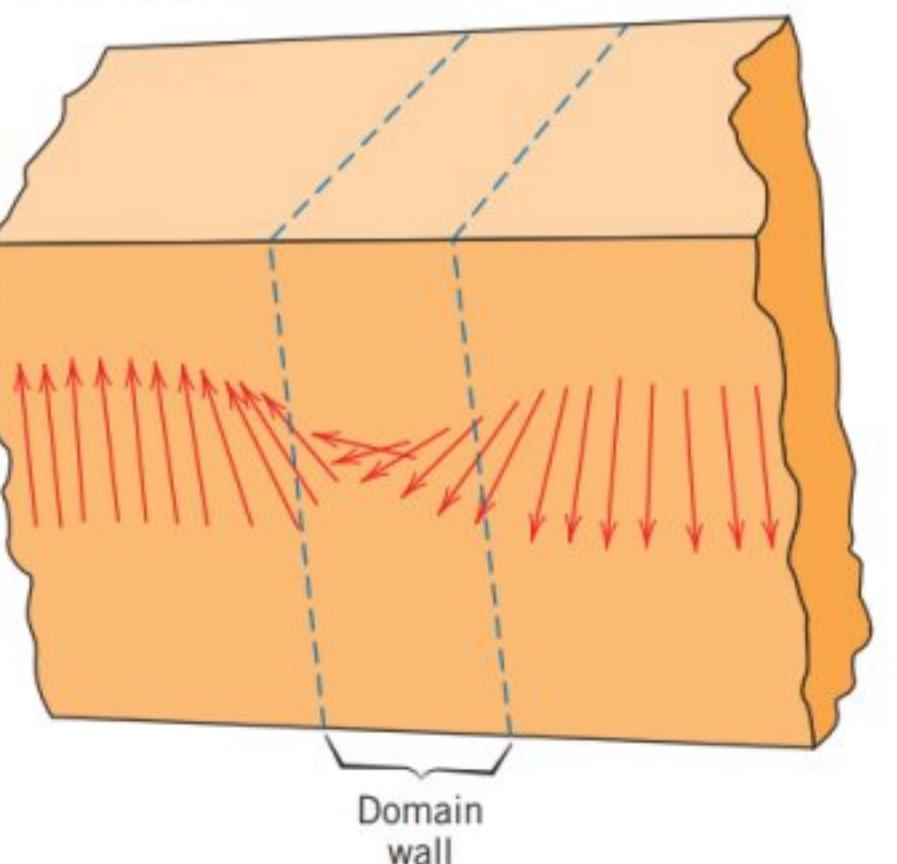
Region where magnetic dipoles are aligned in one particular direction

domains are microscopic in size,

Single Crystal: One domain

polycrystalline specimen : large no. of grains and each grain may consist of more than a single domain.

Thus, in a macroscopic piece of material, large number of domains, and all may have different magnetization orientations.



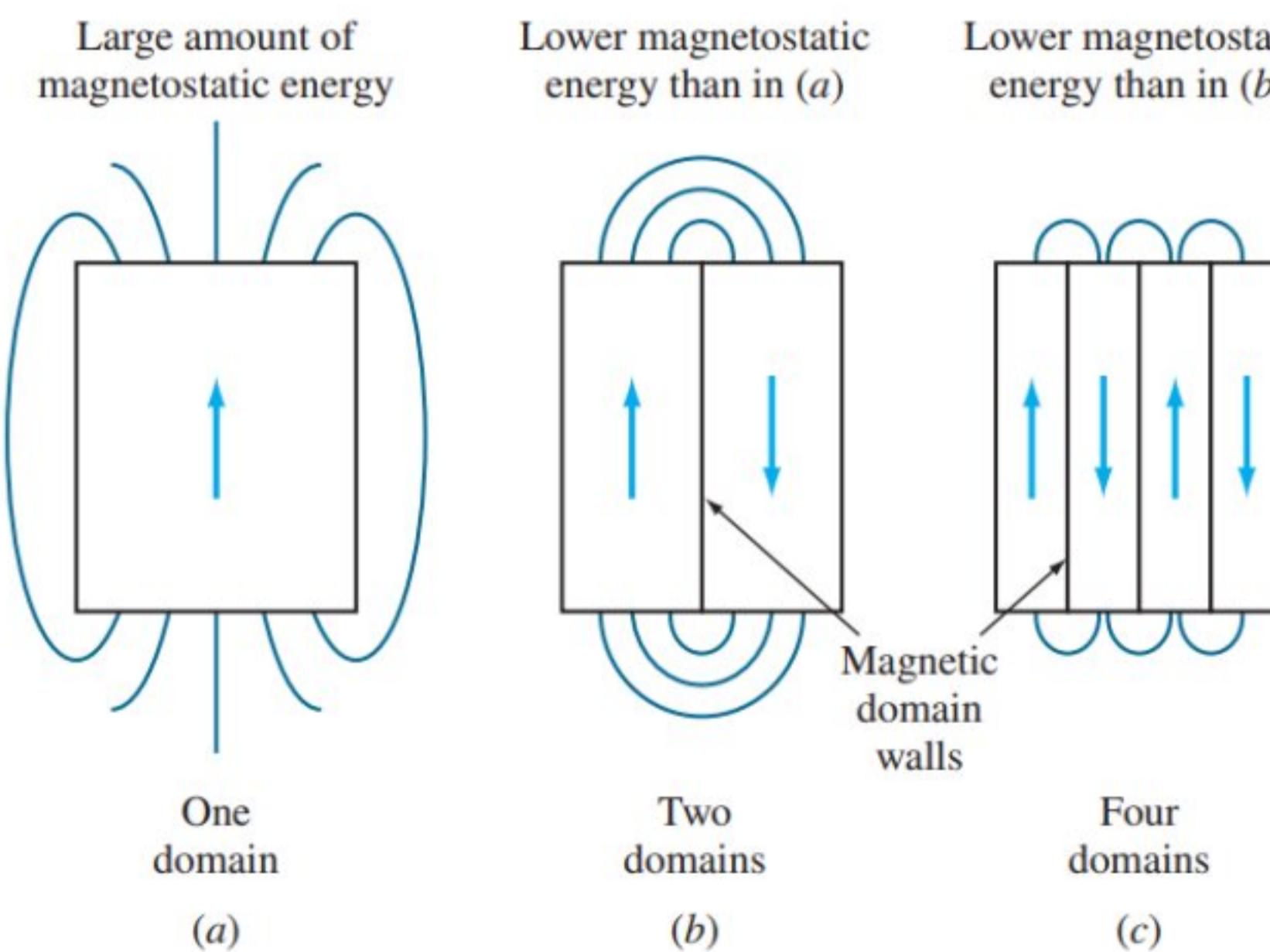
Domains
randomly
aligned

Domains
aligned with
external field

TYPES OF ENERGIES THAT DETERMINE THE STRUCTURE OF FERROMAGNETIC DOMAINS

Exchange Energy

- The potential energy *within* a domain of a ferromagnetic solid is minimized when all its atomic dipoles are aligned in one direction (**exchange energy**).
- This alignment is associated with a positive exchange energy.
- Even though the potential energy within a domain is minimized, its external potential energy is increased by the formation of an external magnetic field.



Schematic illustration showing how reducing the domain size in a magnetic material decreases the magnetostatic energy by reducing the external magnetic field.

(a) One domain, (b) two domains, and (c) four domains.

Magnetostatic Energy

Magnetostatic energy is the **potential magnetic energy** of a ferromagnetic material produced by its external field. This potential energy can be minimized in a ferromagnetic material by domain formation.

For a unit volume of a ferromagnetic material, a single-domain structure has the highest potential energy, as indicated.

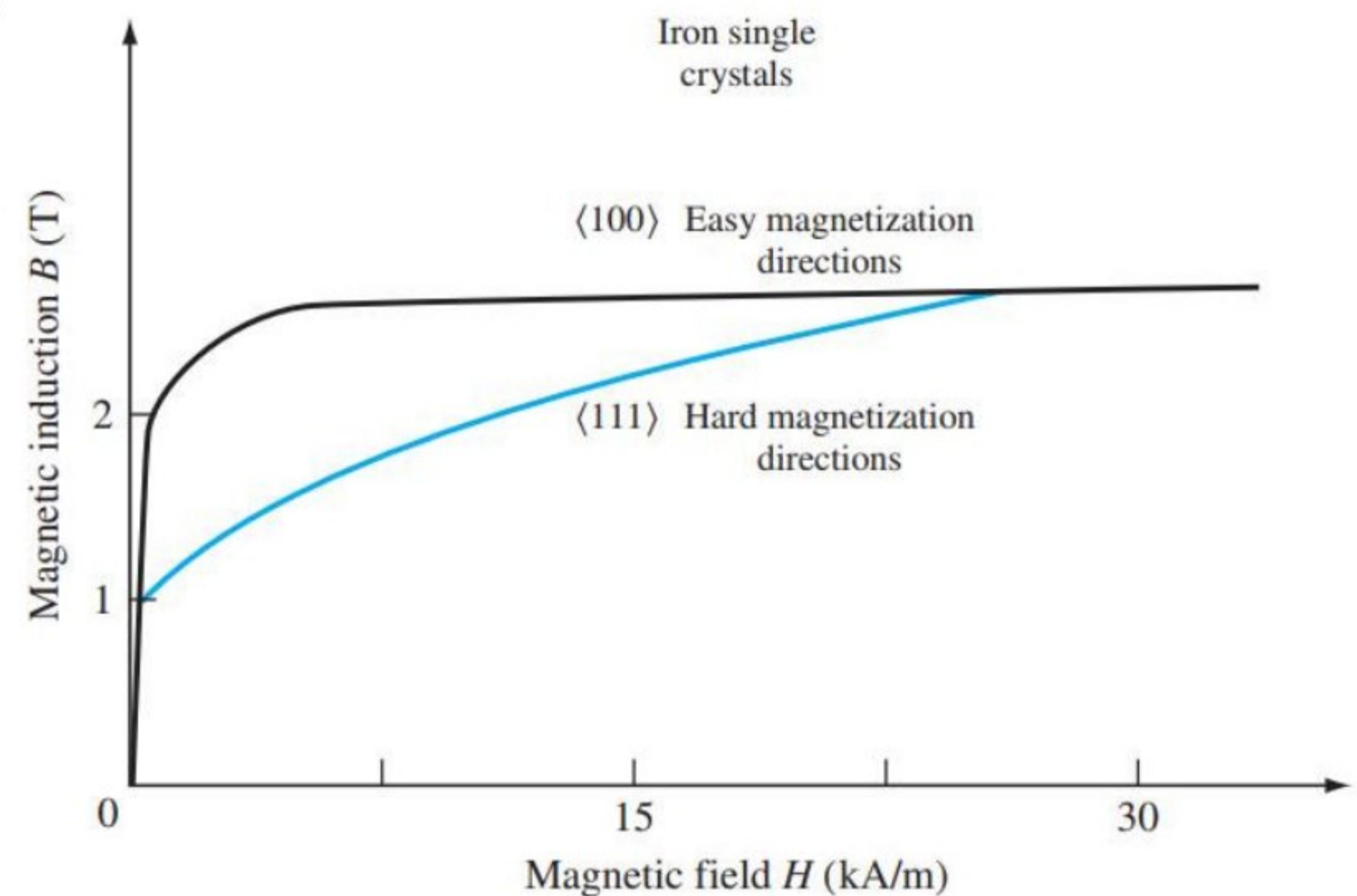
By dividing the single domain of into two domains, the intensity and extent of the external magnetic field are reduced. By further subdividing the single domain into four domains, the external magnetic field is reduced still more.

Since the **intensity of the external magnetic field** of a ferromagnetic material is **directly related** to its **magnetostatic energy**, the formation of multiple domains reduces the magnetostatic energy of a unit volume of material.

- Domain, Alignment of domains= Potential energy of a domain
- External magnetic field due to domain
- Potential magnetic energy due to the External Manetic Field = Magnetostatic Energy

Magnetocrystalline Anisotropy Energy

- Grains whose orientations are in the easy direction of magnetization will saturate at low applied fields.
- Grains oriented in the hard directions must rotate their resultant moment in the direction of the applied field and thus will reach saturation under much higher fields.
- The work done to rotate all the domains because of this anisotropy is called the **magnetocrystalline anisotropy energy**.



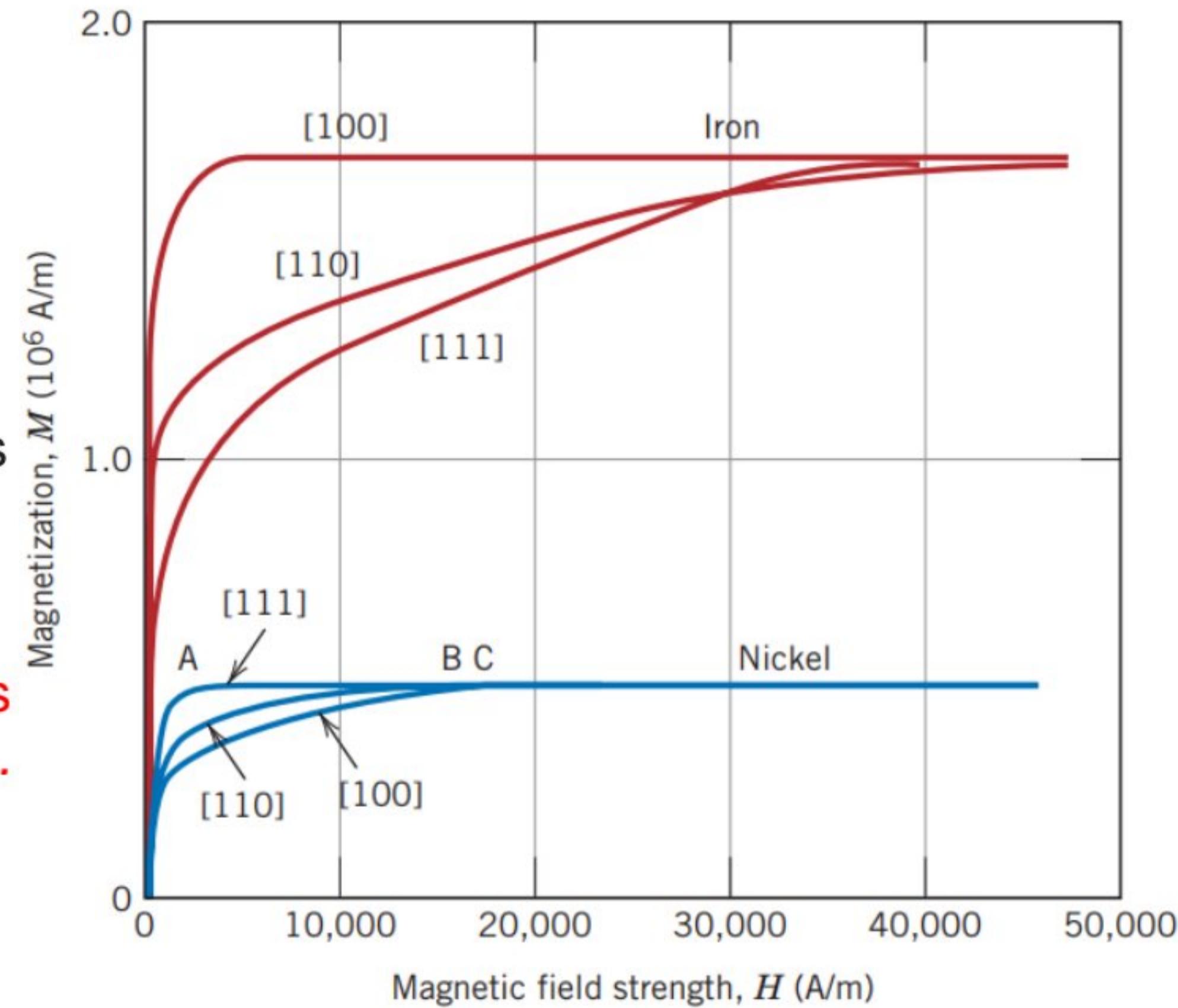
Magnetic Anisotropy

Magnetic Hysteresis depends on

- (1) Whether the specimen is a **single crystal** or **polycrystalline**;
- (2) If polycrystalline, **any preferred orientation of the grains**;
- (3) The presence of **pores or second-phase particles**; and
- (4) Other factors such as **temperature** and, if a mechanical stress is applied, the **stress state**

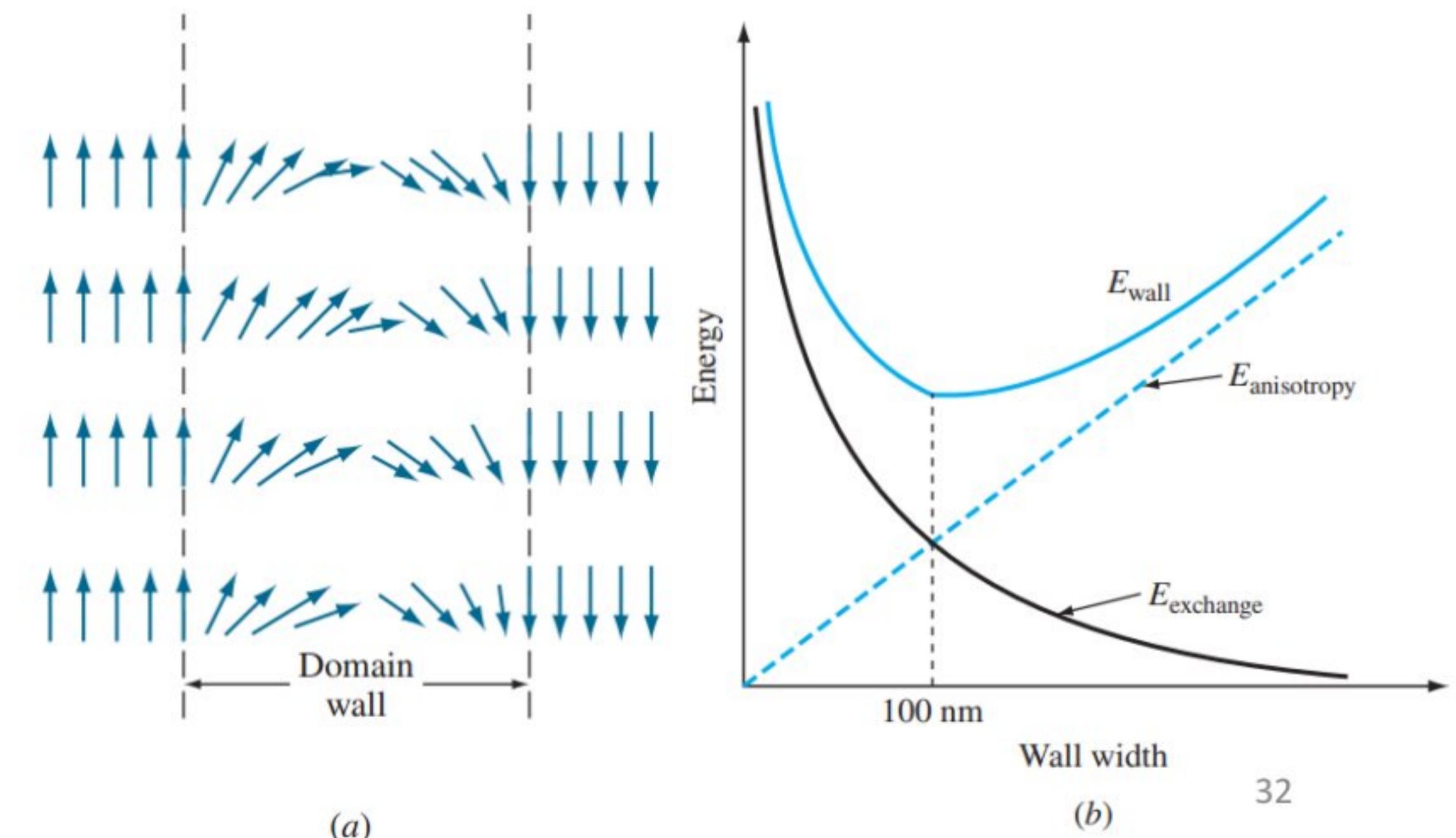
Dependence of magnetic behavior on crystallographic orientation is termed **magnetic anisotropy** (or sometimes **magnetocrystalline**).

For each of these materials there is one crystallographic direction in which magnetization is easiest—that is, saturation (of M) is achieved at the lowest H field; this is termed a direction of **easy magnetization**



Domain Wall Energy

- In contrast to a **grain boundary**, at which grains change orientation abruptly and which is **about three atoms wide**, a domain changes orientation gradually with a **domain boundary being about 300 atoms wide**.
- The large width of a domain wall is due to a balance between two forces: **exchange energy** and **magnetocrystalline anisotropy**.
- When there is only a **small difference in orientation between the dipoles**, the **exchange forces between the dipoles are minimized** and the exchange energy is reduced.
- Thus, the exchange forces will tend to widen the domain wall.



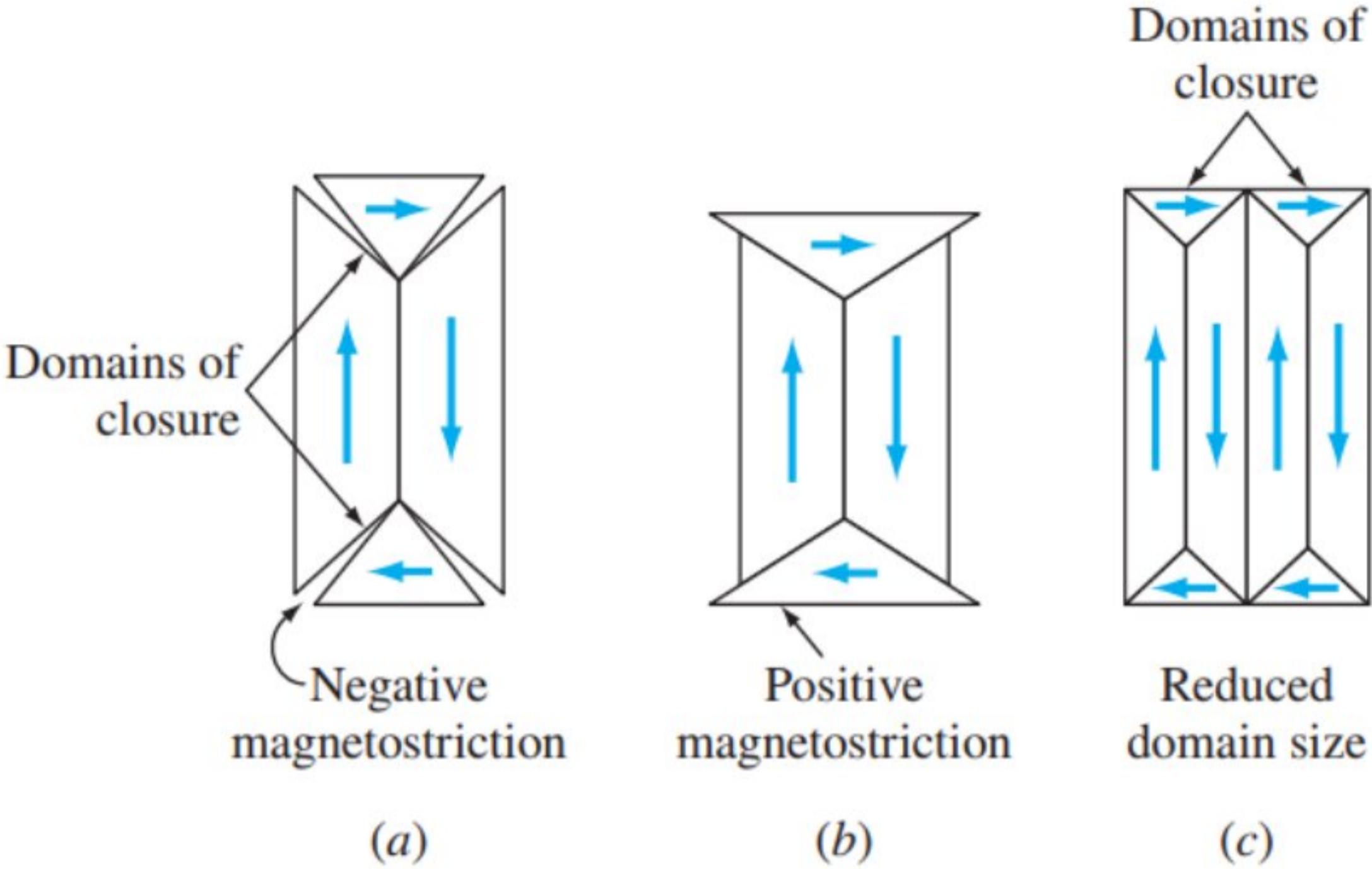
(a)

(b)

Magnetostrictive Energy

- When a ferromagnetic material is magnetized, its **dimensions change slightly**, and the sample being magnetized either expands or contracts in the direction of magnetization.
- This magnetically induced reversible elastic strain ($\Delta l/l$) is called **magnetostriction** and is of the order of 10^{-6} .
- The energy due to the mechanical stresses created by magnetostriction is called **magnetostrictive energy**.
- The **cause of magnetostriction** is attributed to the change in the bond length between the atoms in a ferromagnetic metal when their electron-spin dipole moments are rotated into alignment during magnetization.
- The fields of the dipoles may attract or repel each other, leading to the contraction or expansion of the metal during magnetization.

- Because of the cubic symmetry of the crystals, the formation of triangular-shaped domains, called *domains of closure*, at the ends of the crystal eliminates the magnetostatic energy associated with an external magnetic field and hence lowers the energy of the material.
- It might appear that very large domains would be the lowest energy and most stable configuration since there is minimum wall energy.
- However it is not the case since **magnetostrictive stresses introduced during magnetization tend to be larger for larger domains.**
- Smaller magnetic domains, reduce magnetostrictive stresses but increase domain wall area and energy.
- The equilibrium domain configuration is reached when the sum of the magnetostrictive and **domain wall energies** is a minimum.
-



Magnetostriction in cubic magnetic materials. Schematic exaggeration of (a) negative and (b) positive magnetostriction pulling apart the domain boundaries of a magnetic material. (c) Lowering of magnetostrictive stresses by the creation of a smaller-domain-size structure.

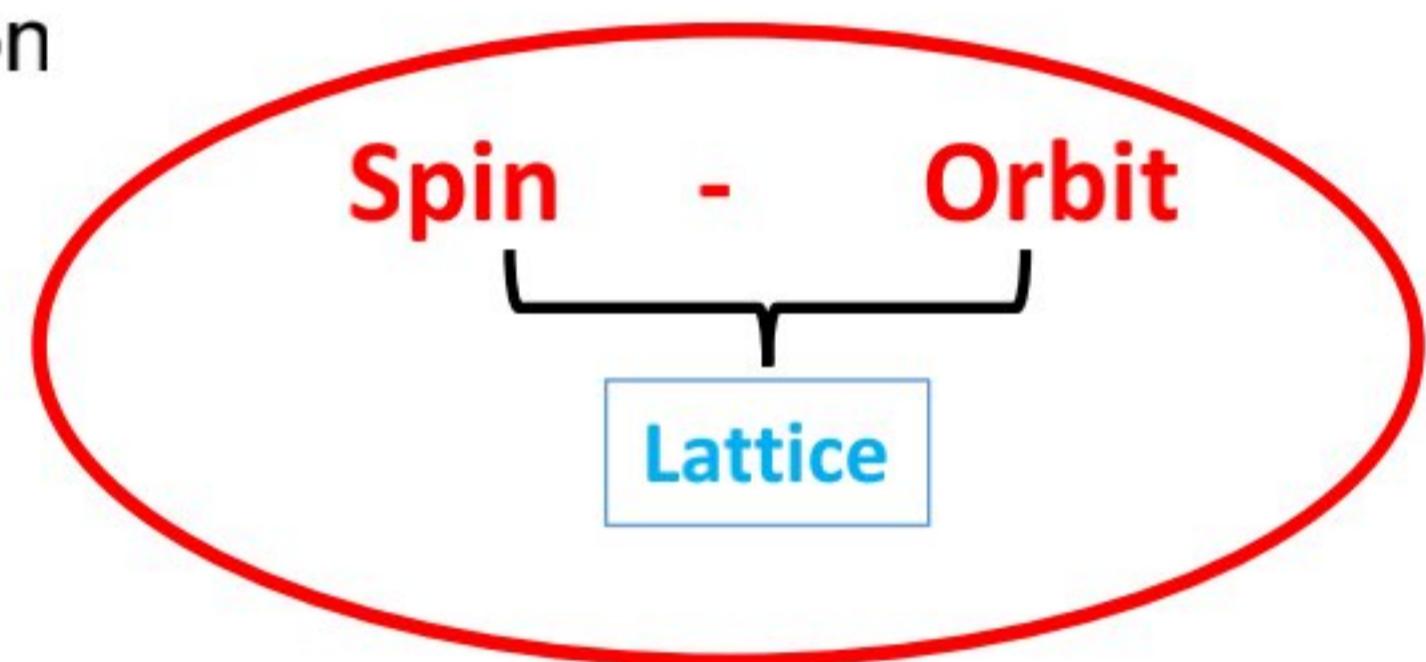
Magnetostriction

Spin - Orbit - Lattice

A restraint leading to finite permeabilities in magnetic materials is caused by a coupling *between the spins and the crystal lattice through the agency of the orbital motion of the electron.*

This **spin-orbit lattice coupling results in orientation of the spins relative to the crystal lattice in a minimum energy direction**, the so-called 'easy direction' of magnetization

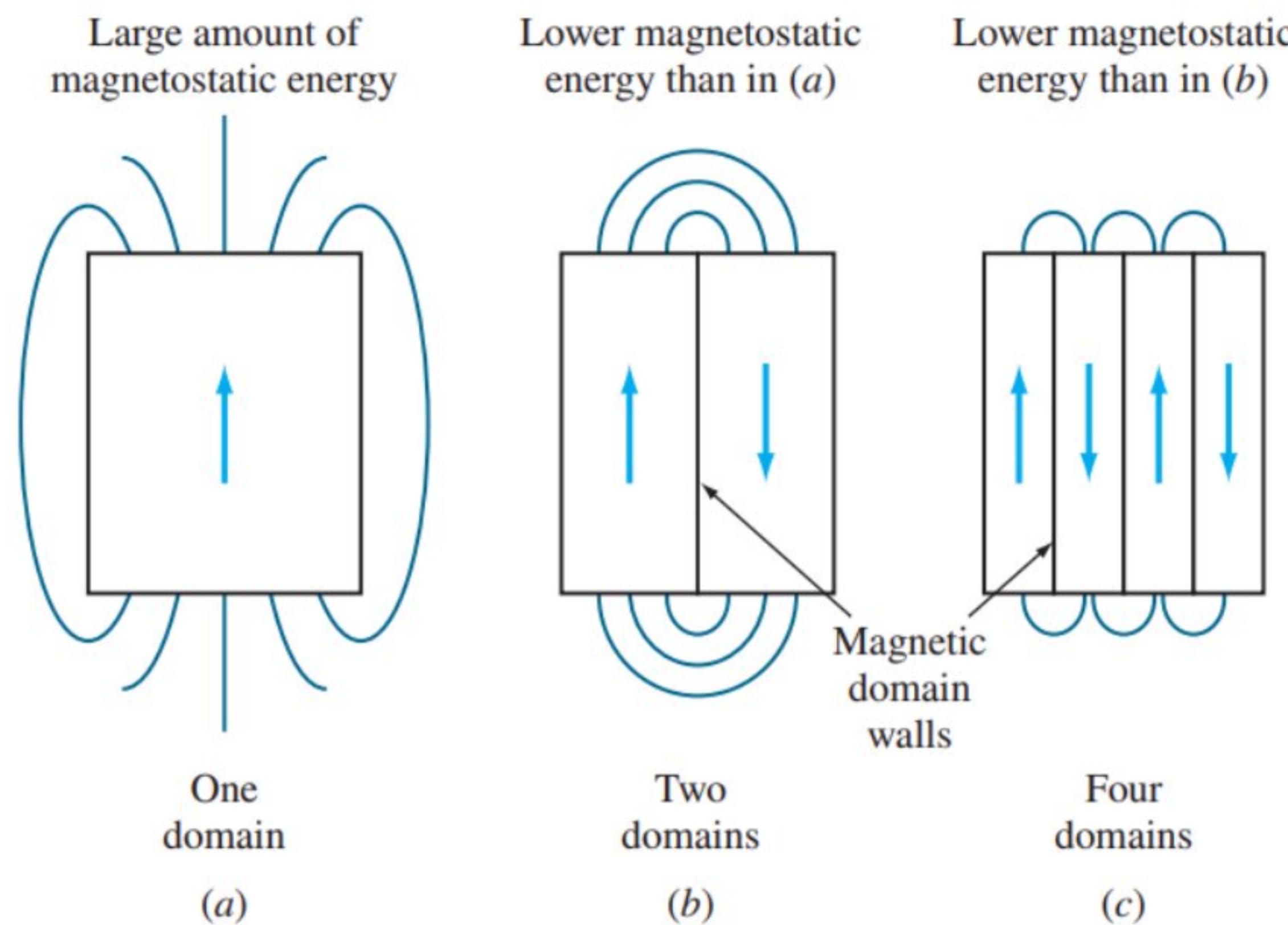
Change in the dimension of material with applied Magnetic Field



Because of the spin-orbit lattice coupling, changes in the spin directions result in changes in the orientation of the orbits which, because they are restrained by the lattice, have the effect of slightly altering the lattice dimensions.

This effect is known as **magnetostriction**.

The magnetostriction constant λ_m is defined as the strain induced by a saturating field; it is given a positive sign if the field causes an increase in dimensions in the field direction. For single crystals λ_m varies with the crystallographic direction, and so for the ceramic form it is an average of the single-crystal values



Schematic illustration showing how reducing the domain size in a magnetic material decreases the magnetostatic energy by reducing the external magnetic field. (a) One domain, (b) two domains, and (c) four domains.

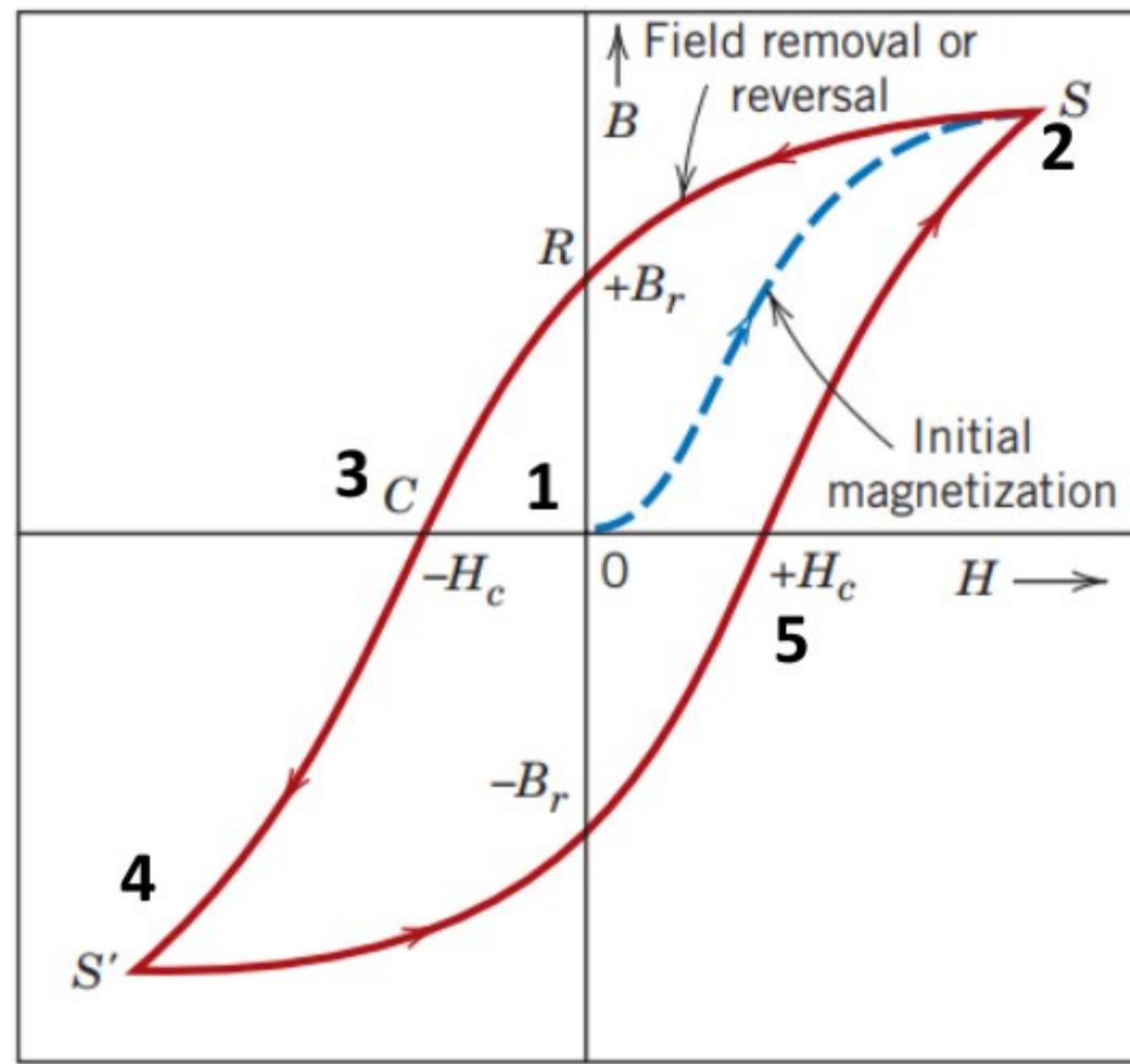
DOMAINS AND HYSTERESIS

S : Saturation Magnetization

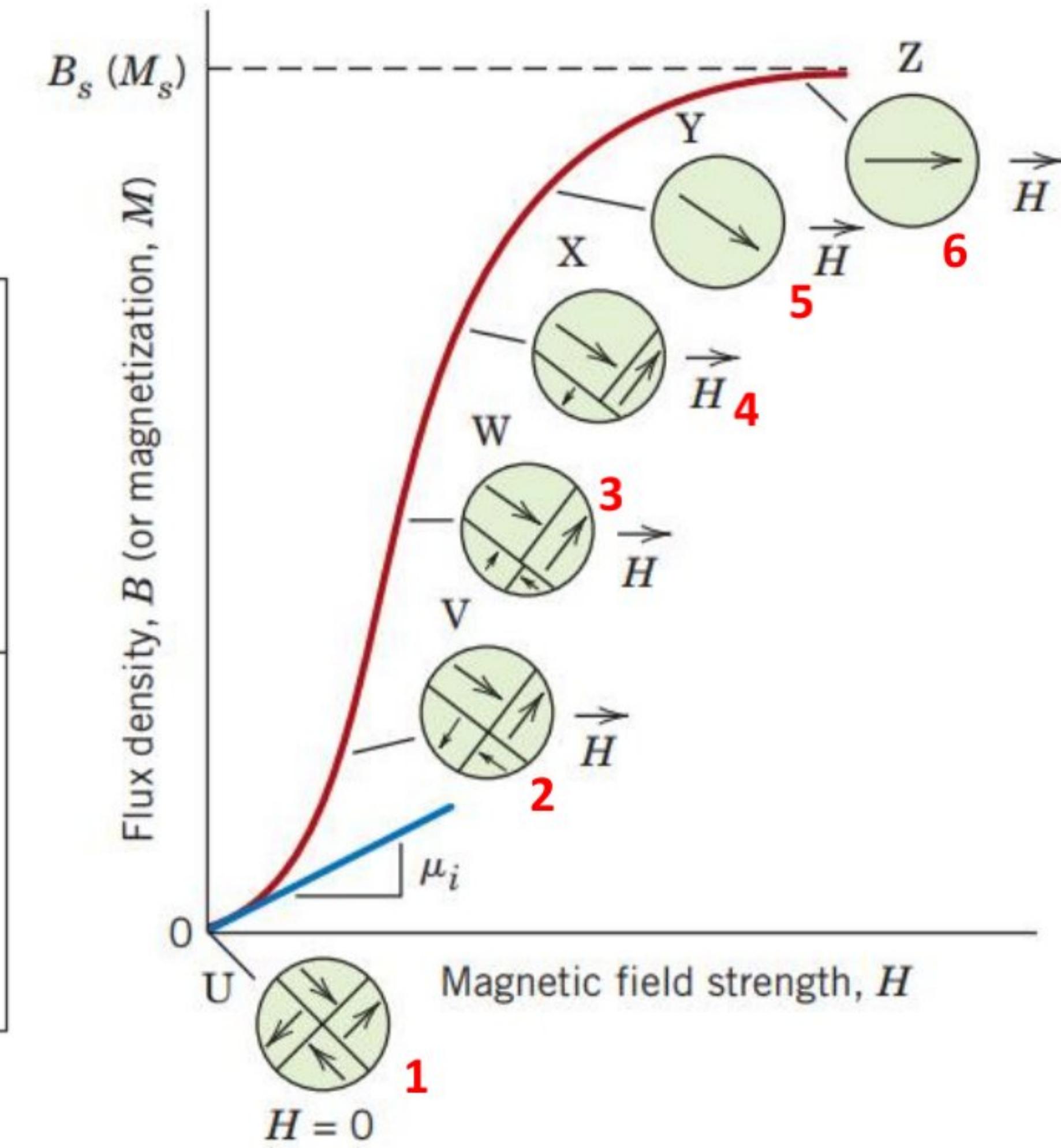
R: Remanent magnetization

C: Corecive Magnetic Field

At C magnetization (**B**) is zero



Corecive Magnetic Field: Magnetic field required to demagnetize the specimen by applying H in a direction which is opposite to the initially applied H

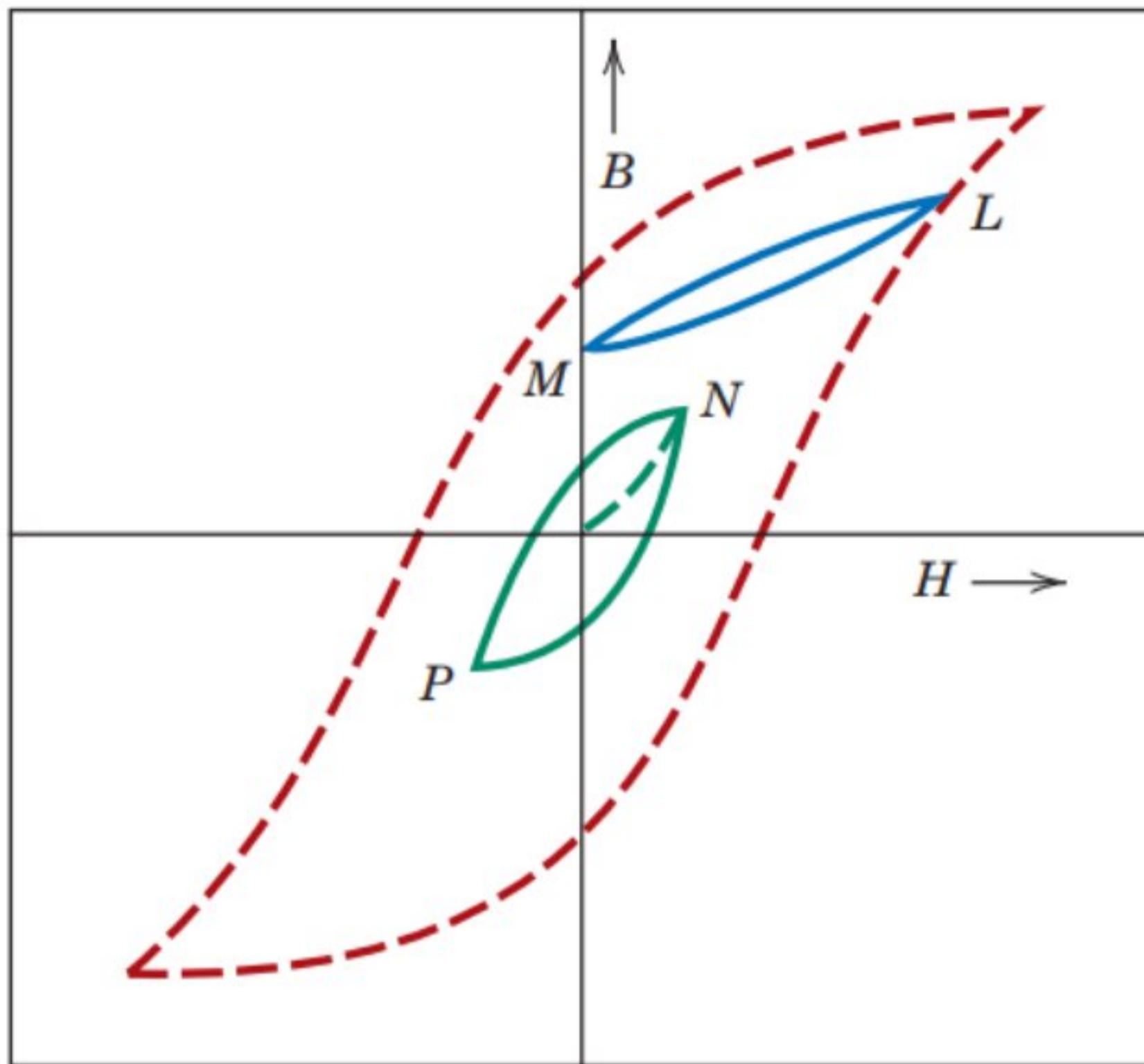


Domains whose directions of easy magnetization are most closely aligned with the H field grow, at the expense of the other domains that shrink

it is not necessary to increase the H field to saturation before reversing the field direction

L-M When H is reversed before Saturation B

N-P Hysteresis loop with low saturation point

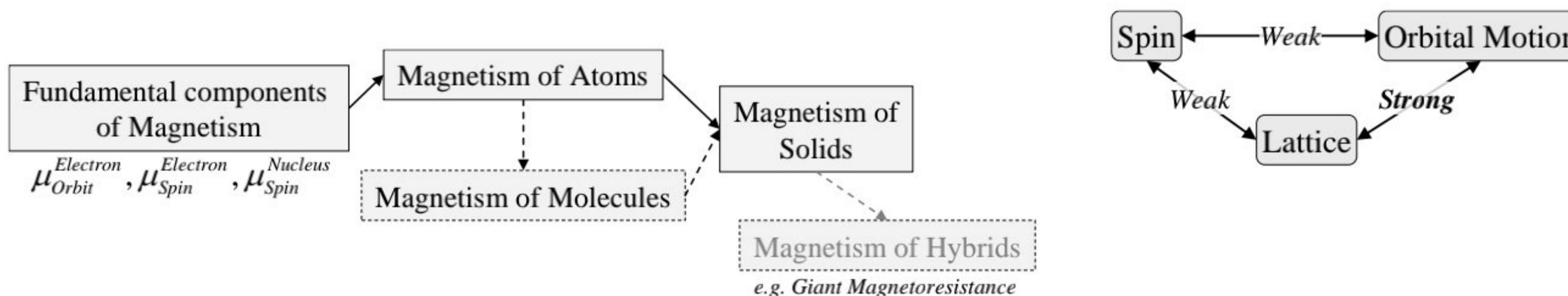


One method of demagnetizing a ferromagnet or ferrimagnet is to repeatedly cycle it in an H field that alternates direction and decreases in magnitude

Understanding magnetism (and formulating theories) to understand the effects observed:

- **Direct coupling** → Moments (spin, orbital motion, nuclear) localized to an atom and their direct interaction with moments in neighbouring atoms
- **Mediated interaction** → Moments (magnetism) arising from itinerant electrons in the bands of metals (with the possibility of mediation of interaction via free electrons).
- **Superexchange** → Local magnetic moments interacting with other local moments via the mediation of non-magnetic elements (super-exchange) → e.g. antiferromagnetism in MnO.

From magnetism of the fundamental components to magnetism of devices



Diamagnetic and paramagnetic

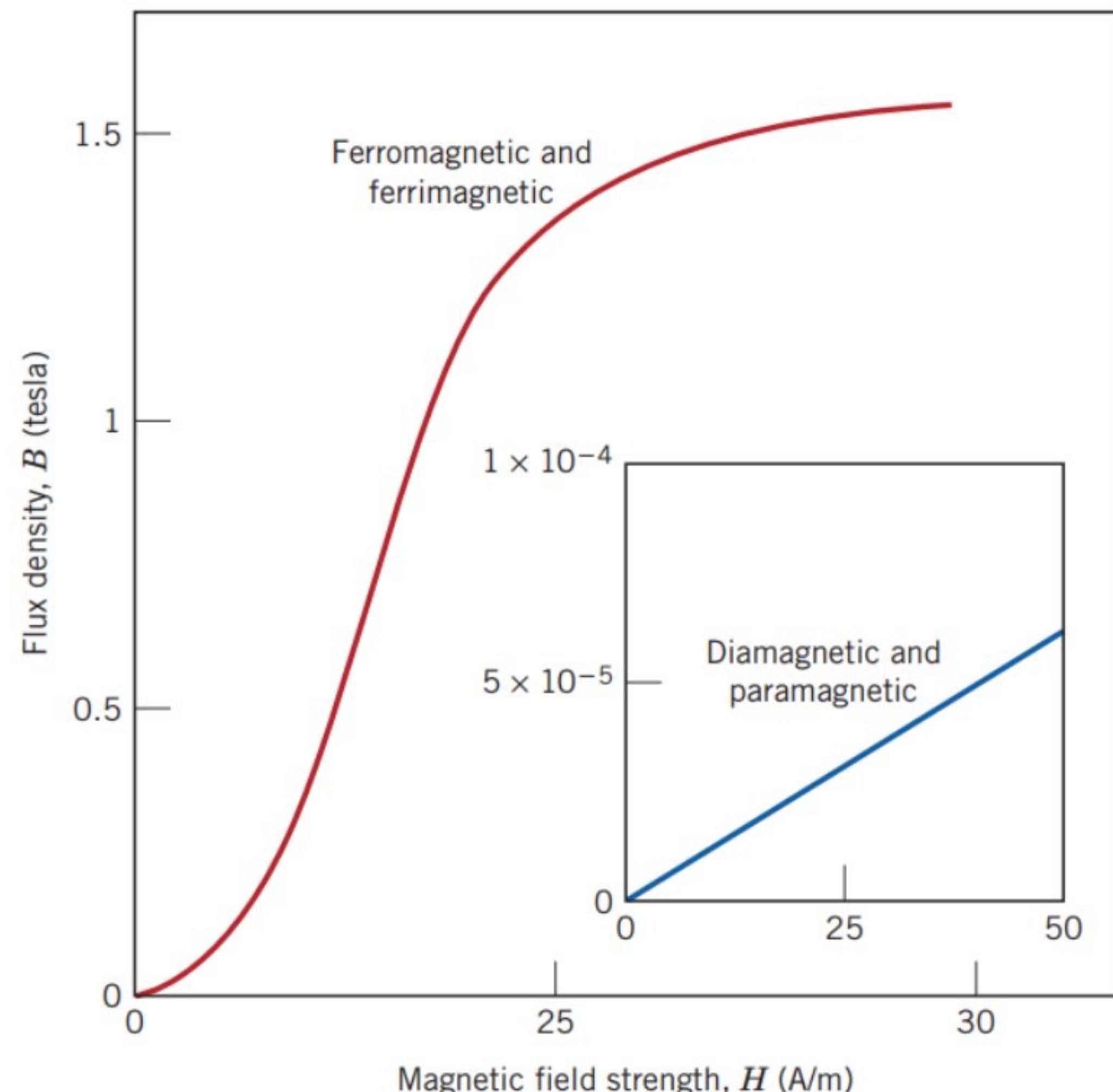
- Linear B and H Plot
- Value of B is very very less

At $H = 50 \text{ A/m}$
 $B = 0.00005 \text{ tesla}$

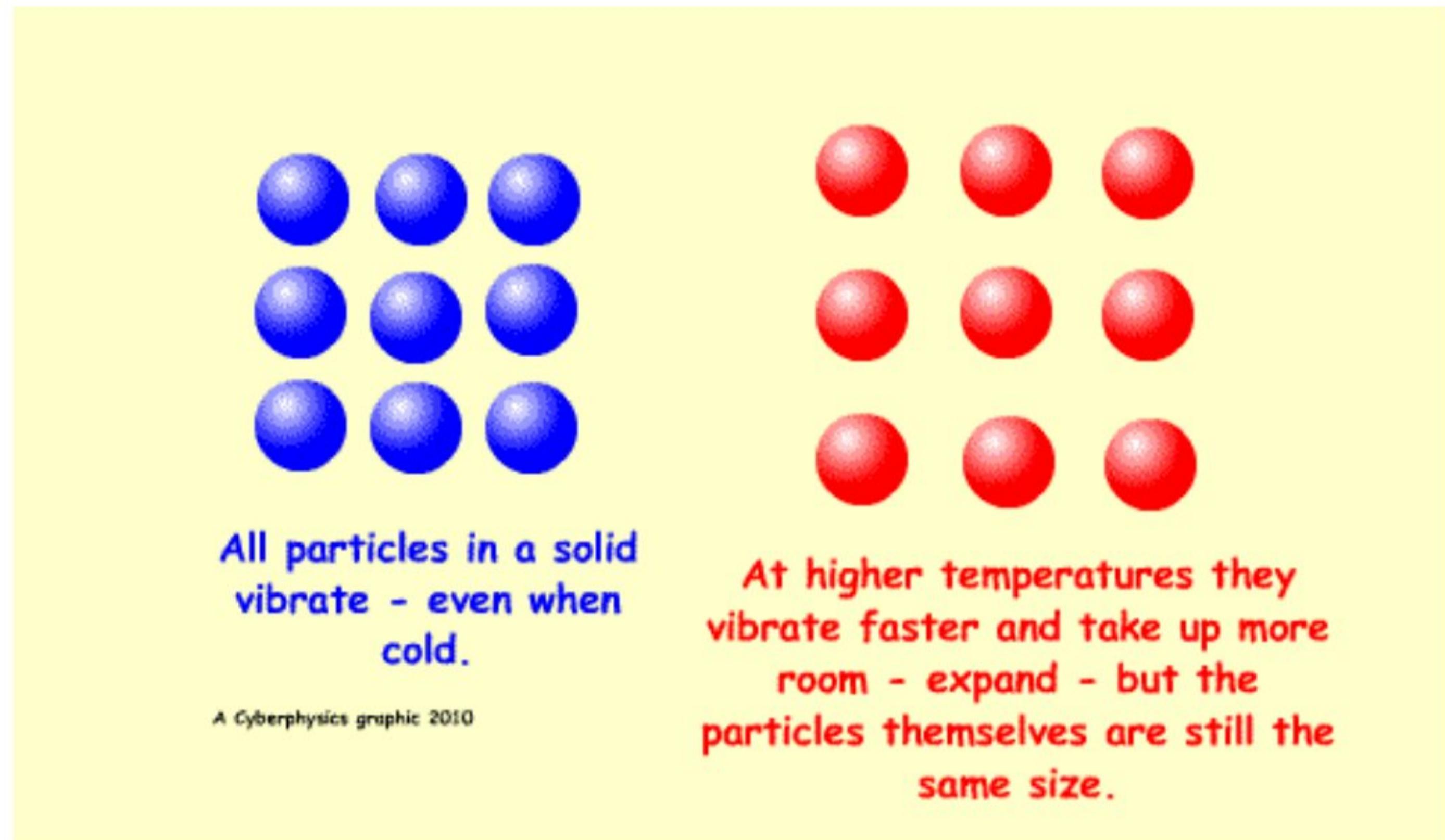
Ferromagnetic and Ferrimagnetic

- Non Linear B and H Plot
- Value of B is comparatively high

At $H = 50 \text{ A/m}$
 $B = 1.5 \text{ tesla}$



High Temperature Vibrations



THE INFLUENCE OF TEMPERATURE ON MAGNETIC BEHAVIOR

The atomic magnetic moments are free to rotate;

Randomize the orbital and spin moments

The increased thermal motion of the atoms tends to randomize the directions of any moments that may be aligned.

For ferromagnetic, antiferromagnetic, and ferrimagnetic materials, the atomic thermal motions counteract the coupling forces between the adjacent atomic dipole moments, causing some dipole misalignment, regardless of whether an external field is present.

This results in a decrease in the saturation magnetization for both ferro and ferrimagnets.

At 0 K thermal vibrations are the least

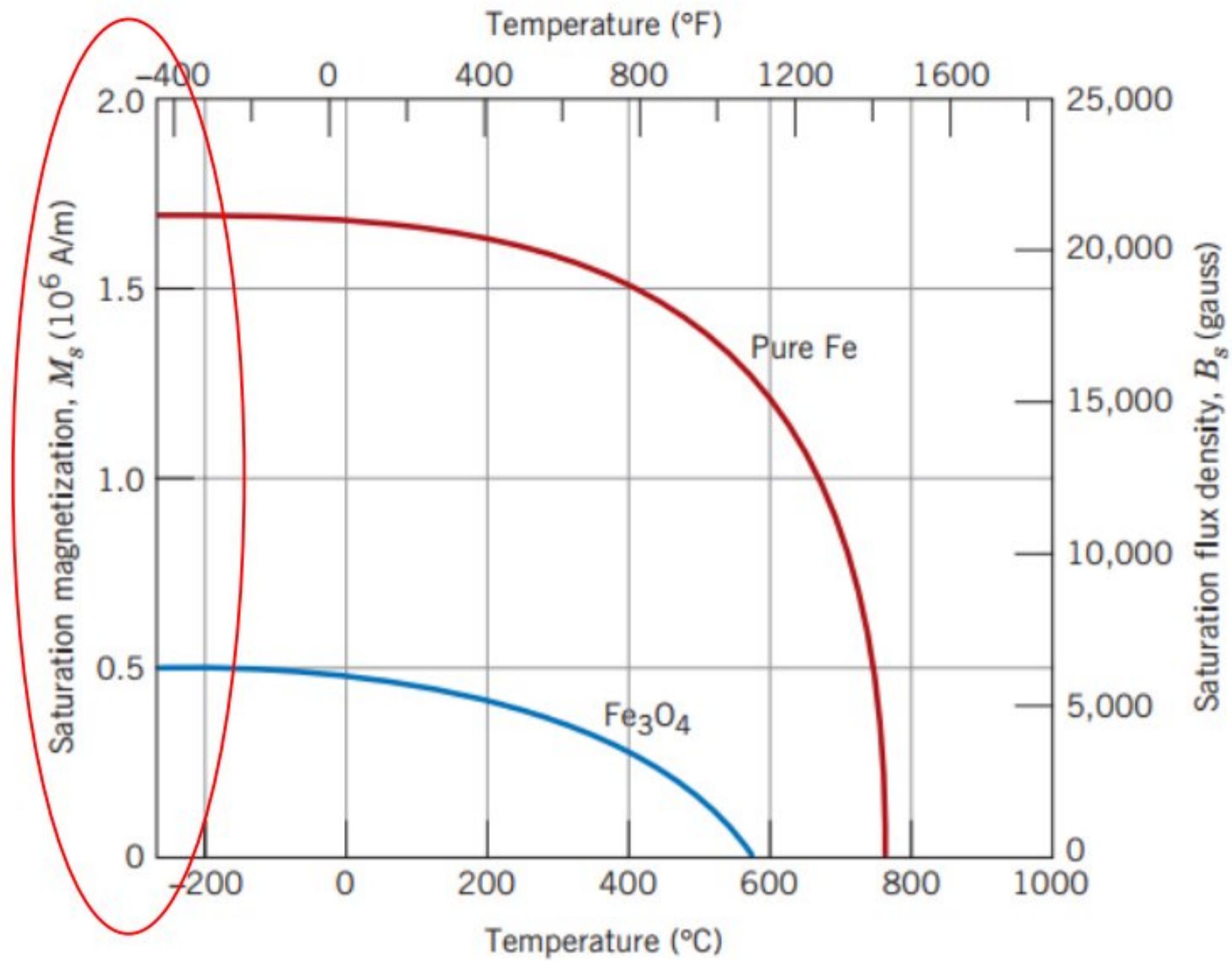
The saturation magnetization is a maximum at 0 K, at which the thermal vibrations are a minimum. With increasing temperature, the saturation magnetization diminishes gradually and then abruptly drops to zero at what is called the **Curie temperature** T_c .

Antiferromagnetism is also affected by temperature; this behavior vanishes at what is called the *Néel temperature*. At temperatures above this point, antiferromagnetic materials also become paramagnetic.

At T_c the mutual spin-coupling forces are completely destroyed, such that for temperatures above T_c both ferromagnetic and ferrimagnetic materials are paramagnetic.

The magnitude of the Curie temperature varies from material to material; for example, for iron, cobalt, nickel, and Fe_3O_4 , the respective values are 768, 1120, 335, and 585 deg. C.

Antiferromagnetism is also affected by temperature; this behavior vanishes at what is called the *Néel temperature*. At temperatures above this point, antiferromagnetic materials also become paramagnetic.



SOFT and HARD MAGNETIC MATERIALS

The area within a loop represents a magnetic energy loss per unit volume of material per magnetization–demagnetization cycle; this energy loss is manifested as heat and is capable of raising its temperature.

Soft magnetic materials are used in devices that are subjected to alternating magnetic fields and in which energy losses must be low

high initial permeability and a low coercivity

saturation field or magnetization depends on composition

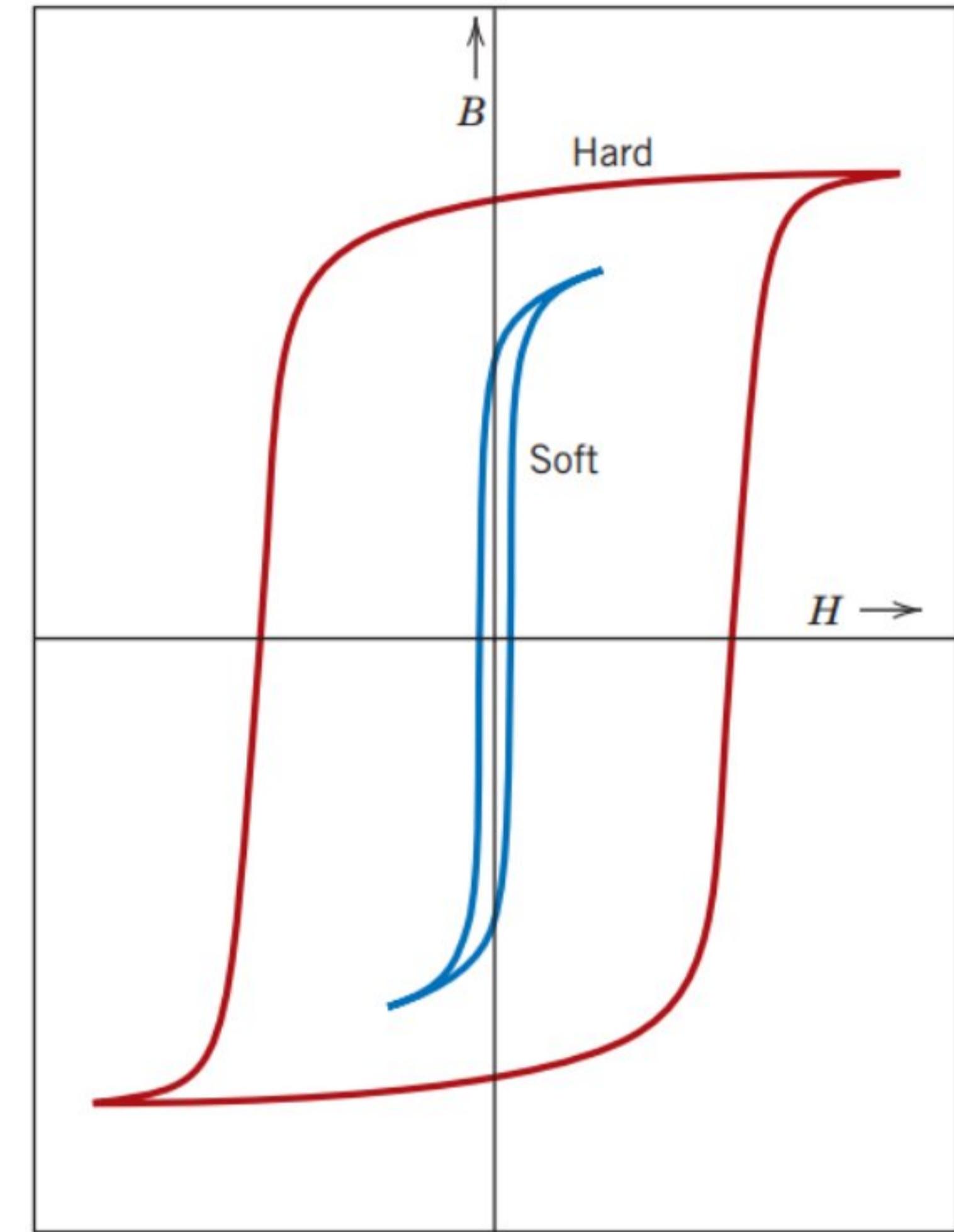
susceptibility and coercivity (H_c), which also influence the shape of the hysteresis curve, are sensitive to structural variables

Structural defects such as particles of a nonmagnetic phase or voids in the magnetic material tend to restrict the motion of domain walls, and thus increase the coercivity.

soft magnetic material must be free of such structural defects

High electrical resistivity to reduce eddy currents

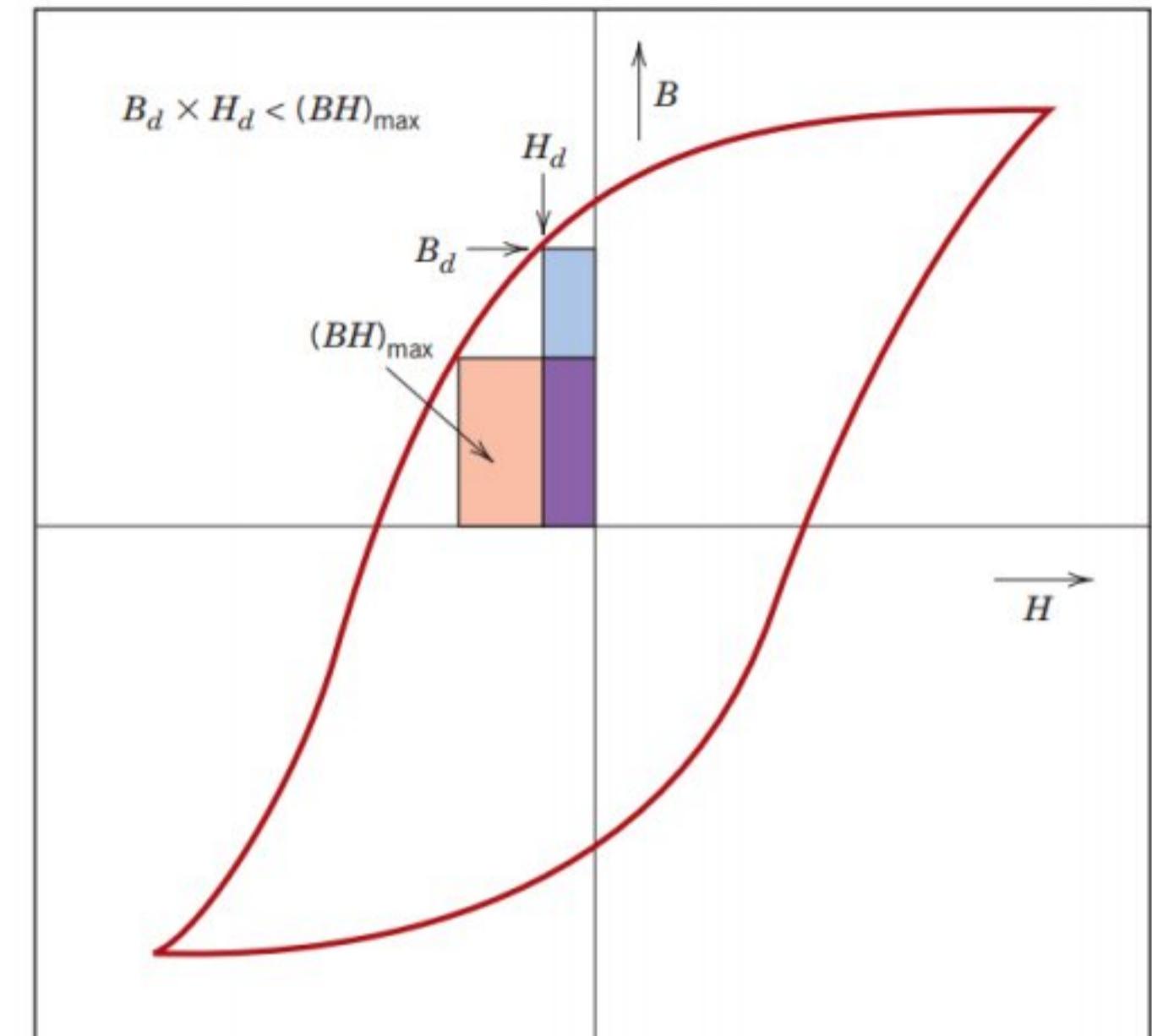
soft magnetic materials are used in generators, motors, dynamos, and switching circuits.



in cubic ferrites, substitution of a divalent metal ion such as Ni^{2+} for Fe^{2+} in $\text{FeO}-\text{Fe}_2\text{O}_3$ will change the saturation magnetization

HARD MAGNETIC MATERIALS

- high remanence,
- High coercivity, and
- High saturation flux density,
- low initial permeability and
- high hysteresis energy losses



by **impeding domain wall motion**, the coercivity and susceptibility are enhanced, such that a large external field is required for demagnetization.

Furthermore, these characteristics are interrelated to the microstructure of the material.

Main factors which decide their hard properties :

The **coercivity** and the **energy product**, designated as **(BH)max**

$(BH)_{\max}$ corresponds to the area of the largest B - H rectangle that can be constructed within the second quadrant of the hysteresis curve

Conventional Hard Magnetic Materials

- The conventional materials have $(BH)_{\max}$ values that range between about 2 and 80 kJ/m³ (0.25 and 10 MGOe).
- These include ferromagnetic materials—magnet steels, cunife (Cu–Ni–Fe) alloys, alnico (Al–Ni–Co) alloys—as well as the hexagonal ferrites ($\text{BaO} \cdot 6\text{Fe}_2\text{O}_3$)
- Hard magnet steels are normally alloyed with tungsten and/or chromium.
- Under the proper heat-treating conditions these two elements readily combine with carbon in the steel to form tungsten and chromium carbide precipitate particles, which are especially effective in obstructing domain wall motion.
- For other metal alloys, an appropriate heat treatment forms extremely small single-domain and strongly magnetic iron–cobalt particles within a nonmagnetic matrix phase.

Soft Magnetic Materials

<i>Material</i>	<i>Composition (wt %)</i>	<i>Initial Relative Permeability μ_i</i>	<i>Saturation Flux Density B_s [tesla (gauss)]</i>	<i>Hysteresis Loss/Cycle [J/m³ (erg/cm³)]</i>	<i>Resistivity ρ ($\Omega \cdot m$)</i>
Commercial iron ingot	99.95Fe	150	2.14 (21,400)	270 (2700)	1.0×10^{-7}
Silicon–iron (oriented)	97Fe, 3Si	1400	2.01 (20,100)	40 (400)	4.7×10^{-7}
45 Permalloy	55Fe, 45Ni	2500	1.60 (16,000)	120 (1200)	4.5×10^{-7}
Supermalloy	79Ni, 15Fe, 5Mo, 0.5Mn	75,000	0.80 (8000)	—	6.0×10^{-7}
Ferroxcube A	48MnFe ₂ O ₄ , 52ZnFe ₂ O ₄	1400	0.33 (3300)	~40 (~400)	2000
Ferroxcube B	36NiFe ₂ O ₄ , 64ZnFe ₂ O ₄	650	0.36 (3600)	~35 (~350)	10^7

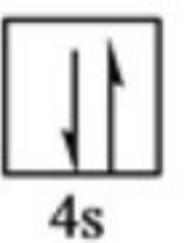
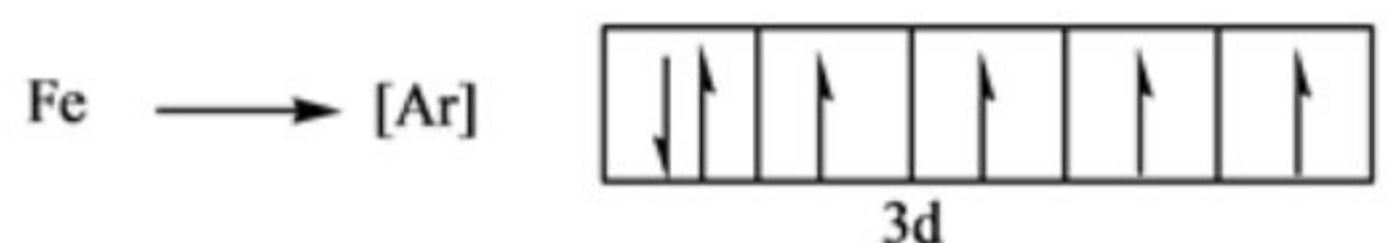
Hard Magnetic Materials

<i>Material</i>	<i>Composition (wt%)</i>	<i>Remanence B_r [tesla (gauss)]</i>	<i>Coercivity H_c [amp-turn/m (Oe)]</i>	<i>(BH)_{max} [kJ/m³ (MGOe)]</i>	<i>Curie Temperature T_c [°C (°F)]</i>	<i>Resistivity ρ ($\Omega \cdot m$)</i>
Tungsten steel	92.8 Fe, 6 W, 0.5 Cr, 0.7 C	0.95 (9500)	5900 (74)	2.6 (0.33)	760 (1400)	3.0×10^{-7}
Cunife	20 Fe, 20 Ni, 60 Cu	0.54 (5400)	44,000 (550)	12 (1.5)	410 (770)	1.8×10^{-7}
Sintered alnico 8	34 Fe, 7 Al, 15 Ni, 35 Co, 4 Cu, 5 Ti	0.76 (7600)	125,000 (1550)	36 (4.5)	860 (1580)	—
Sintered ferrite 3	BaO–6Fe ₂ O ₃	0.32 (3200)	240,000 (3000)	20 (2.5)	450 (840)	$\sim 10^4$
Cobalt rare earth 1	SmCo ₅	0.92 (9200)	720,000 (9,000)	170 (21)	725 (1340)	5.0×10^{-7}
Sintered neodymium–iron–boron	Nd ₂ Fe ₁₄ B	1.16 (11,600)	848,000 (10,600)	255 (32)	310 (590)	1.6×10^{-6}

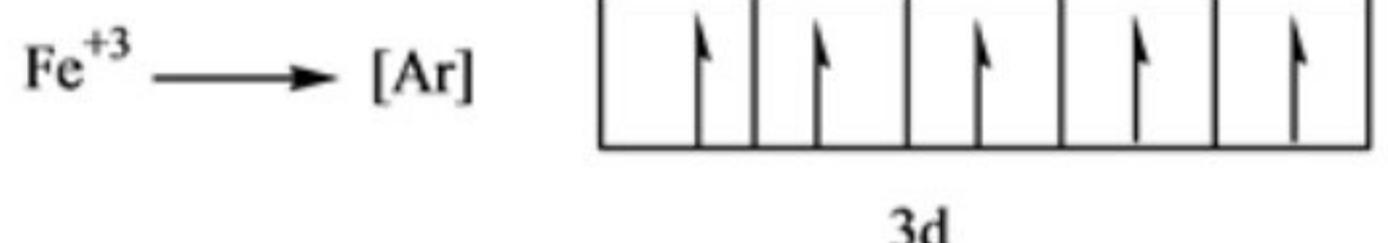
Spinel Ferrite (Fe_3O_4)

$\text{Fe} : 1s^2 2s^2 2p^6 3s^2 3p^6 \textcolor{red}{4s^2 3d^6}$

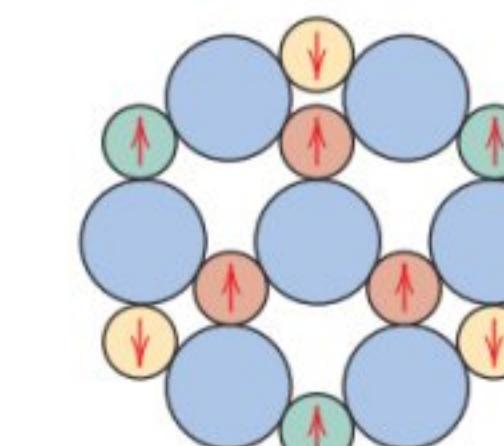
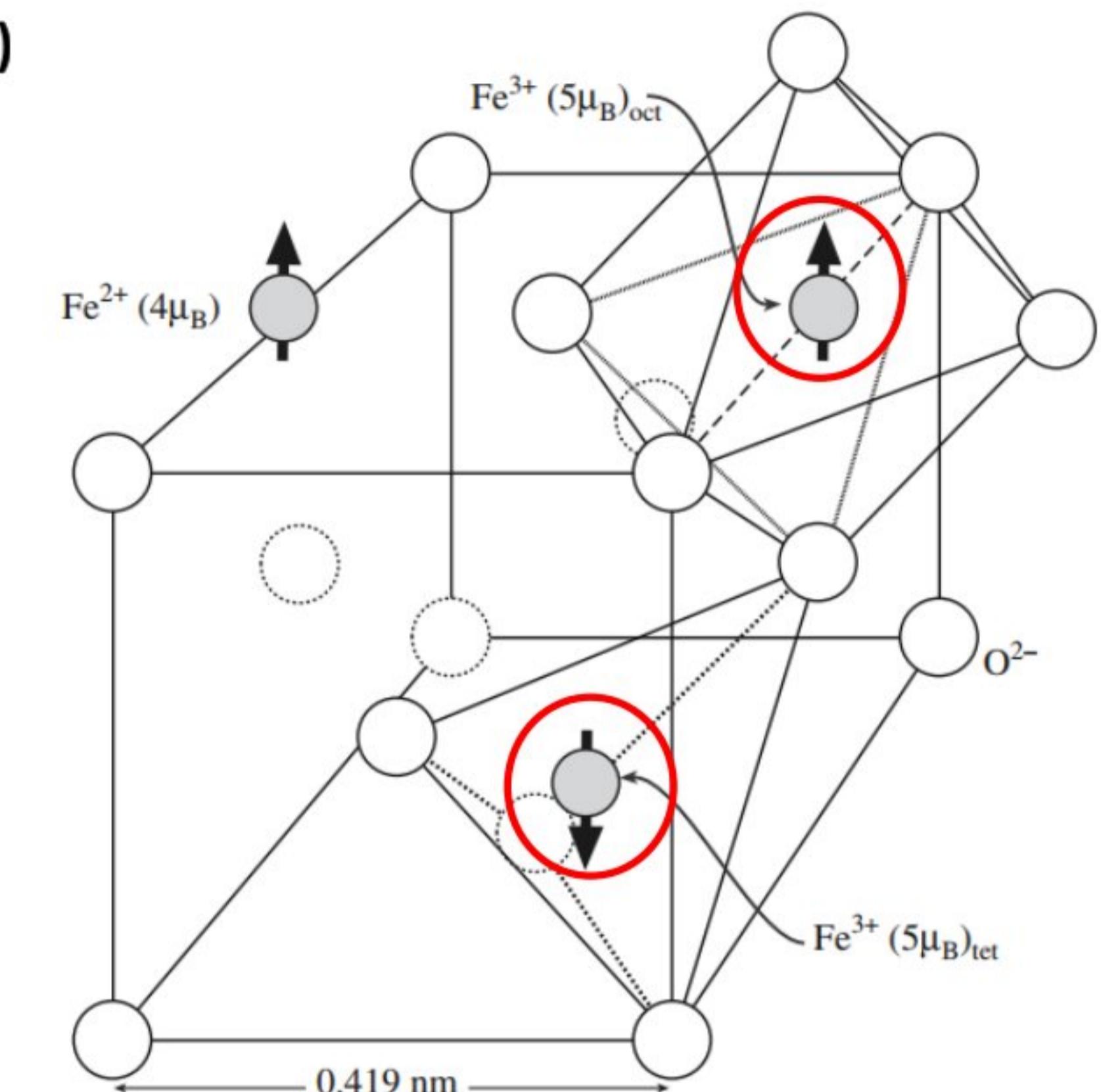
$\text{Fe}^{3+} : 1s^2 2s^2 2p^6 3s^2 3p^6 \textcolor{red}{3d^5}$



→ two electrons removed
4s



→ three electrons removed
4s



O^{2-}
 Fe^{2+}
 Fe^{3+}
 Fe^{3+} 48
 (Octahedral) (Octahedral) (Tetrahedral)

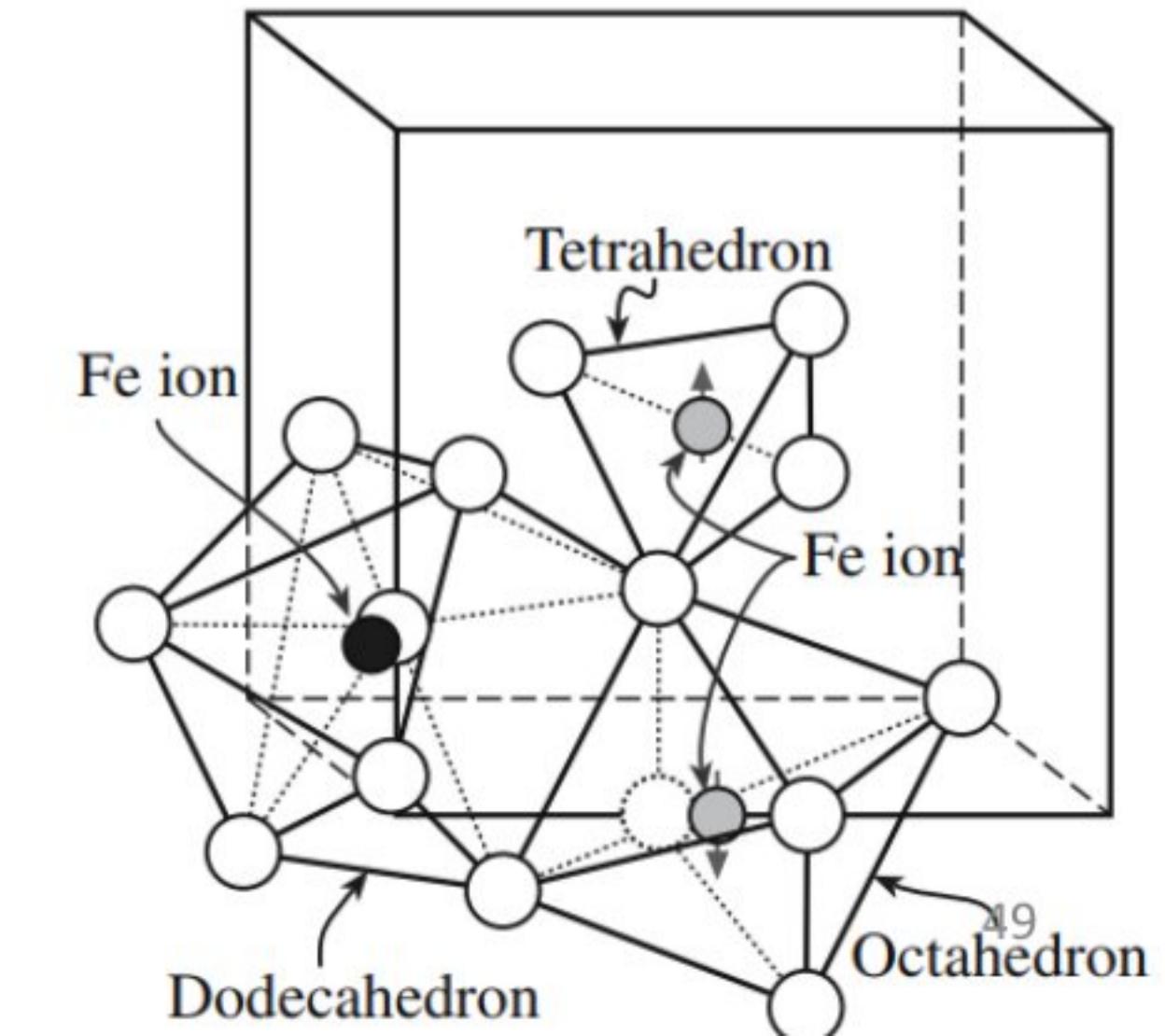
- Ceramic materials other than the cubic ferrites are also ferrimagnetic; these include the **HEXAGONAL FERRITES** and garnets. Hexagonal ferrites have a crystal structure similar to the inverse spinel, with **hexagonal symmetry rather than cubic**.

- The chemical formula for these materials may be represented by $AB_{12}O_{19}$, in which A is a divalent metal such as barium, lead, or strontium, and B is a trivalent metal such as aluminum, gallium, chromium, or iron. The two most common examples of the hexagonal ferrites are $PbFe_{12}O_{19}$ and $BaFe_{12}O_{19}$.

- The **GARNETS** have a very complicated crystal structure, which may be represented by the general formula $M_3Fe_5O_{12}$; here, M represents a rare earth ion such as samarium, europium, gadolinium, or yttrium. Yttrium iron garnet ($Y_3Fe_5O_{12}$), sometimes denoted YIG, is the most common material of this type.

Detailed Reference: Electroceramics A.J Moulson

Material	θ_c (K)	B_{sat} (T) at RT
Spinel ferrites [AO·B ₂ O ₃]		
Fe ³⁺ [Cu ²⁺ Fe ³⁺]O ₄	728	0.20
Fe ³⁺ [Ni ²⁺ Fe ³⁺]O ₄	858	0.34
Fe ³⁺ [Co ²⁺ Fe ³⁺]O ₄	1020	0.50
Fe ³⁺ [Fe ²⁺ Fe ³⁺]O ₄	858	0.60
Fe ³⁺ [Mn ²⁺ Fe ³⁺]O ₄	573	0.51
Fe ³⁺ [Li _{0.5} Fe _{1.5}]O ₄	943	
Mg _{0.1} Fe _{0.9} [Mg _{0.9} Fe _{1.1}]O ₄	713	0.14
Hexagonal ferrites		
BaO:6Fe ₂ O ₃	723	0.48
SrO:6Fe ₂ O ₃	723	0.48
Y ₂ O ₃ :5Fe ₂ O ₃	560	0.16
BaO:9Fe ₂ O ₃	718	0.65
Garnets		
YIG{Y ₃ }Fe ₂ O ₁₂	560	0.16
(Gd ₃)Fe ₂ O ₁₂	560	
Binary oxides		
EuO	69	
CrO ₂	386	0.49



High-Energy Hard Magnetic Materials

- Permanent magnetic materials having **energy products in excess of about 80 kJ/m³** are considered to be of the high-energy type.
- These are recently developed intermetallic compounds that have a variety of compositions

Samarium–Cobalt Magnets

- SmCO₅ is a member of a group of alloys that are combinations of cobalt or iron and a light rare earth element; a number of these alloys exhibit high-energy, hard magnetic behavior, but SmCo₅ is the only one of commercial significance.
- The energy product of these SmCo₅ materials [between 120 and 240 kJ/m³] are considerably higher than the conventional hard magnetic materials large coercivities.
- Powder metallurgical techniques are used to fabricate SmCO₅ magnets.
 - *The appropriately alloyed material is first ground into a fine powder; the powder particles are aligned using an external magnetic field and then pressed into the desired shape. The piece is then sintered at an elevated temperature, followed by another heat treatment that improves the magnetic properties.*

Neodymium–Iron–Boron Magnets $\text{Nd}_2\text{Fe}_{14}\text{B}$

- Samarium is a rare and relatively expensive material; furthermore, the price of cobalt is variable and its sources are unreliable.
- The magnetization–demagnetization behavior of these materials is a function of domain wall mobility, which, in turn, is controlled by the final microstructure—that is, the size, shape, and orientation of the crystallites or grains, as well as the nature and distribution of any second-phase particles that are present.
- One common application is in motors.
- Permanent magnets are far superior to electromagnets in that their magnetic fields are continuously maintained and without the necessity of expending electrical power; furthermore, no heat is generated during operation.

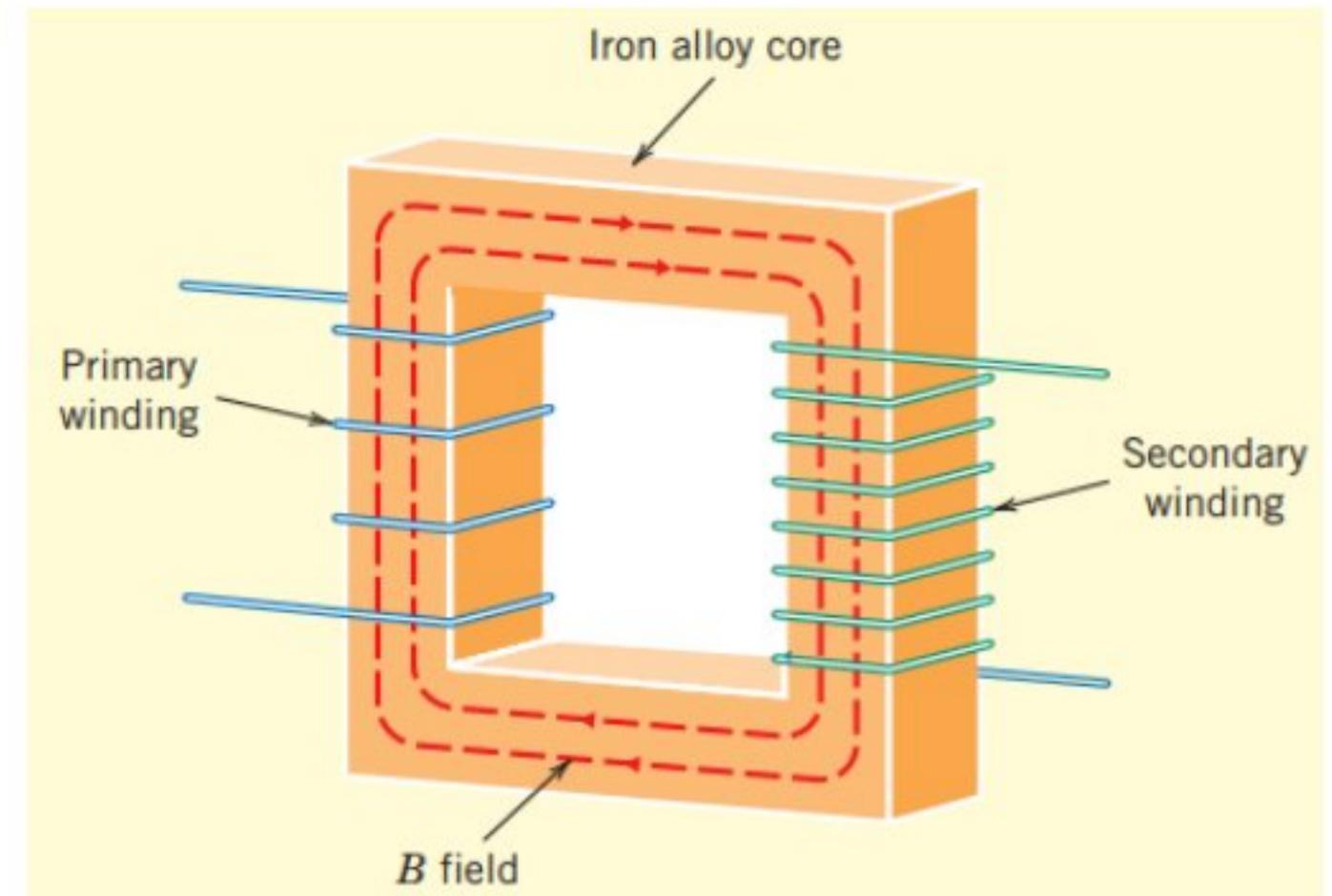
**powder metallurgy (sintering) and
rapid solidification (melt spinning).**

Applications

Transformer Cores

Fe – Si Alloy

Transformer cores require the use of soft magnetic materials, which are easily magnetized and demagnetized (and also have relatively high electrical resistivities).



Magnetic materials are important in the area of information storage; in fact, magnetic recording has become virtually the universal technology for the storage of electronic information.

Magnetic Storage

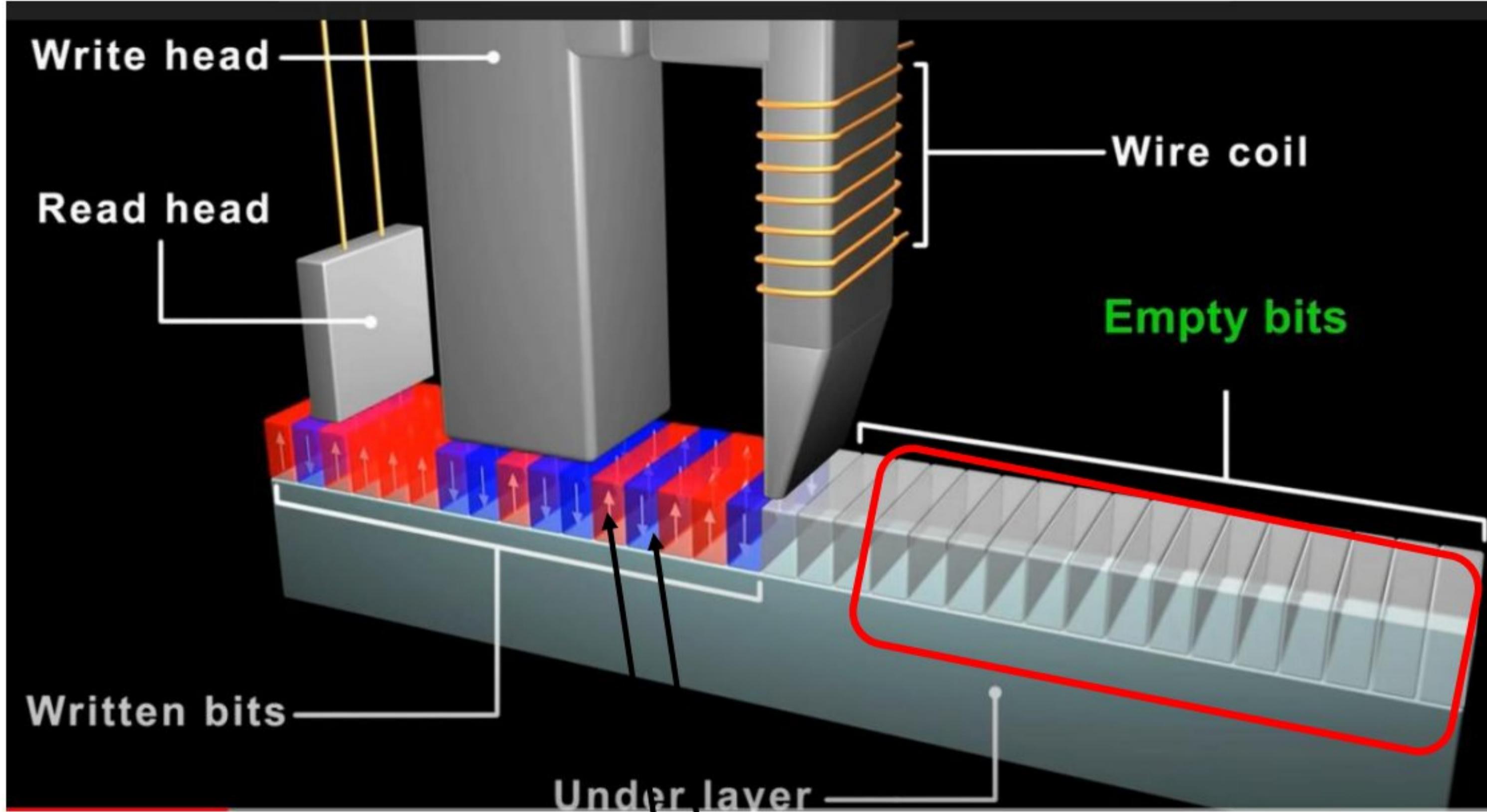
- **Magnetic Tape**
- **Hard Disk**

In computers, semiconductor elements serve as primary memory, magnetic hard disks are normally used for secondary memory because they are capable of storing larger quantities of information and at a lower cost; however, their transfer rates are slower

- **Magnetic Tape**

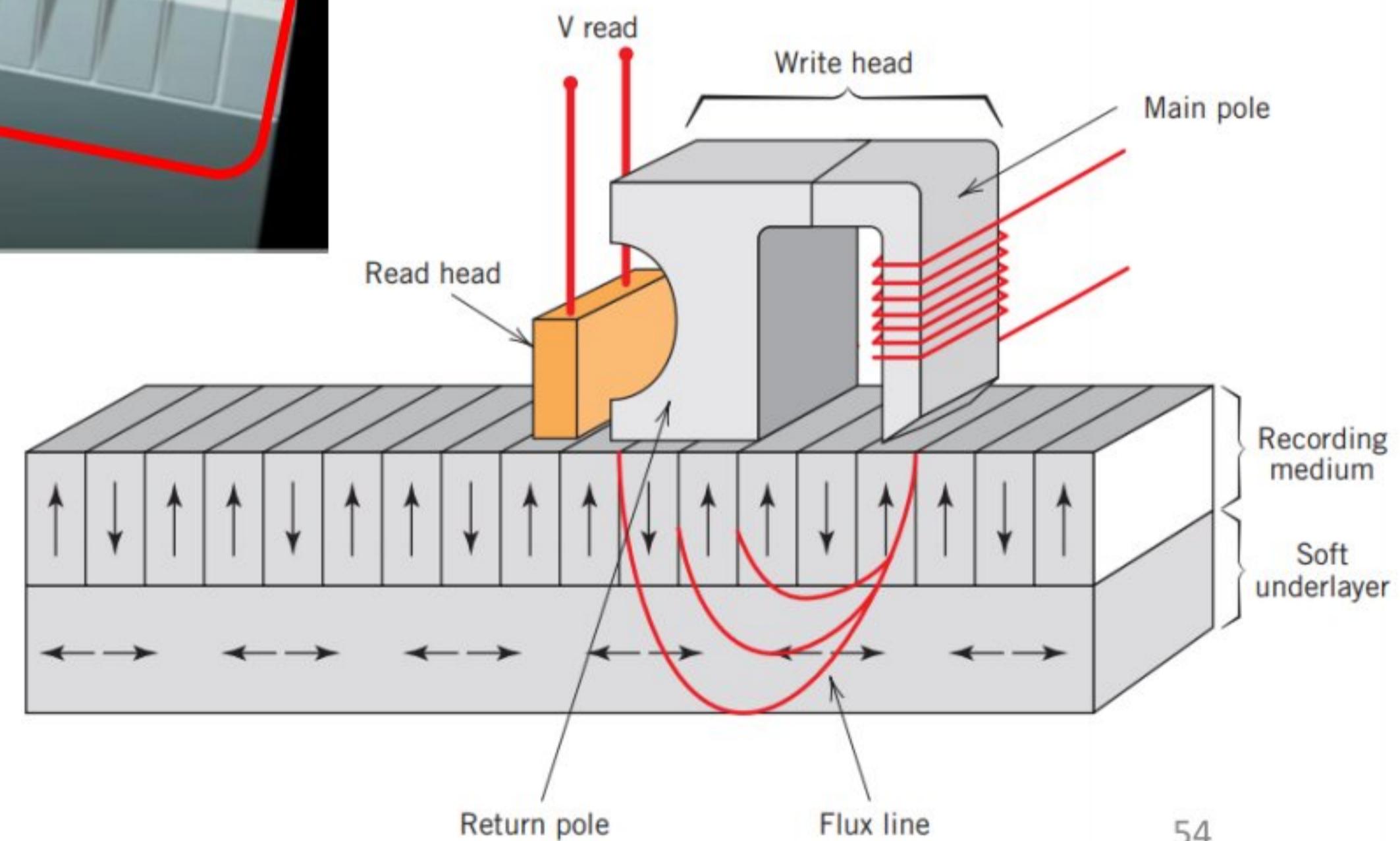


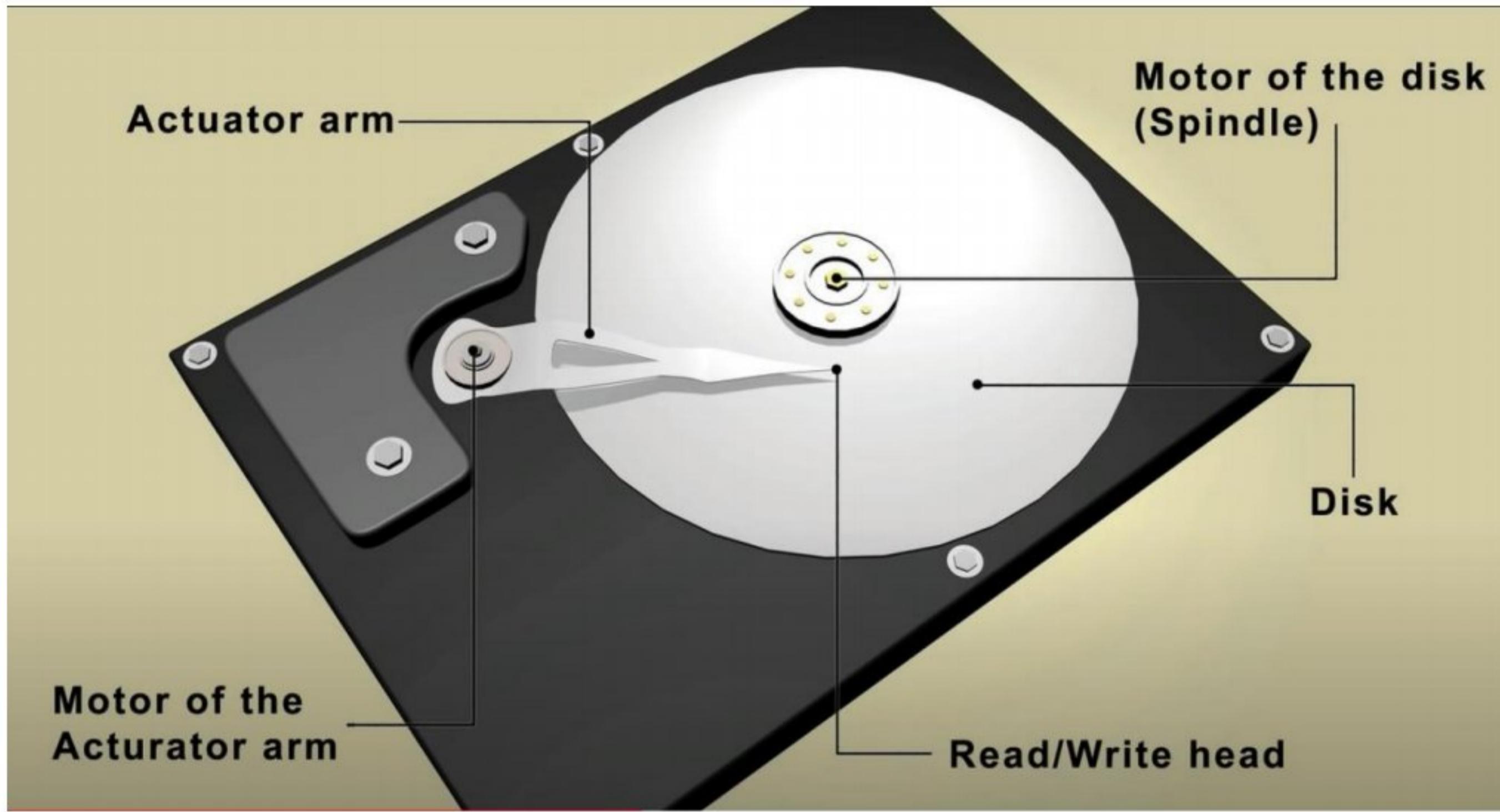
- In essence, computer bytes, sound, or visual images in the form of electrical signals are recorded magnetically on very small segments of the magnetic storage medium—a tape or disk.
- For the current HDD technology, “magnetic bits” point up or down perpendicular to the plane of the disk surface; this scheme is appropriately called *perpendicular magnetic recording* (abbreviated *PMR*)
- Data retrieval from the storage medium is accomplished using a **magneto resistive read head**. During read-back, magnetic fields from the written magnetic patterns are sensed by this head; these fields produce changes in electrical resistance.



**Change Electric Field direction
In wire coil changes direction of
Magnetic Field**

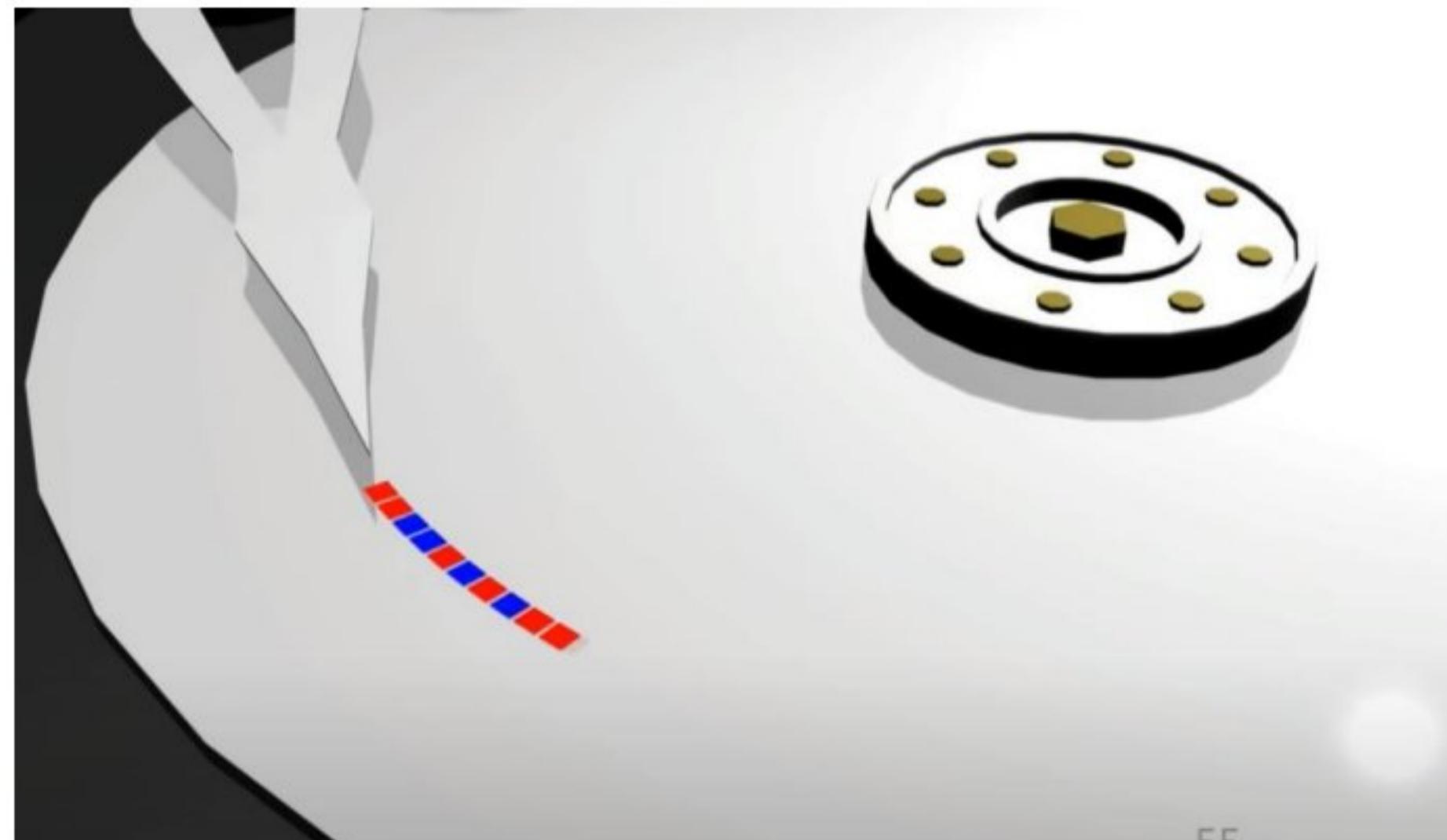
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Hard Disk Drive

Areal density is a measure of the quantity of information bits that can be **stored** on a given length of track, **area of surface**, or in a given volume of a computer **storage** medium.



Magnetic Tapes

- The development of magnetic tape storage preceded that for the hard disk drives.
- Today, tape storage is less expensive than HDD; however, areal storage densities are lower for tape (by a factor of on the order of 100).
- Tapes [of standard 0.5-in. (12.7- mm) width] are wound onto reels and enclosed within cartridges, for protection and to facilitate handling.
- During operation, a tape drive, using precision-synchronized motors, winds the tape from one reel onto another past a read/write head system in order to access a point of interest.
- Typical tape speeds are 4.8 m/s; some systems, however, run as high as 10 m/s.