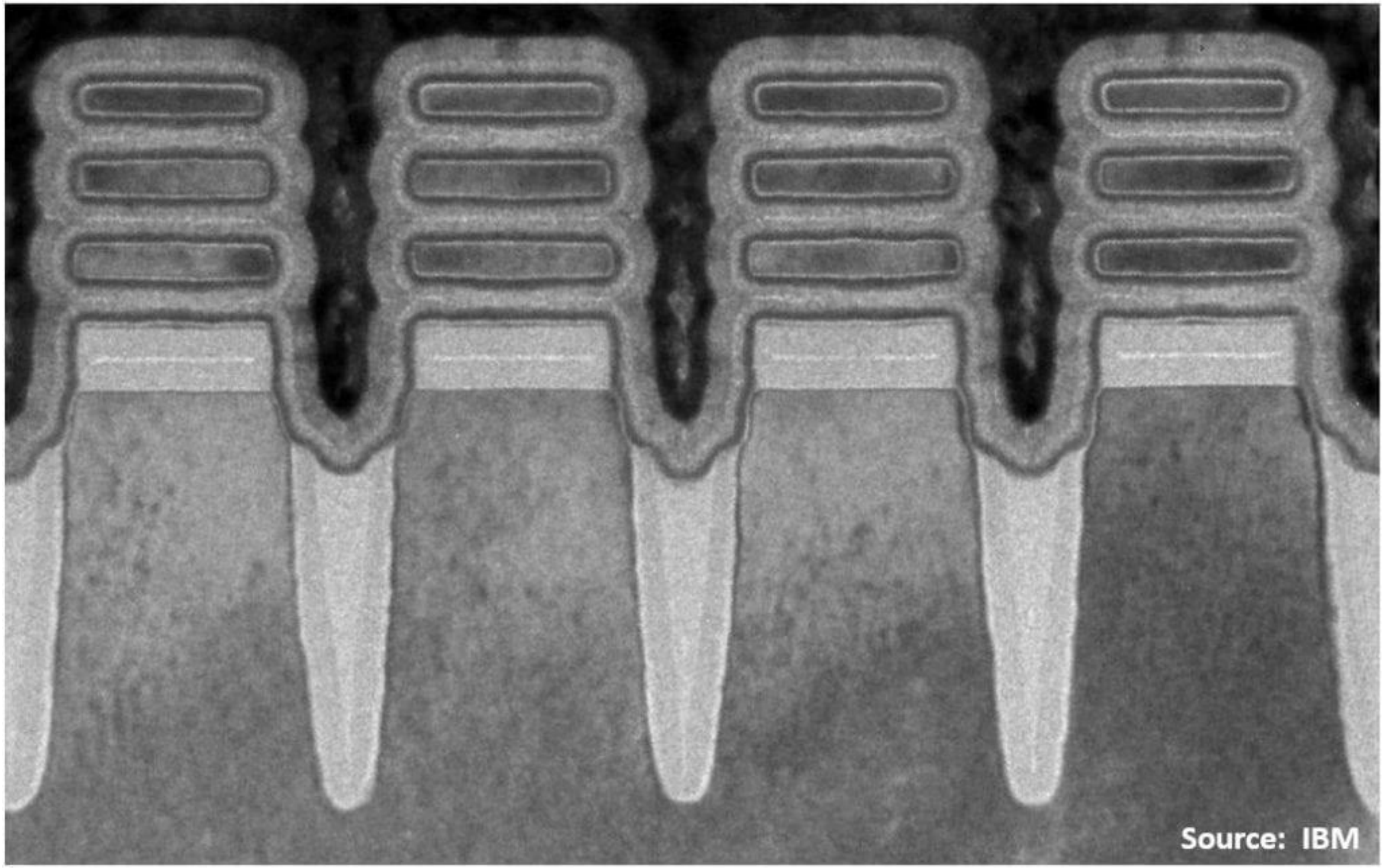
Module 2 Unit 2: Dielectrics

Dr. Suren Patwardhan



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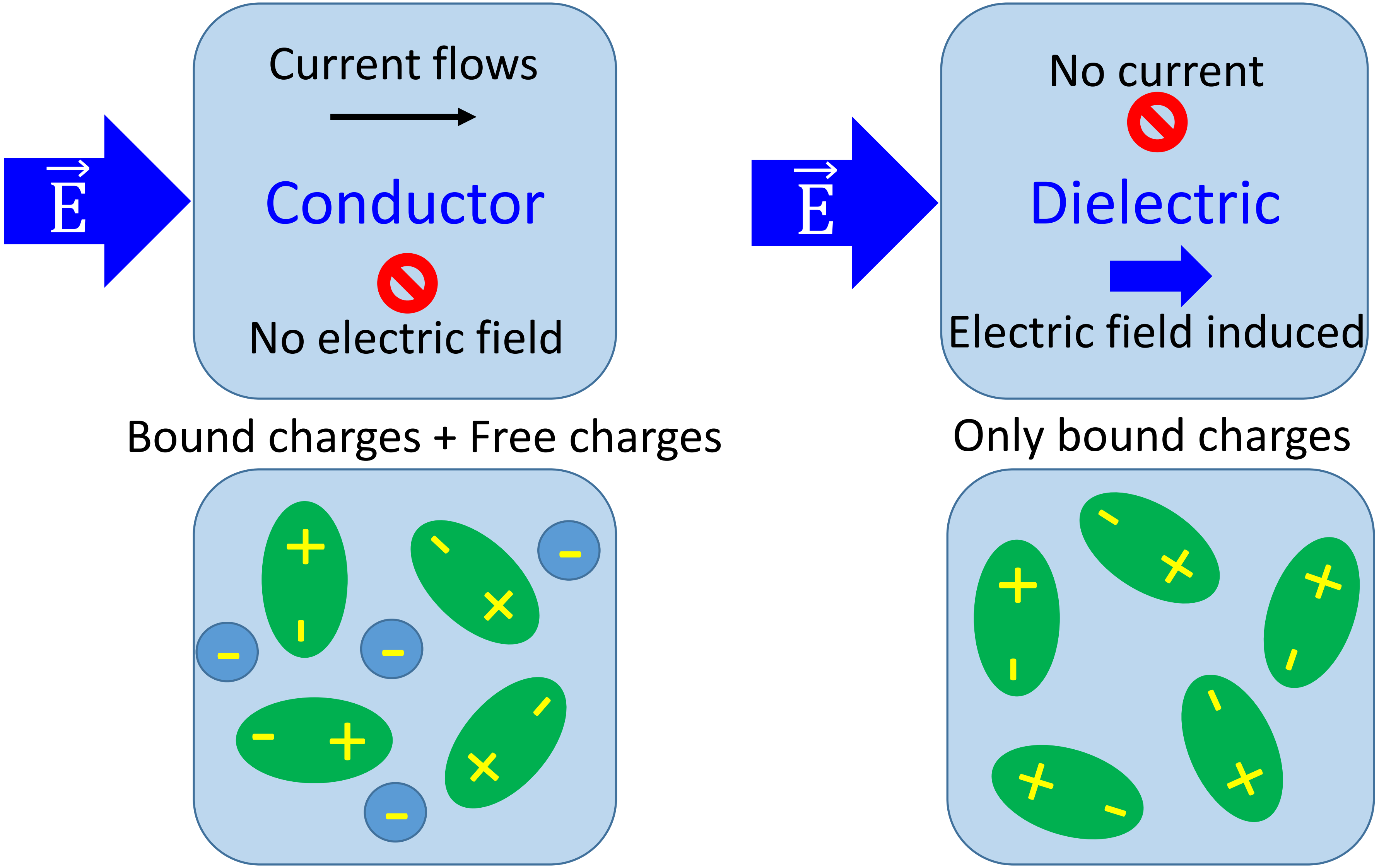
Difference between Conductor and Dielectric



Classification of Materials Based on Electric Polarization

Application of Electric Field

Conductors
- Free charges respond
- constitute current
- No electric field is set
- Example: Cu
- Use: Electric Interconnections

Insulators
- Bound charges respond
- No current flows
- Electric field is set up
- Example: Glass, Ceramic

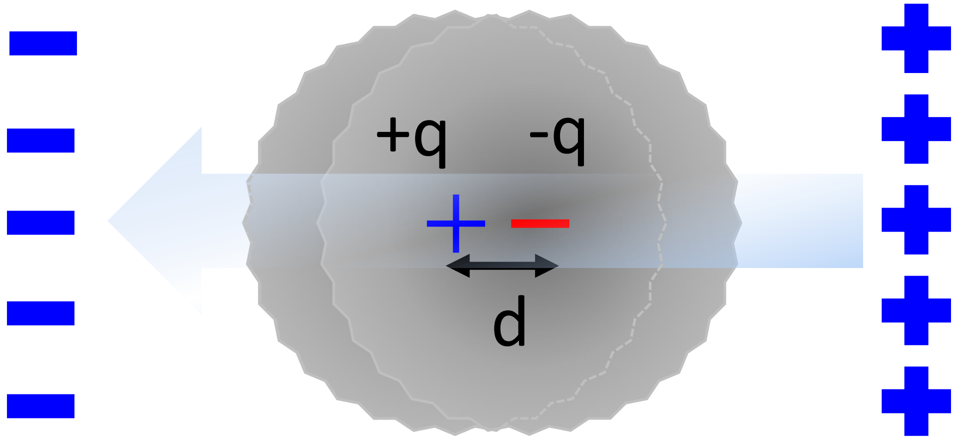
Conventional
- Weak response
- No polarization*
- Example: PVC
- Use: Electrical isolation

Dielectrics
- Strong response
- Material is polarized
- Example: Mica
- Use: Capacitors

*static charge and heat energy conversion takes place

Types of Polarization

1) Electronic/Atomic (all materials)



Induced electric dipole moment: $\vec{\mu} = qd\,\hat{r}$

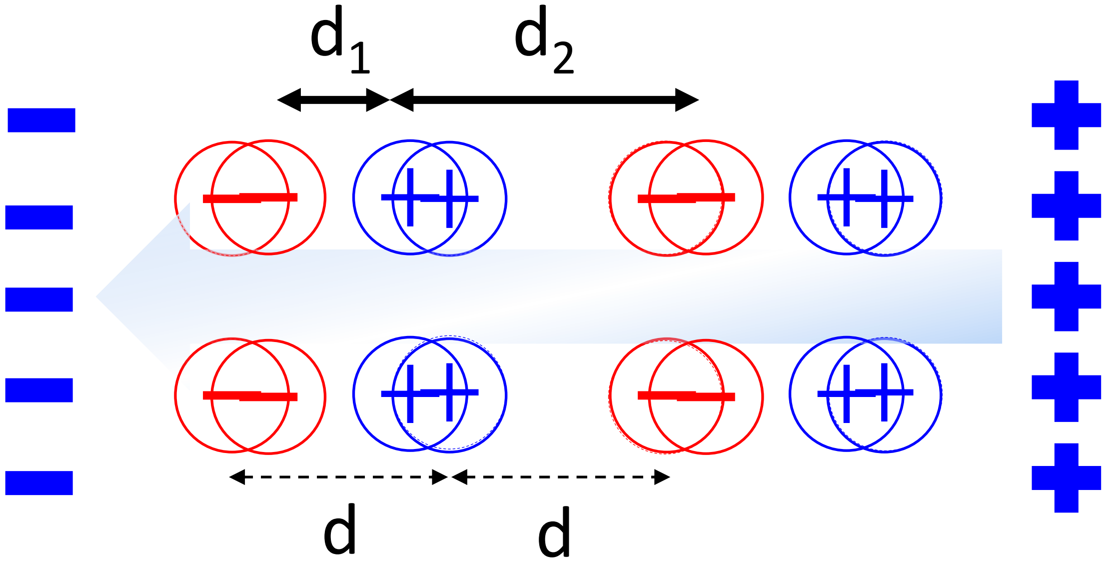
Polarization: $\vec{P} = \sum_{i=1}^{n} \vec{\mu}_i \Rightarrow \vec{P}_e = 4\pi\epsilon_0 N R^3 \vec{E}$

Types of Polarization

2) Ionic (solids possessing ionic bonds e.g. NaCl)

net dipole moment: $\vec{\mu} = \mu_2 - \mu_1 = Q(d_2 - d_1)\hat{r}$

After applying field



Before applying field

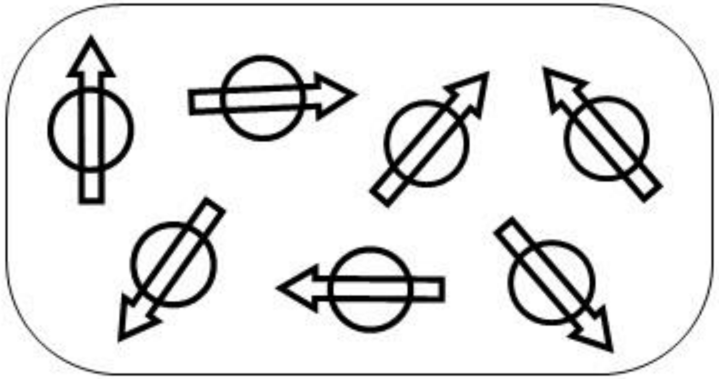
net polarization: $\vec{p} = 0$

Polarization:

$$\vec{P_i} = \frac{Ne^2}{\omega_0^2}\left[\frac{1}{M} + \frac{1}{m}\right]\vec{E}$$

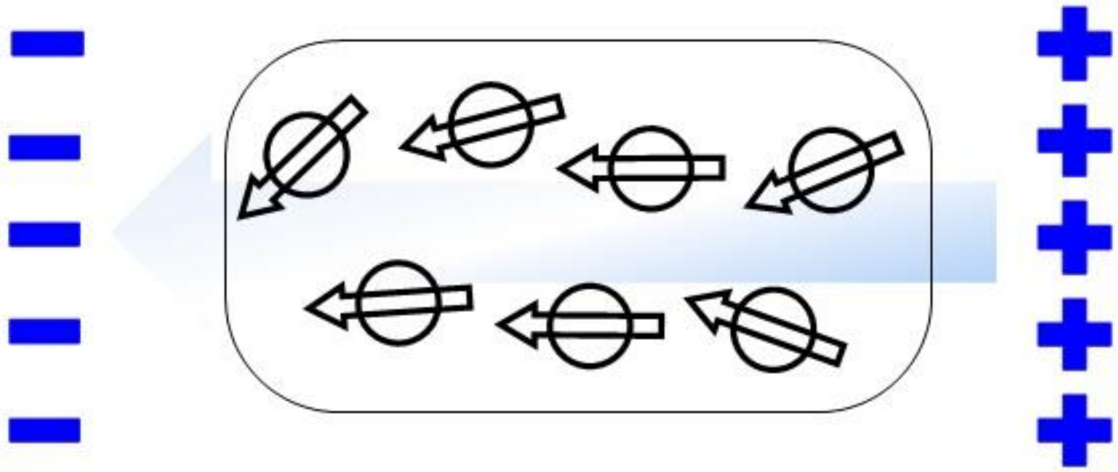
Types of Polarization

Orientational or Dipolar (polar fluids e.g. liquid crystals)



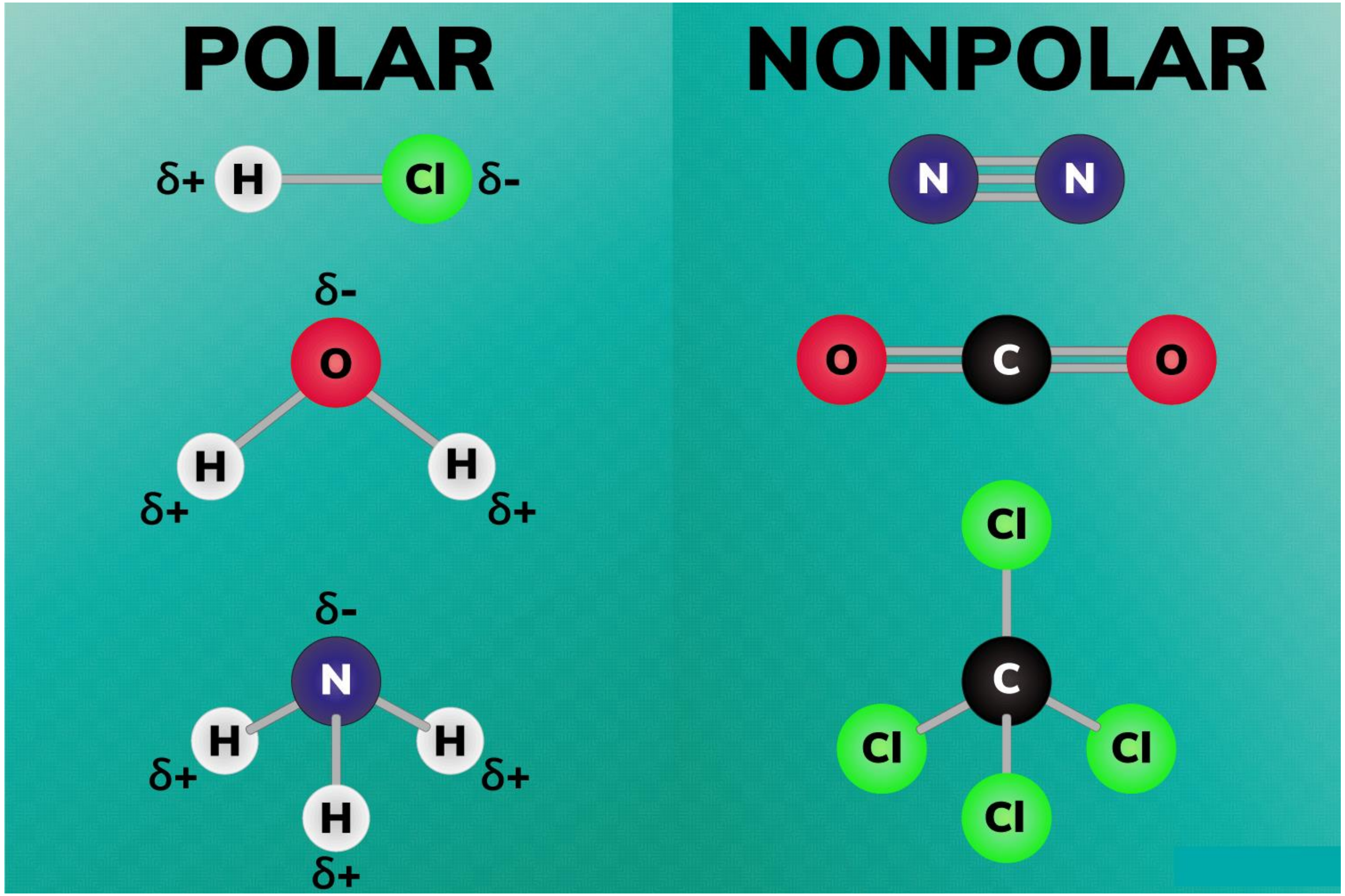
Types of Polarization

Orientational or Dipolar (polar fluids e.g. liquid crystals)



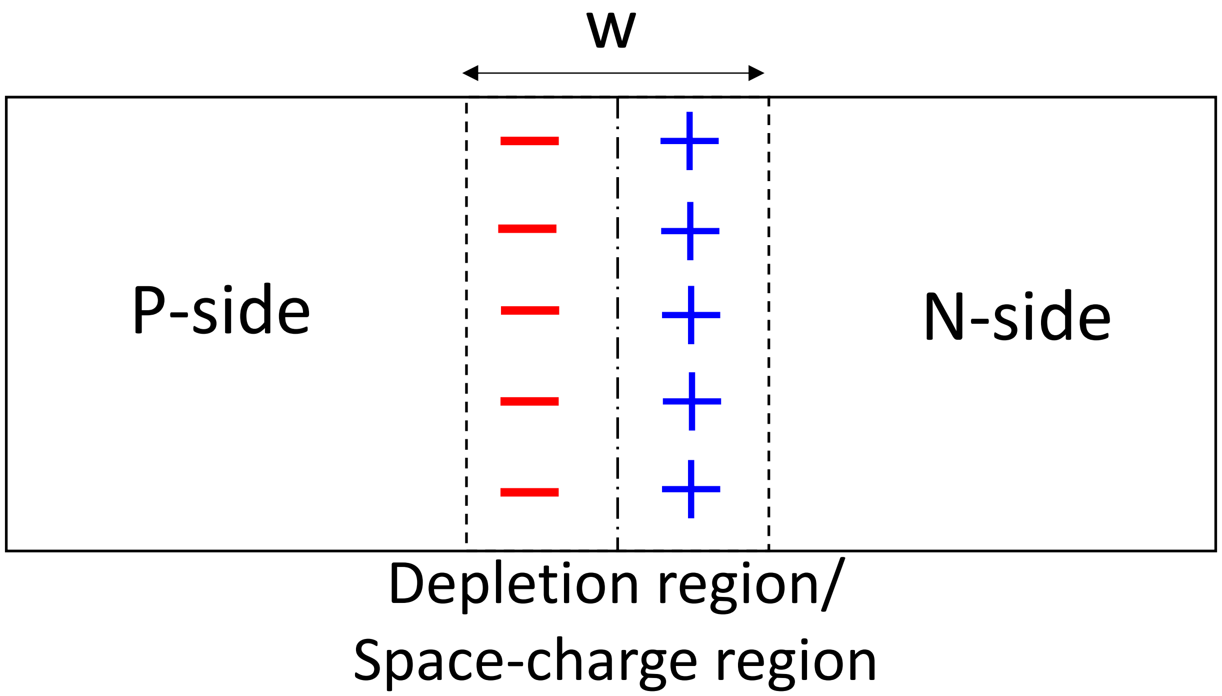
Polarization: $\vec{P} = \sum_{i=1}^{n} \vec{\mu}_i = \vec{P}_o = \frac{N\mu^2\vec{E}}{3kT}$

Polar and Non-polar Molecules



Types of Polarization

Space-charge or Interfacial (e.g. p-n junction, metal-semiconductor junction, Metal Oxide-Semiconductor junction)



Polarization: $\vec{P} = qN_D A w\hat{r}$

Expressions for Dielectric Parameters

Dielectric Quantity	Expression
Electric field ($\vec{E}$)	$\vec{E} = -\vec{\nabla}V = -\frac{dV}{dx}$ (in 1 − D) (for calculations, $E = \frac{V}{d}$)
Electric Displacement ($\vec{D}$)	$\vec{D} = \epsilon_0 k\vec{E}$, $\vec{D} = \epsilon_0\vec{E} + \vec{P}$
Polarization ($\vec{P}$):	$\vec{P} = \epsilon_0\chi_e\vec{E} = \epsilon_0(k-1)\vec{E}$ $\vec{P} = \frac{\sum \vec{\mu}_j}{V} = \alpha N\vec{E}$
Capacitance (C):	$C = \frac{k\epsilon_0 A}{d}$
Electric dipole moment ($\vec{\mu}$):	$\vec{\mu} = Qd\,\hat{r}$

Polarizability and Dielectric Constant

Dielectric Quantity	Expression
Polarizability (α):	$\vec{\mu} = \alpha\vec{E}$
Electronic polarizability:	$\alpha_e = 4\pi\epsilon_0 R^3$

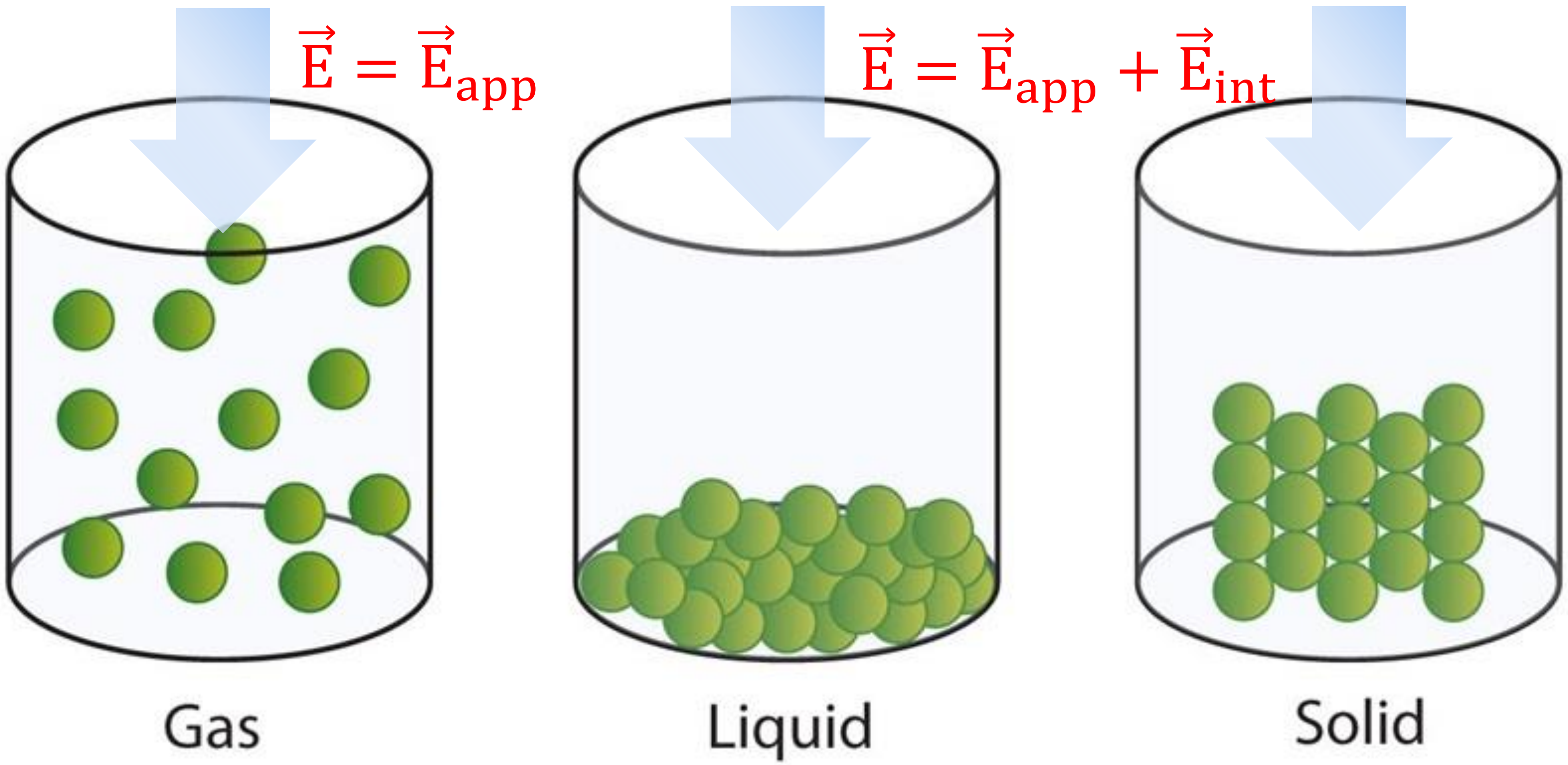
$\alpha = \dfrac{\epsilon_0(k-1)}{N}$	gases
$\alpha = \dfrac{3\epsilon_0}{N}\dfrac{(k-1)}{(k+2)}$ (Claussius-Mosotti Equation)	solids and liquids

Internal Fields in Solids and Liquids

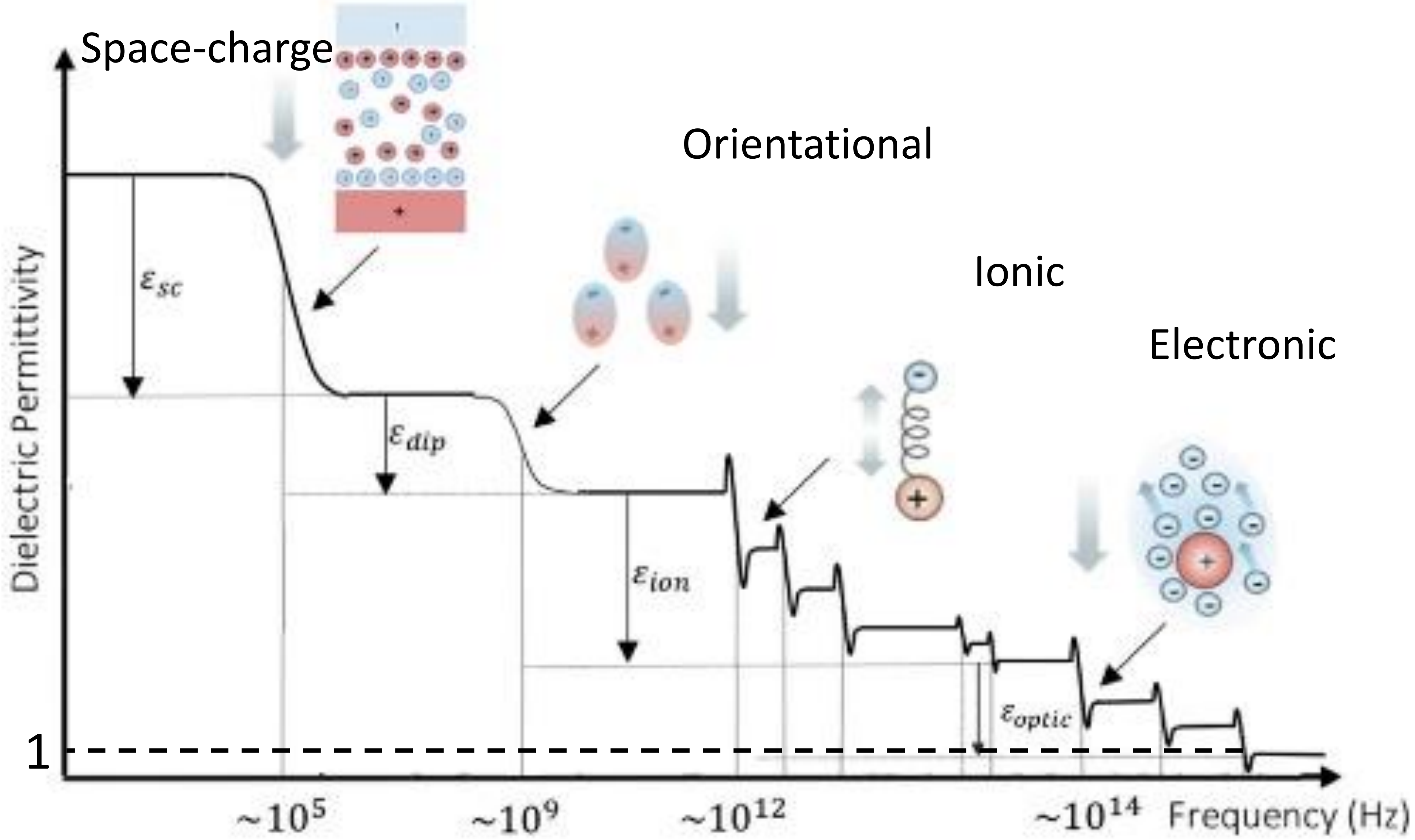
- In gases, atoms/molecules are far away from each other
- In solids and liquids, atoms/molecules are in close proximity
- Each atom/molecule is influenced by polarization of neighbours

Internal field: $\vec{E}_i = \frac{\gamma \vec{P}}{\epsilon_0}$;

γ: Internal field constant



Frequency Dependence Of Dielectric "Constant"



Frequency Dependence Of Polarization

Total polarization is given by

$$P = \mathrm{Electronic} + \mathrm{Ionic} + \mathrm{Orientational} = N(\alpha_e + \alpha_i + \alpha_o)E$$

Frequency regime	Range	Type of polarization present
Quasi-DC	1-10 Hz	All of electronic, ionic, orientational and Space charge
Audio	KHz – MHz (10^3-10^6)	All electronic, ionic and orientational *except* space charge
RF to Microwave	MHz – THz (10^6-10^{12})	Only electronic and ionic
IR to Optical	THz – PHz (10^{12}-10^{15})	Only electronic
UV	> PHz (10^{15})	None

Dielectric Strength

Insulating material	Dielectric constant or relative permittivity	Dielectric Strength in kV/mm
Air	1.0006	3.2
Asbestos*	2	2
Bakelite	5	15
Epoxy	3.3	20
Glass	5-12	12-100
Marble*	7	2
Mica	4-8	20-200
Micanite	4-5-6	25-35
Mineral Oil	2.2	10
Mylar	3	400
Nylon	4.1	16
Paper	1.8-2.6	18
Paraffin wax	1.7-2.3	30
Polyethylene	2.3	40
Polyurethane	3.6	35
Porcelain	5-6.7	15
PVC	3.7	50
Quartz	4.5-4.7	8
Rubber	2.5-4	12-20
Teflon	2	20

Max voltage a dielectric material can withstand before electric discharge

Dielectric Relaxation Time and Relaxation Frequency

- Dielectric relaxation time (τ_r):

  Average time taken by the dipole to orient in the field direction

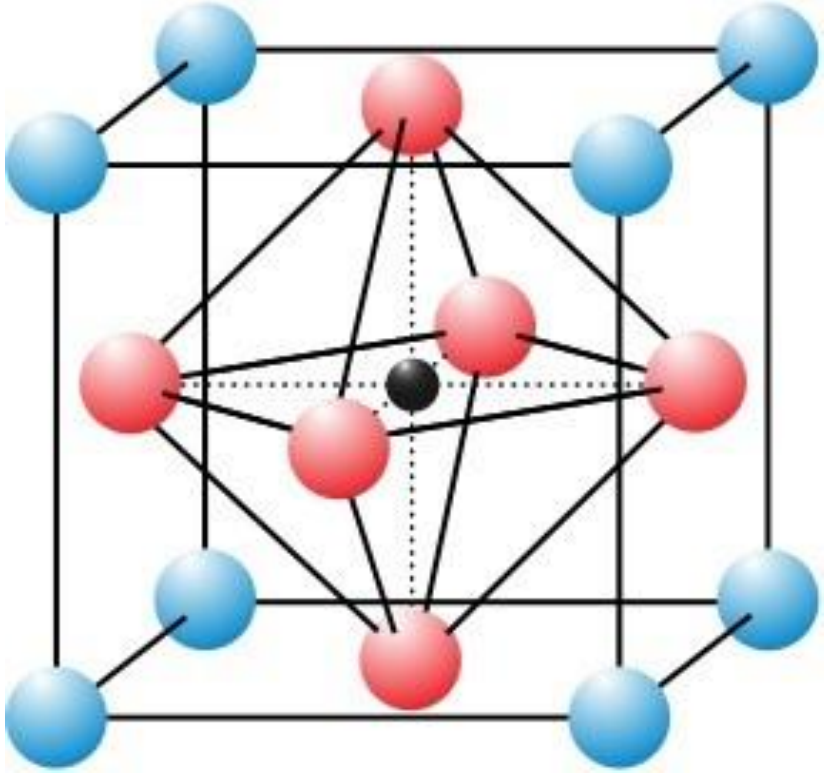
- Dielectric frequency (f_r):

  Reciprocal of relaxation time

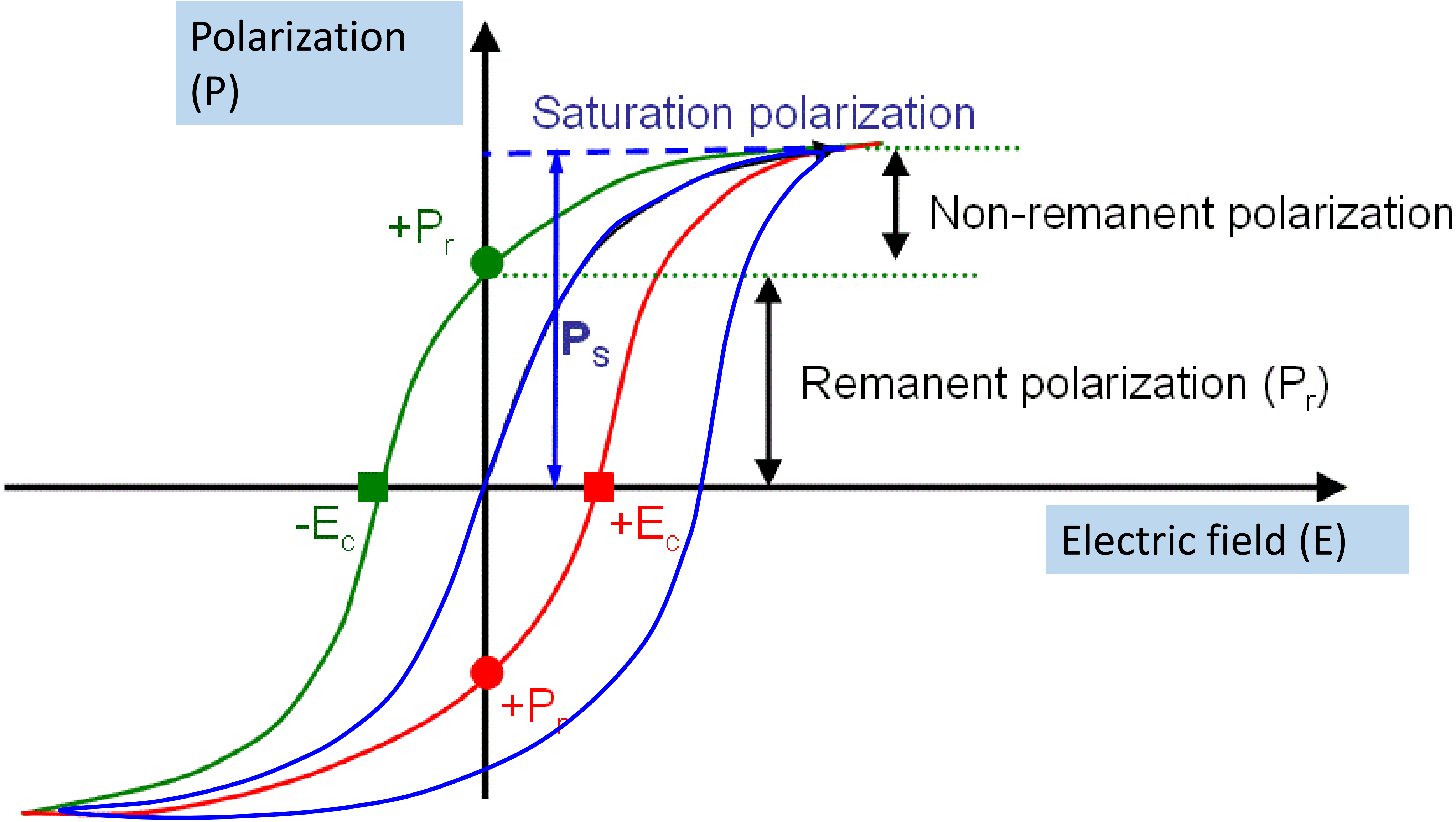
- If $f_{\text{electric field}} > f_r$ dipoles cannot orient themselves along the field
- Condition for alignment of dipoles: $\tau_r \leq \frac{T_{\text{electric field}}}{2}$

Ferroelectricity

- Spontaneous polarization shown by certain materials e.g. $BaTiO_3$, $PbTiO_3$
- Very high permittivity: 1000 to 10000
- Non-linear dependence of polarization on electric field



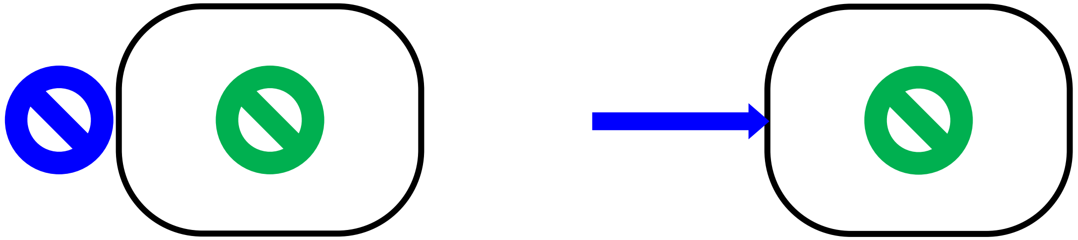
Ferroelectricity



Hysteresis Effect of a Ferroelectric Material

Means: Some electric field is "consumed"

Hysteresis is "non-conservative" process



Initial state was:

Electric field = 0

Polarization = 0

After one cycle:

Electric field ≠ 0

Polarization = 0

Electric field increases
Polarization increases

Electric field increases further
Polarization saturates

Electric field decreases
Polarization decreases

Electric field becomes zero
Polarization retains

Electric field reversed
Polarization becomes zero

Applications of Dielectric Materials

- Capacitors (paper, ceramic, plastic, vacuum)
- Heating appliances (mica)
- Power line transmission (ceramic discs)
- High-tension Transformers (Dielectric liquids)
- Displays (Liquid crystals)
- Sensors (MEMs)
- USB/Flash memory (floating gate MOSFET)
- Semiconductor Chips (conventional MOSFET, FinFETs, GAAFETs, MBCFETs)