Electronic Materials and Devices

6 Dielectric materials and insulation

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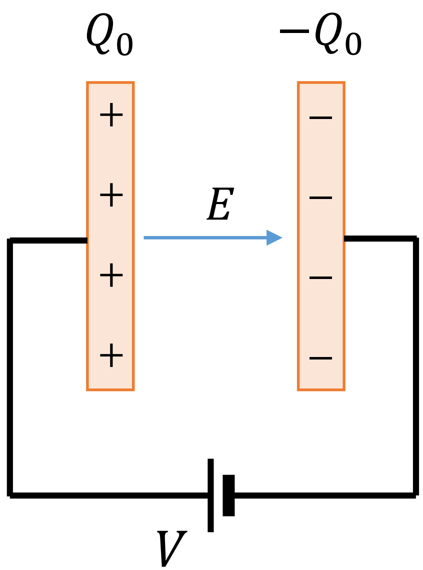
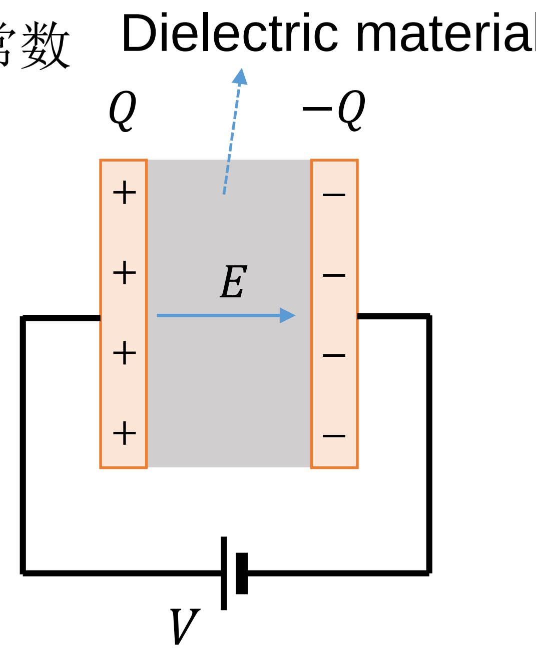
电子与电气工程系

6.1 Matter polarization and relative permittivity

物质极化与相对介电常数



$$E = V/d$$



Capacitance of parallel plate capacitor in vacuum:

$$C_0 = Q_0/V$$

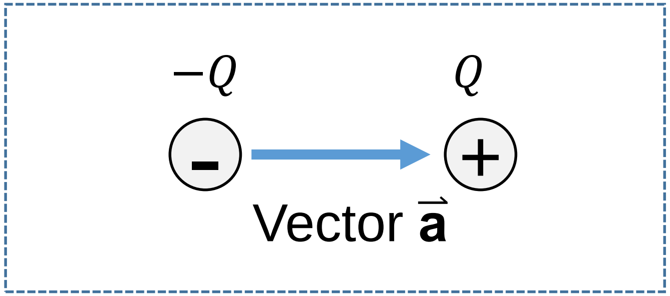
Capacitance of parallel plate capacitor in dielectric material:

$$C = Q/V$$

Relative permittivity/dielectric constant is defined as:

$$\varepsilon_r = Q/Q_0$$

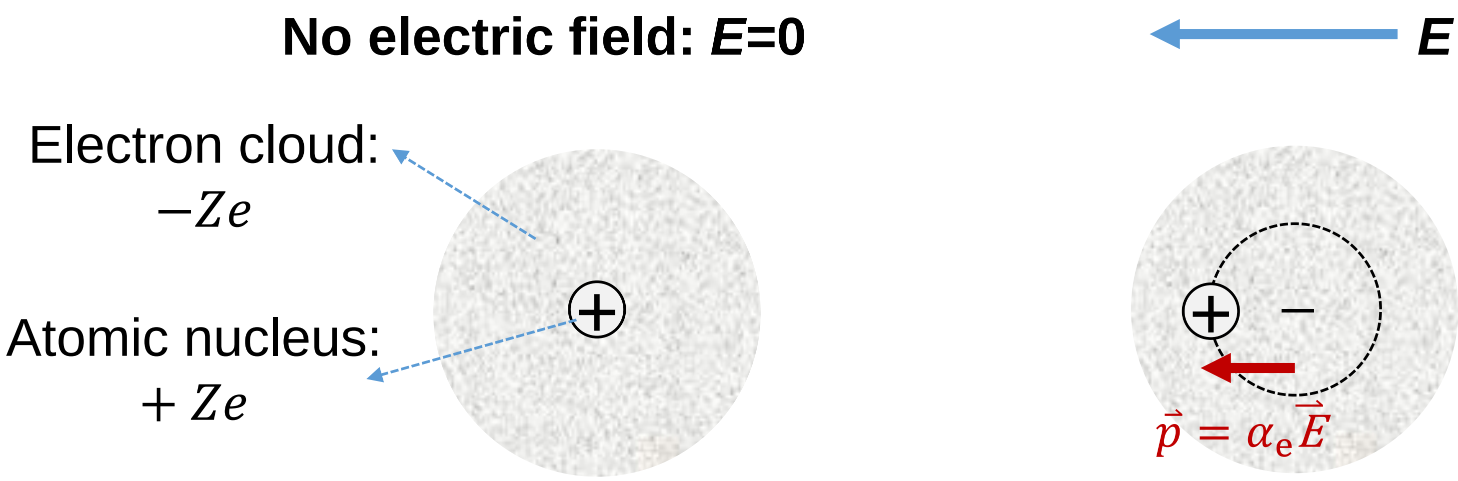
Electric dipole moment 电偶极矩



$Q_{\mathrm{net}} = 0$

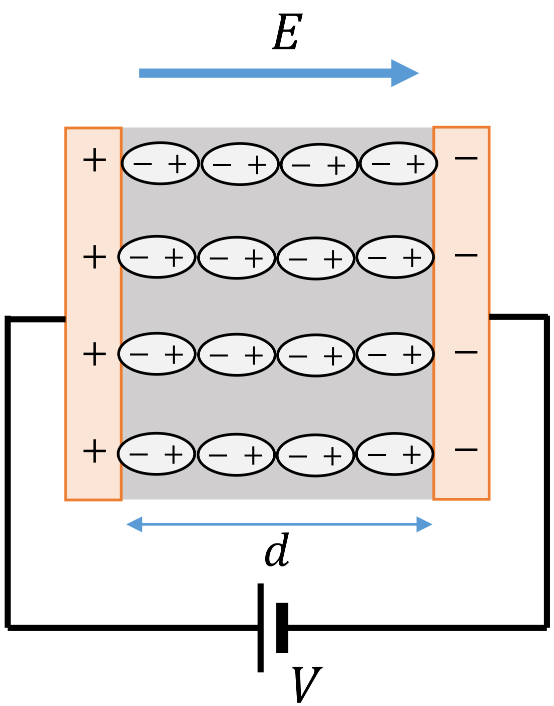
Electric dipole moment: $\vec{p} = Q\vec{\mathbf{a}}$

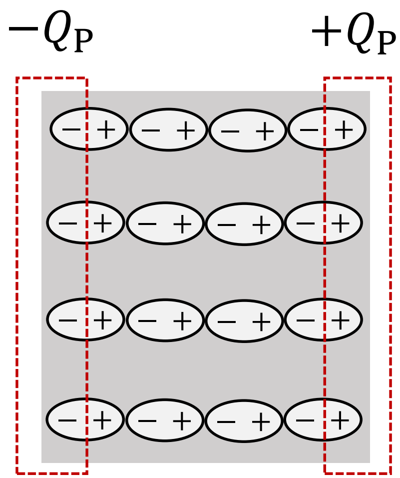
Electric dipole moment in an atom

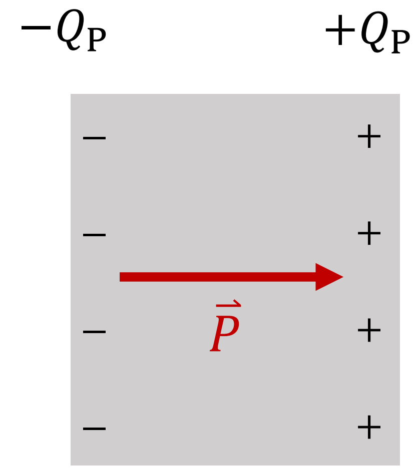


A dipole is induced: $\vec{p} = \alpha_e \vec{E}$

polarizability 极化率α_e is called the electronic polarization







Charges are bound受束缚的.

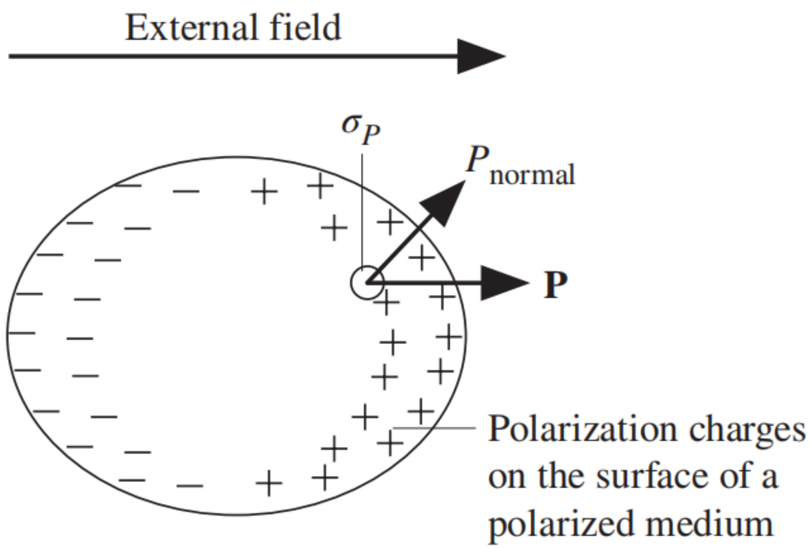
The **polarization vector** of the medium: $\vec{P} = \frac{1}{\mathrm{Volume}}[\vec{p}_1 + \vec{p}_2 + \cdots + \vec{p}_\mathrm{N}]$

极化矢量

$$P = \frac{Q_\mathrm{P} d}{\mathrm{Volume}} = \frac{Q_\mathrm{P} d}{Ad} = \frac{Q_\mathrm{P}}{A} = \sigma_\mathrm{P}$$

Q_P： surface polarization charges

σ_P： surface polarization charge density



$$P_{\text{normal}} = \sigma_{\text{P}}$$

$$P = \chi_{\text{e}} \varepsilon_0 E$$

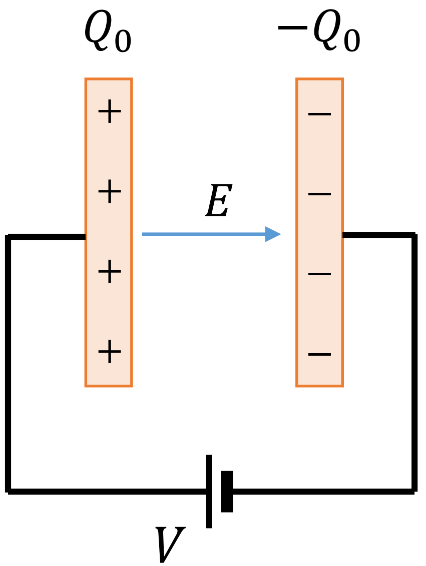
χ_{e}: electric susceptibility 电极化率

Relation between polarizability α_{e} and susceptibility χ_{e}:

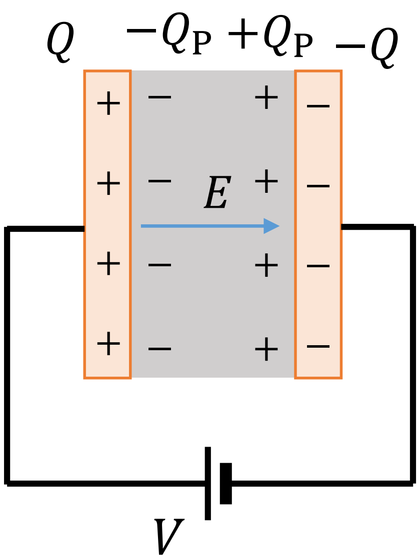
$$\begin{cases} P = \chi_{\text{e}} \varepsilon_0 E \\ P = N \alpha_{\text{e}} E \end{cases} \Rightarrow \chi_{\text{e}} = \frac{1}{\varepsilon_0} N \alpha_{\text{e}}$$

N: number of molecules per unit volume

Relation between relative permittivity and susceptibility χ_e



$$E = V/d$$



Because electric field is the same with and without dielectric medium

$$Q_0 = Q - Q_\mathrm{P}$$

$$\varepsilon_0 E = \sigma - \sigma_\mathrm{P}$$

$$
\begin{cases}
\varepsilon_0 E = \sigma - \sigma_{\mathrm{P}} \\
P = \chi_{\mathrm{e}} \varepsilon_0 E \\
P = \sigma_{\mathrm{P}}
\end{cases}
$$

$$\Downarrow$$

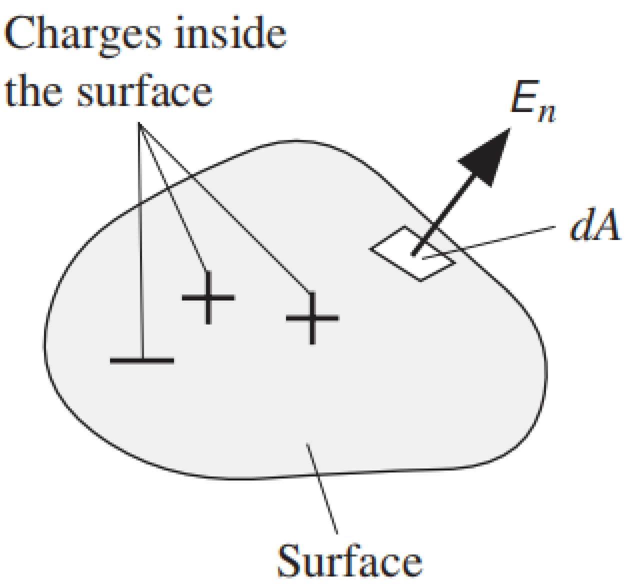
$$\sigma = \varepsilon_0 (1 + \chi_{\mathrm{e}}) E$$

$$\Downarrow$$

$$
\begin{cases}
\varepsilon_{\mathrm{r}} = \dfrac{Q}{Q_0} = \dfrac{\sigma}{\sigma_0} = 1 + \chi_{\mathrm{e}} \\
\varepsilon_{\mathrm{r}} = 1 + \dfrac{1}{\varepsilon_0} N \alpha_{\mathrm{e}}
\end{cases}
$$

$$P = \chi_{\mathrm{e}} \varepsilon_0 E = (\varepsilon_{\mathrm{r}} - 1) \varepsilon_0 E$$

6.2 Gauss's law and boundary conditions



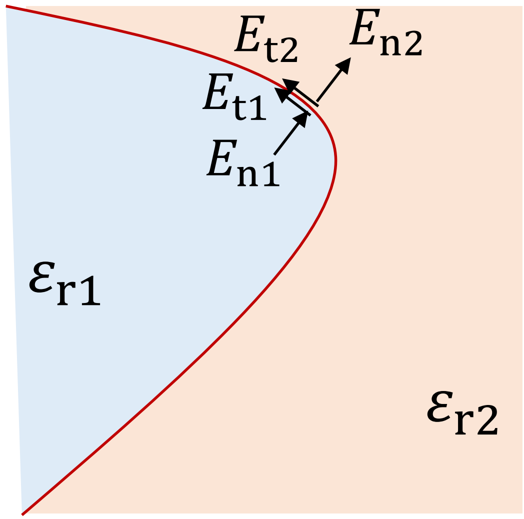
Gauss's law:

$$\oint_{\text{surface}} E_{\mathrm{n}} \mathrm{d}A = \frac{Q_{\text{total}}}{\varepsilon_0}$$

$$\oint_{\text{surface}} E_{\mathrm{n}} \mathrm{d}A = \frac{Q_{\text{free}}}{\varepsilon_{\mathrm{r}}\varepsilon_0}$$

Total charge $\boldsymbol{Q_{\text{total}}}$: free charges Q_{free} and bound polarization charges.

Boundary conditions



The first boundary condition: $\varepsilon_{\mathrm{r1}} E_{\mathrm{n1}} = \varepsilon_{\mathrm{r2}} E_{\mathrm{n2}}$

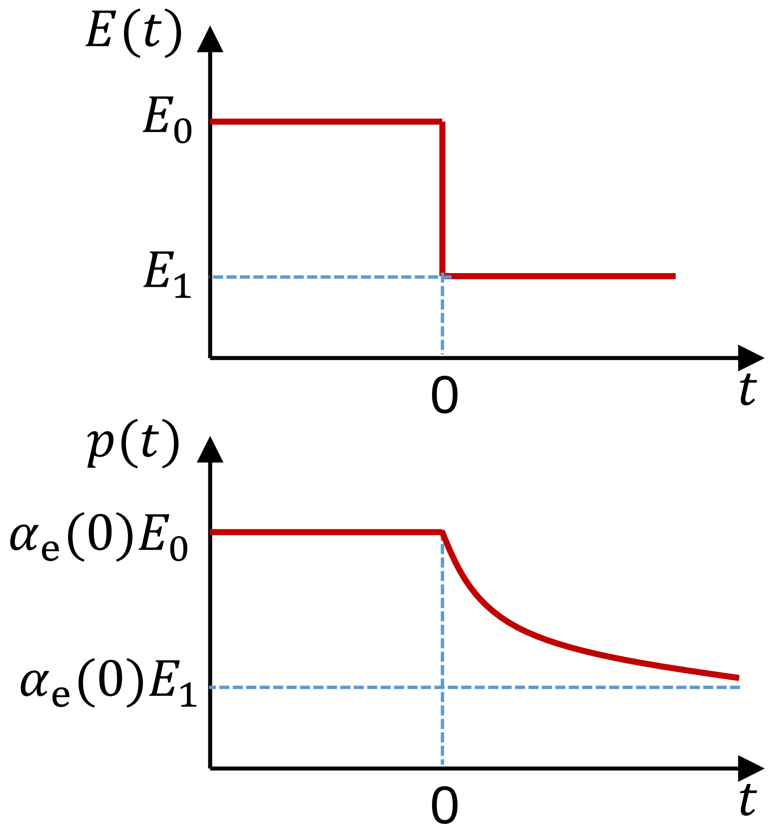
The second boundary condition: $E_{\mathrm{t1}} = E_{\mathrm{t2}}$

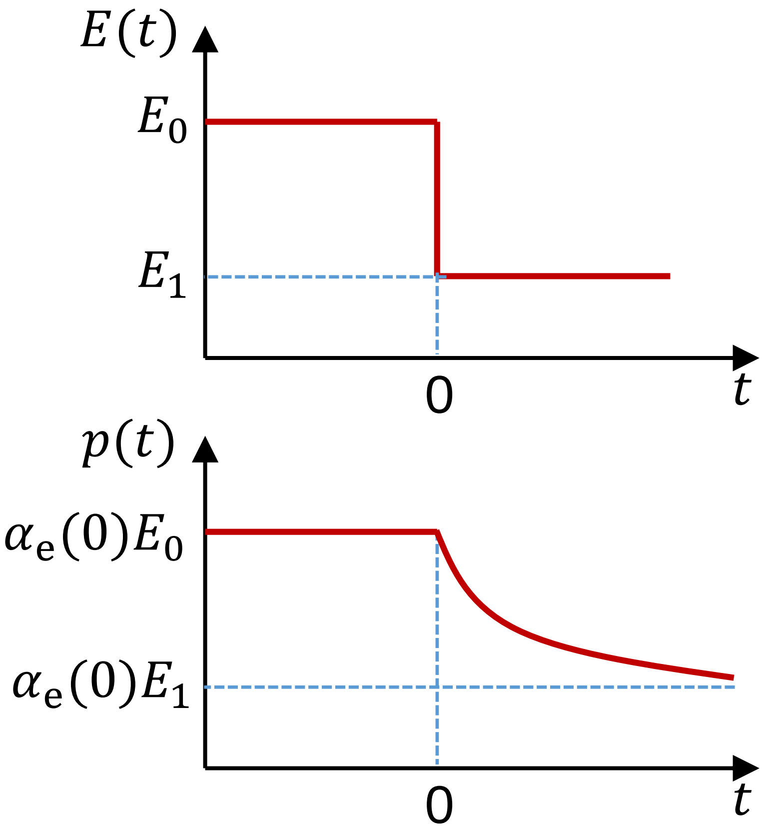
6.3 Frequency dependence: dielectric constant and dielectric loss

Under DC voltage bias ($\omega = 0$), the polarizability is $\alpha_{\mathrm{e}}(0)$.

The dipole moment per molecule: $p = \alpha_{\mathrm{e}} E$.

Transient behavior 瞬时行为





Assume τ is the relaxation time, the relaxation equation:

$$\frac{dp}{dt} = -\frac{p - \alpha_e E}{\tau}$$

For AC voltage bias (ω), $E = E_0 \exp(\mathrm{j}\omega t)$.

$$\frac{dp}{dt} = -\frac{p}{\tau} + \frac{\alpha_\mathrm{e}(0)}{\tau} E_0 \exp(\mathrm{j}\omega t)$$

$$\Downarrow$$

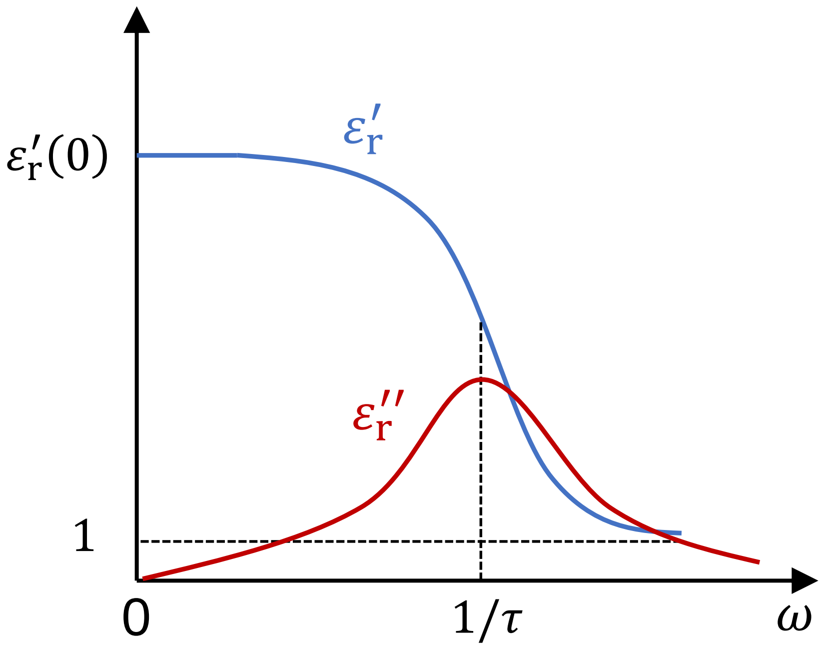
$$\begin{cases} p = \alpha_\mathrm{e}(\omega) E_0 \exp(\mathrm{j}\omega t) \\[2ex] \alpha_\mathrm{e}(\omega) = \dfrac{\alpha_\mathrm{e}(0)}{1 + \mathrm{j}\omega\tau} \end{cases}$$

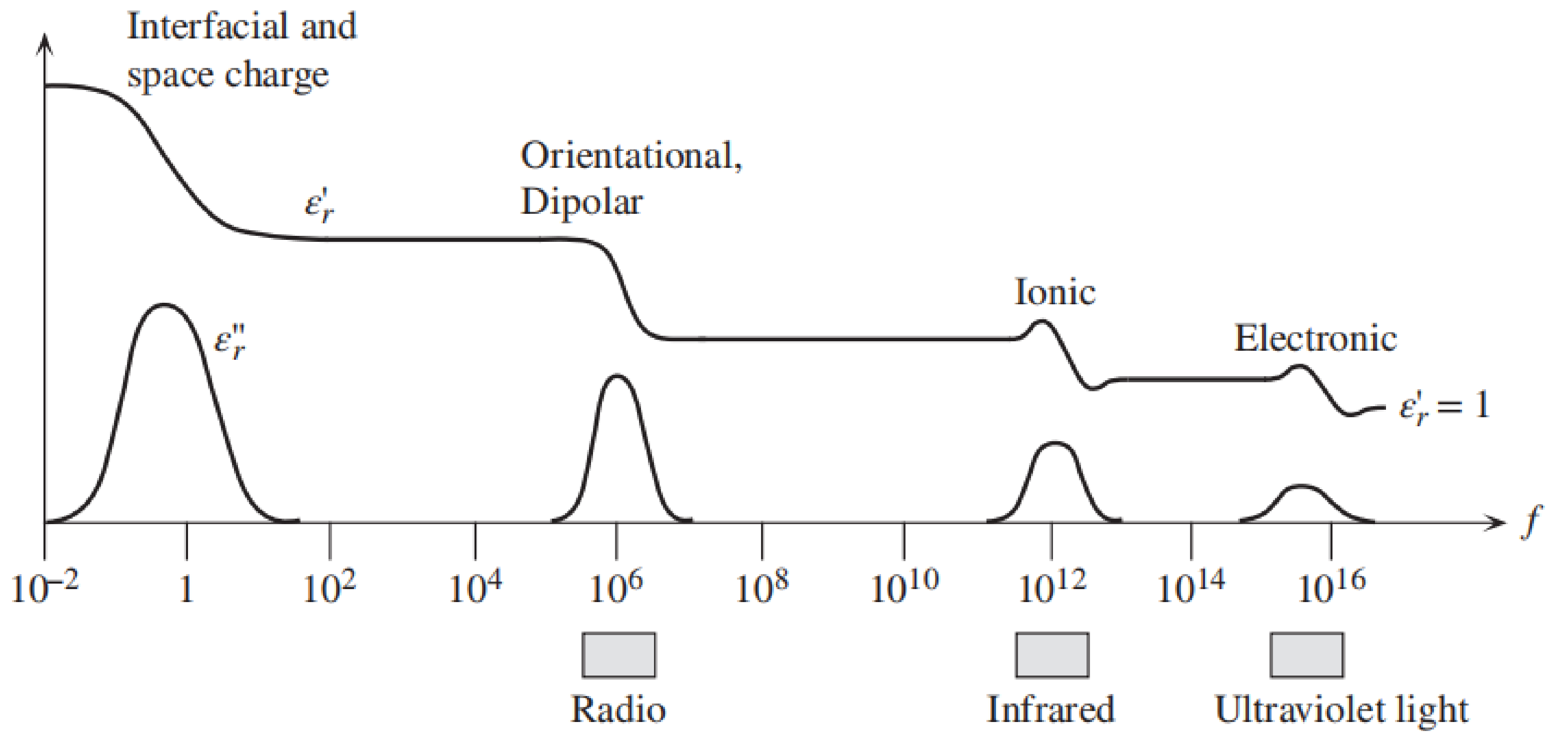
Complex dielectric constant

$$\varepsilon_r(\omega) = 1 + \frac{1}{\varepsilon_0} N \alpha_e(\omega)$$

$$\varepsilon_r(\omega) = 1 + \frac{1}{\varepsilon_0} N \frac{\alpha_e(0)}{1 + j\omega\tau}$$

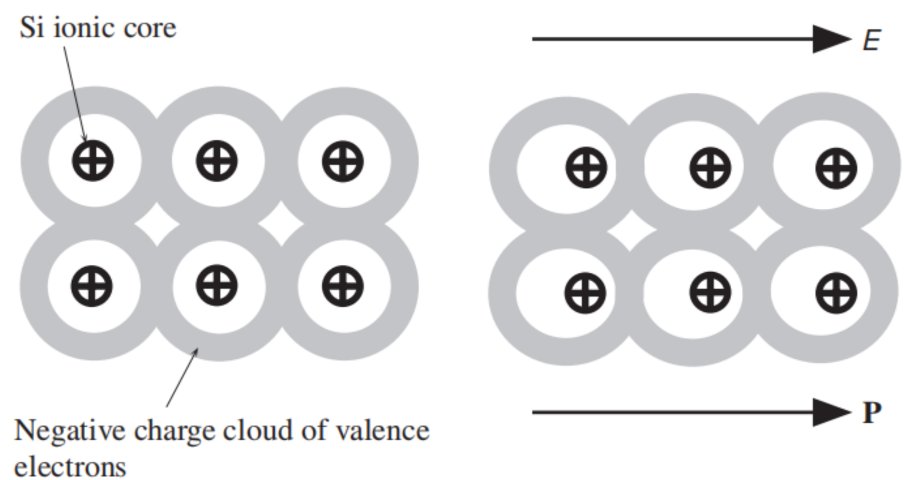
$$\begin{cases} \varepsilon_r(\omega) = \varepsilon_r'(\omega) - j\varepsilon_r''(\omega) \\ \varepsilon_r'(\omega) = 1 + \dfrac{N}{\varepsilon_0(1+\omega^2\tau^2)} \alpha_e(0) \\ \varepsilon_r''(\omega) = \dfrac{N\omega\tau}{\varepsilon_0(1+\omega^2\tau^2)} \alpha_e(0) \end{cases}$$

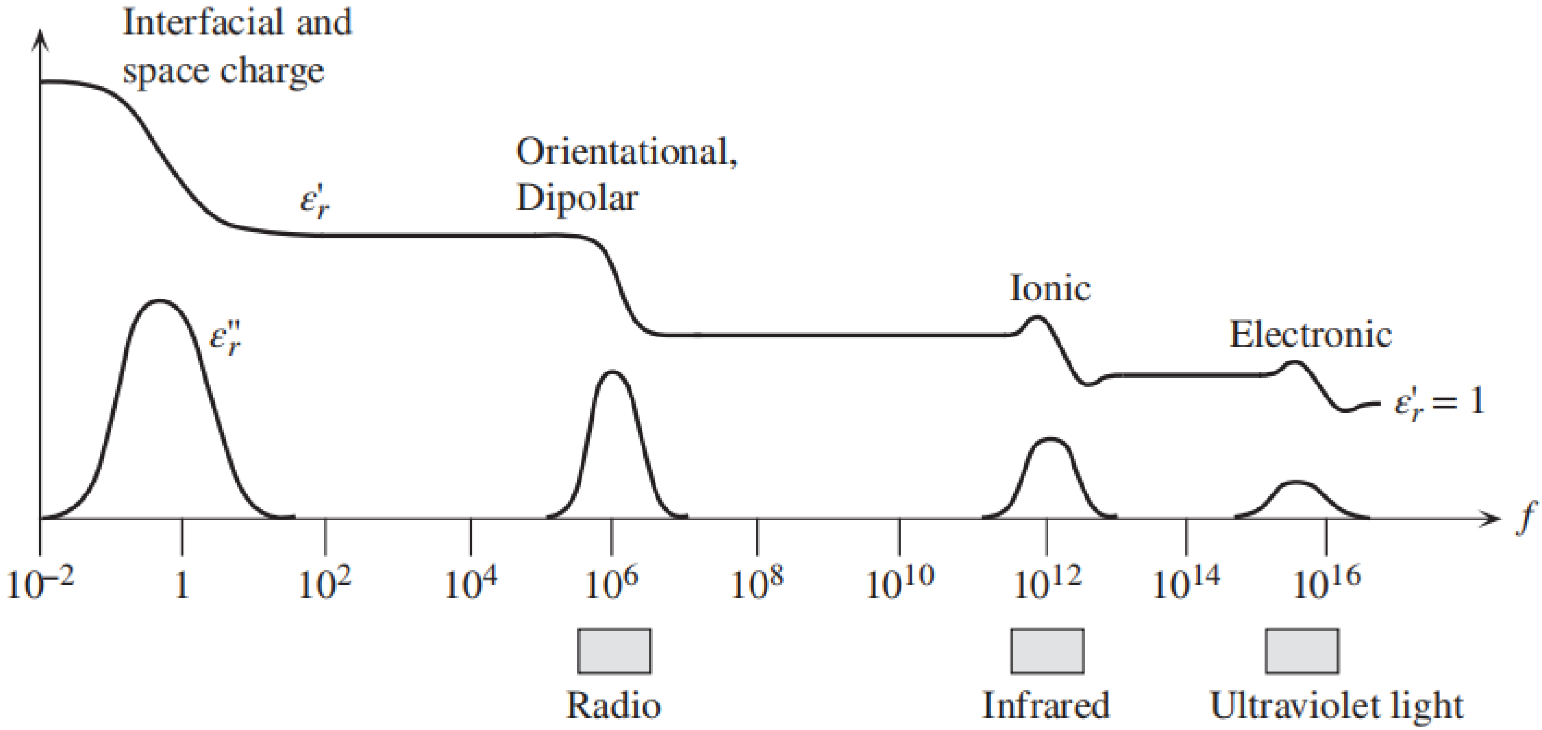




Electronic polarization

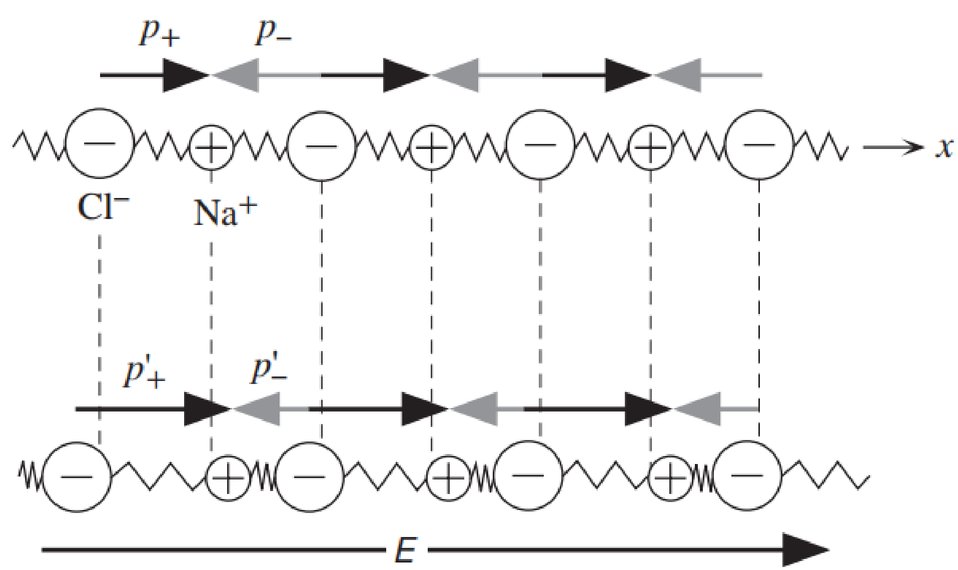
For covalent bond solids

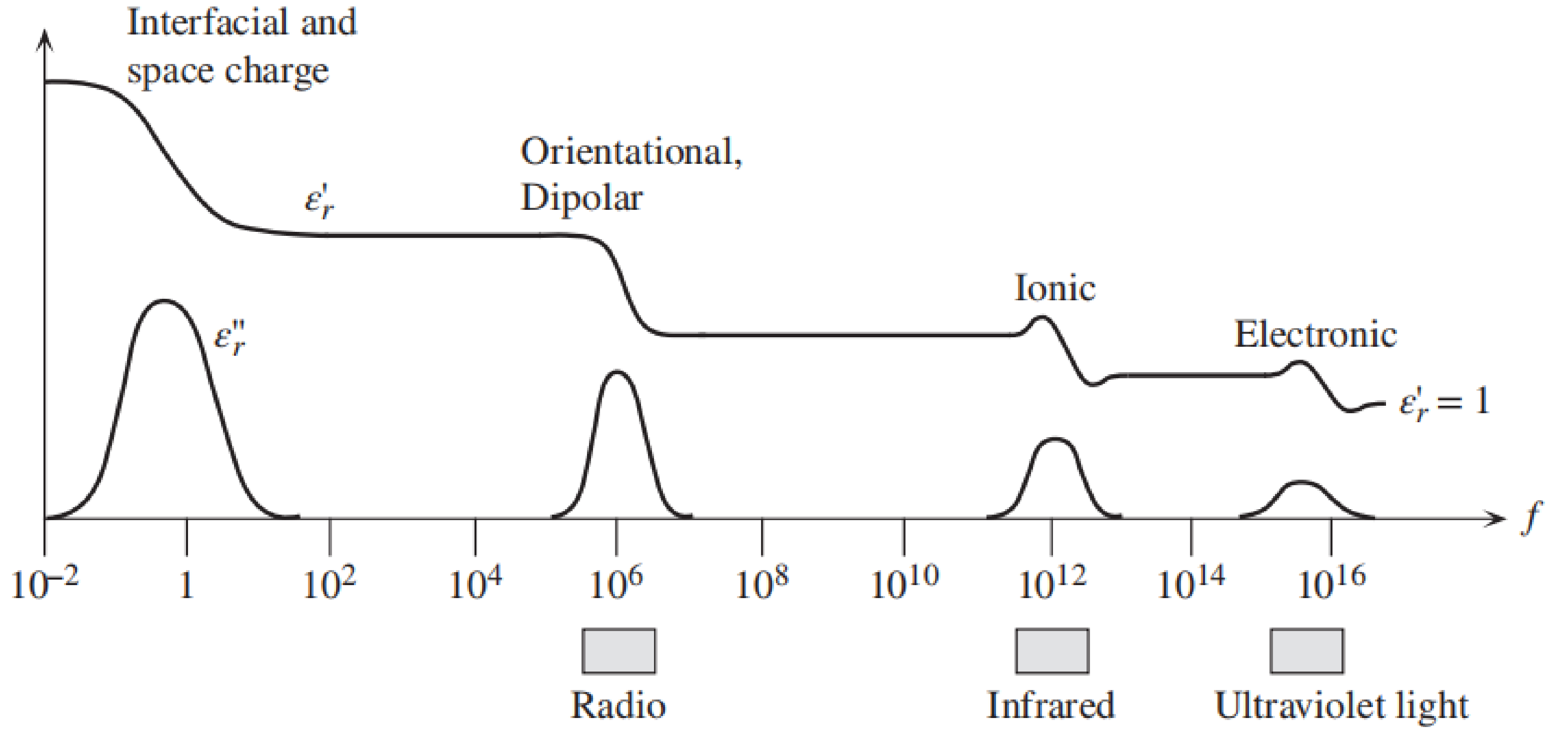




Ionic polarization

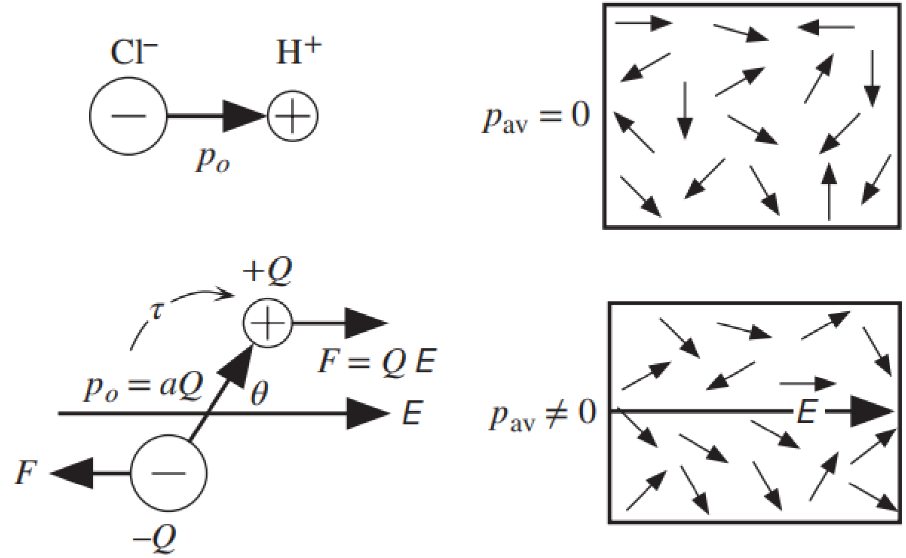
$$p = \alpha_{\mathrm{i}} E$$

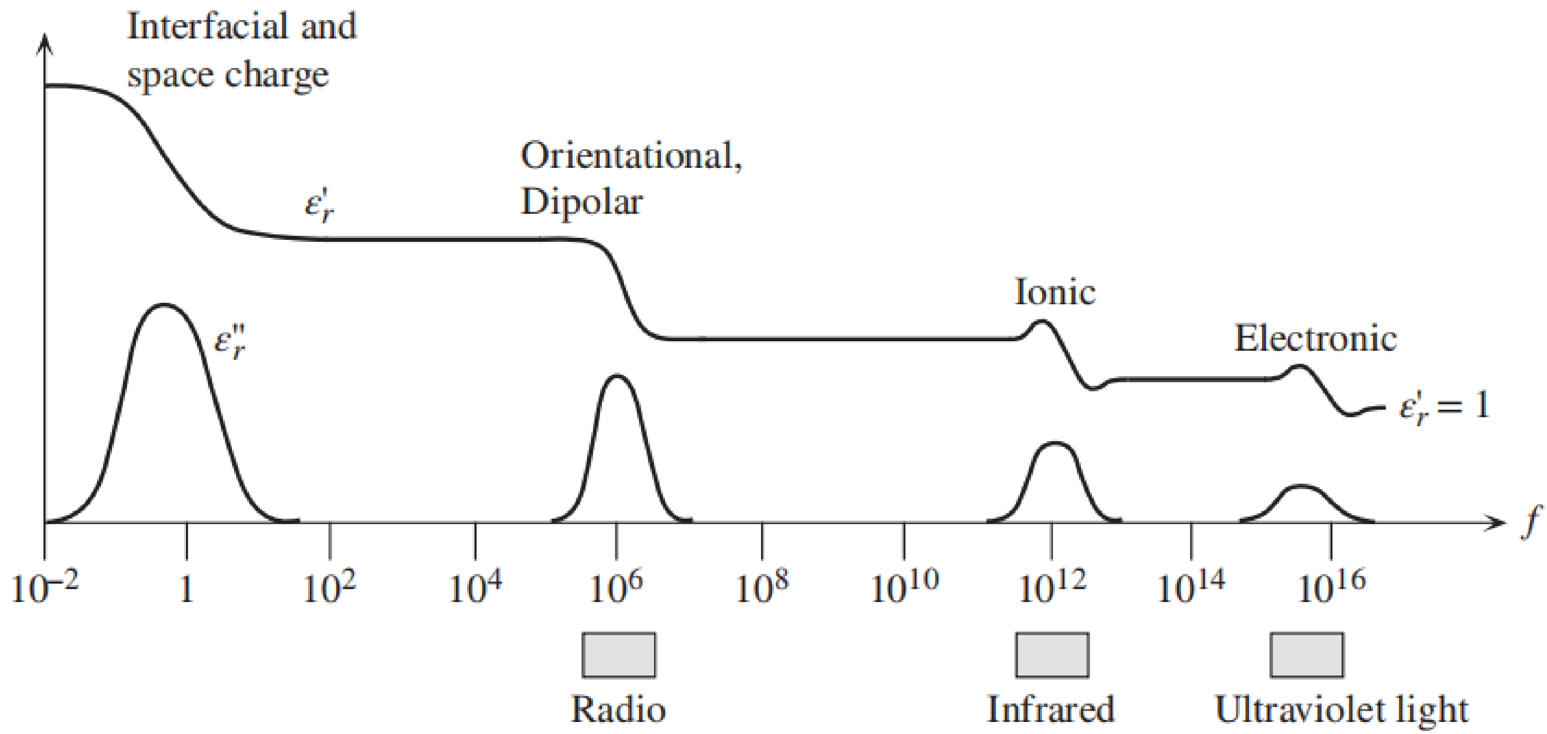




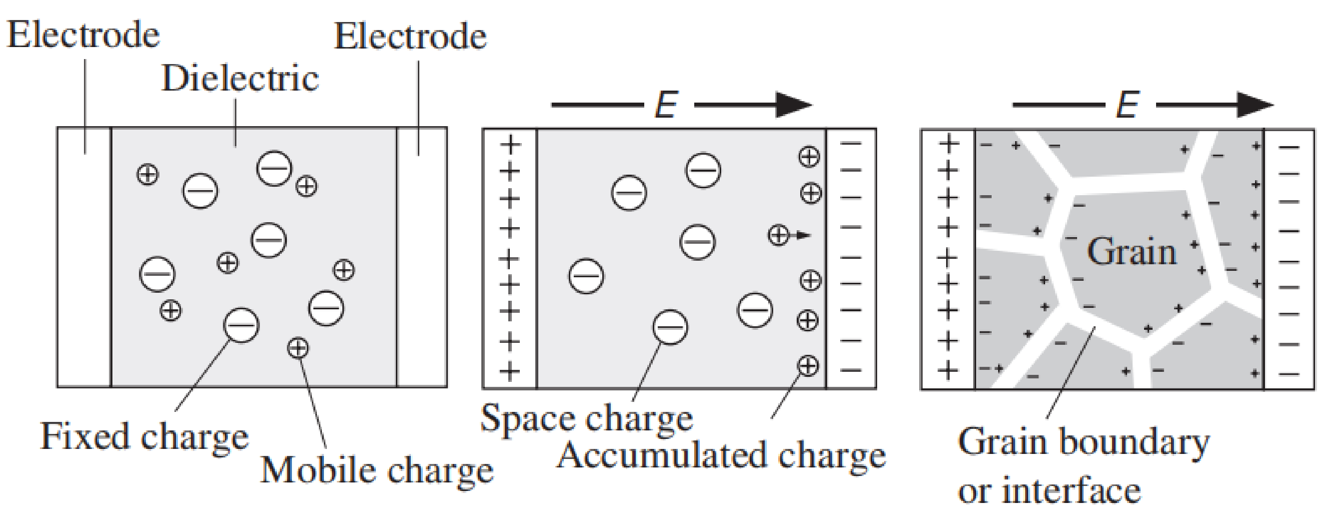
Orientational polarization

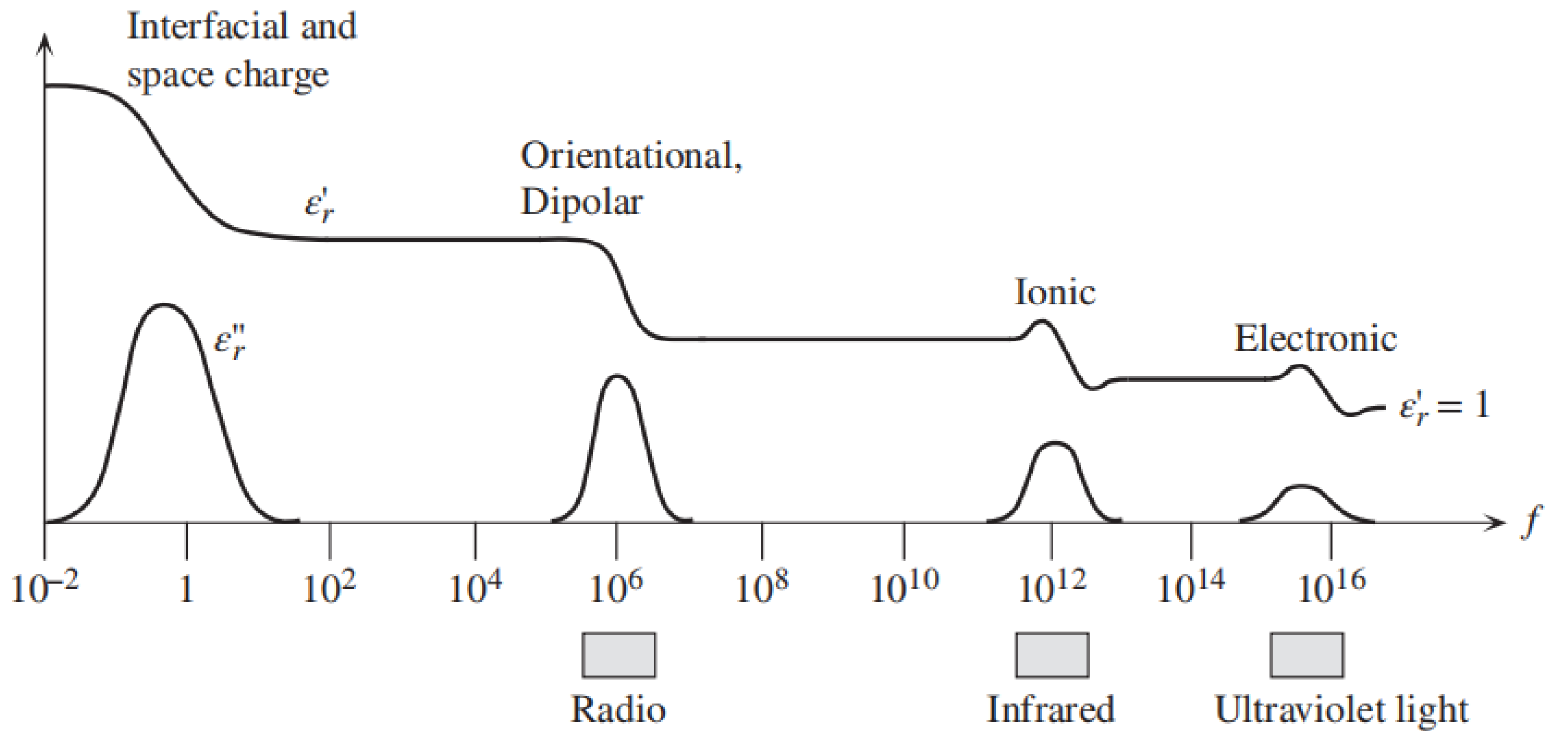
$$p = \alpha_{\mathrm{d}} E$$





Interfacial and space charge



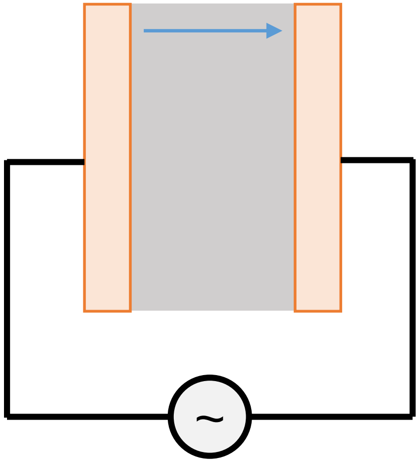


The total dipole moment of per molecule is the sum of all contributions.

Admittance of capacitor 电容的导纳

$$P = P_0 \sin(\omega t - \phi)$$

$$E = E_0 \sin\omega t$$



$$v = V_0 \sin\omega t$$

$$\boxed{C = \frac{A\varepsilon_0\varepsilon_r(\omega)}{d}}$$

Admittance of capacitor Y:

Impedance of capacitor X:

$$Y = \frac{1}{X} = j\omega C$$

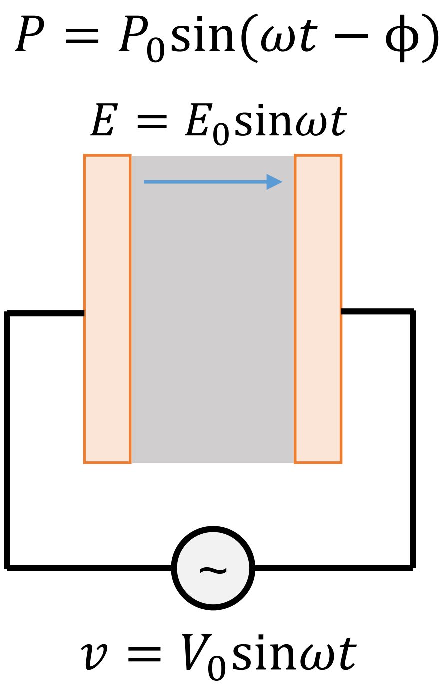
$$Y = \frac{j\omega A\varepsilon_0\varepsilon_r(\omega)}{d}$$

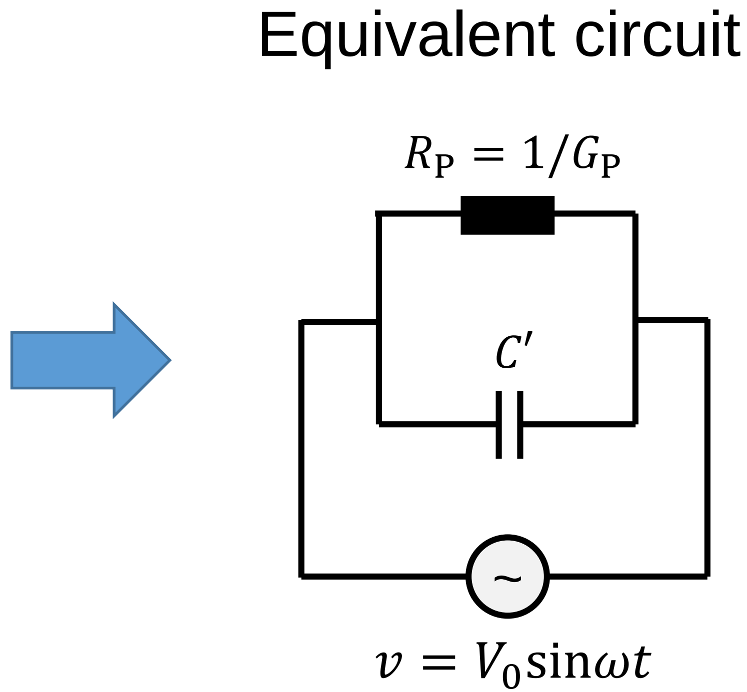
$$Y = \frac{j\omega A\varepsilon_0\varepsilon_r'(\omega)}{d} + \frac{\omega A\varepsilon_0\varepsilon_r''(\omega)}{d}$$

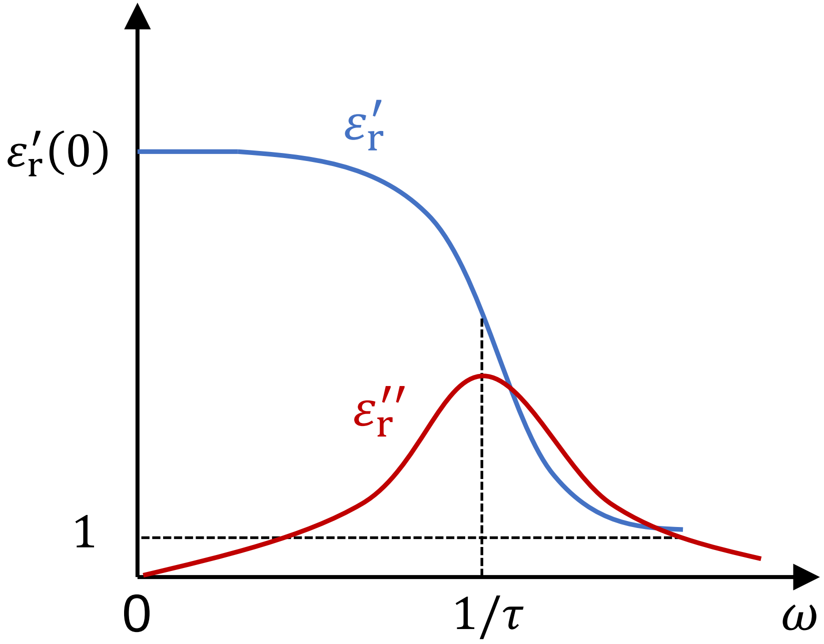
$$= j\omega C' + G_P$$

$$C' = \frac{A\varepsilon_0\varepsilon_r'(\omega)}{d}, \quad G_P = \frac{\omega A\varepsilon_0\varepsilon_r''(\omega)}{d}$$

Admittance of capacitor: $Y = j\omega C' + G_{\mathrm{P}}$







$$\begin{cases} C' = \dfrac{A\varepsilon_0\varepsilon_r'(\omega)}{d} \\[2ex] G_P = \dfrac{\omega A\varepsilon_0\varepsilon_r''(\omega)}{d} \end{cases}$$

Input power:

$$IV = YV^2$$

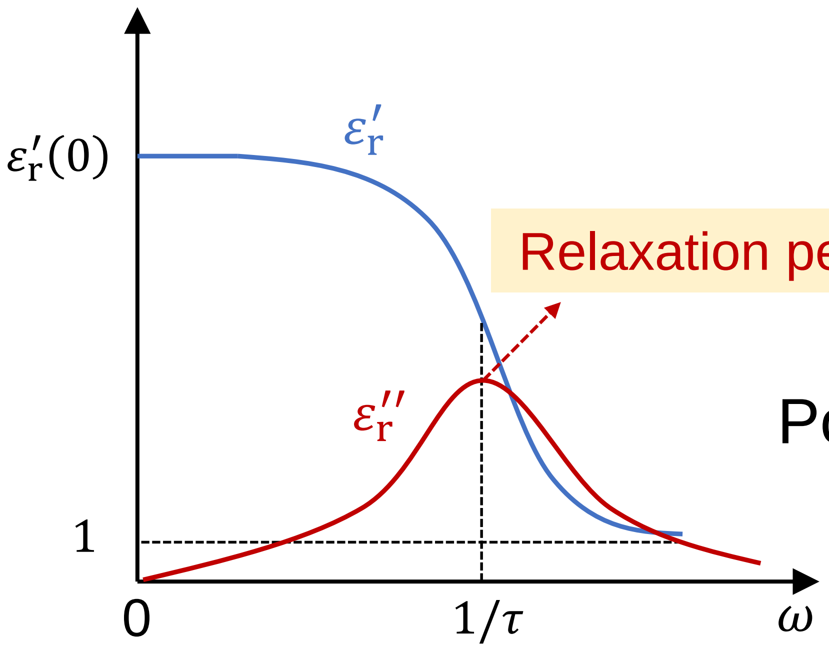
$$= j\omega C'V^2 + G_P V^2$$

$$= j\omega C'V^2 + \frac{V^2}{R_P}$$

The imaginary term:

Power stored in capacitor C'

No power is dissipated in C'



Input power: $j\omega C' V^2 + \dfrac{V^2}{R_P}$

The real term:

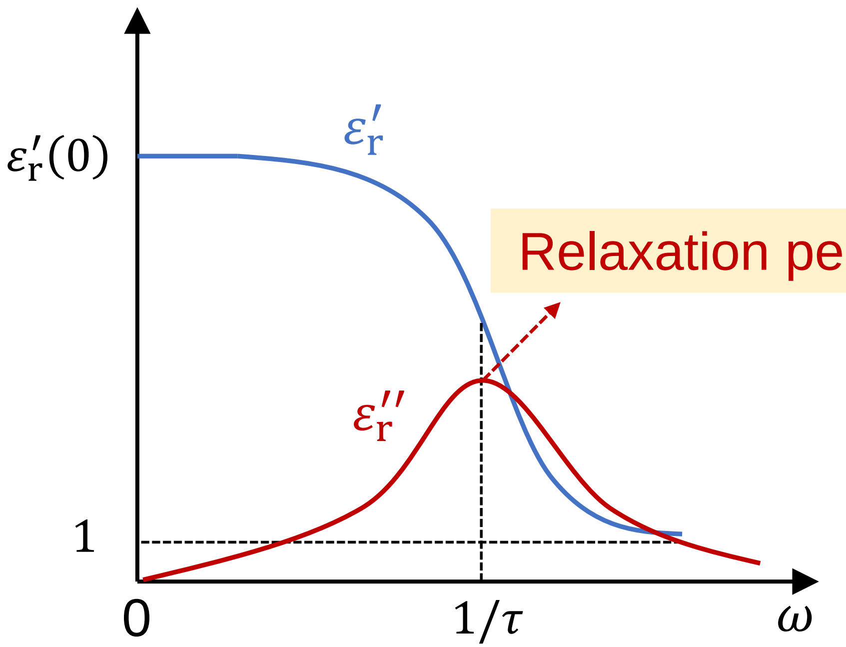
Power dissipated in dielectric medium

Power dissipation reaches the maximum value at $\omega = 1/\tau$

$$\begin{cases} C' = \dfrac{A\varepsilon_0\varepsilon_r'(\omega)}{d} \\[2ex] G_P = \dfrac{\omega A\varepsilon_0\varepsilon_r''(\omega)}{d} \end{cases}$$

At $\omega = 1/\tau$, most energy is transferred to heat with a high efficiency.

This process is called **dielectric resonance**介电谐振.



Input power: $j\omega C'V^2 + \dfrac{V^2}{R_P}$

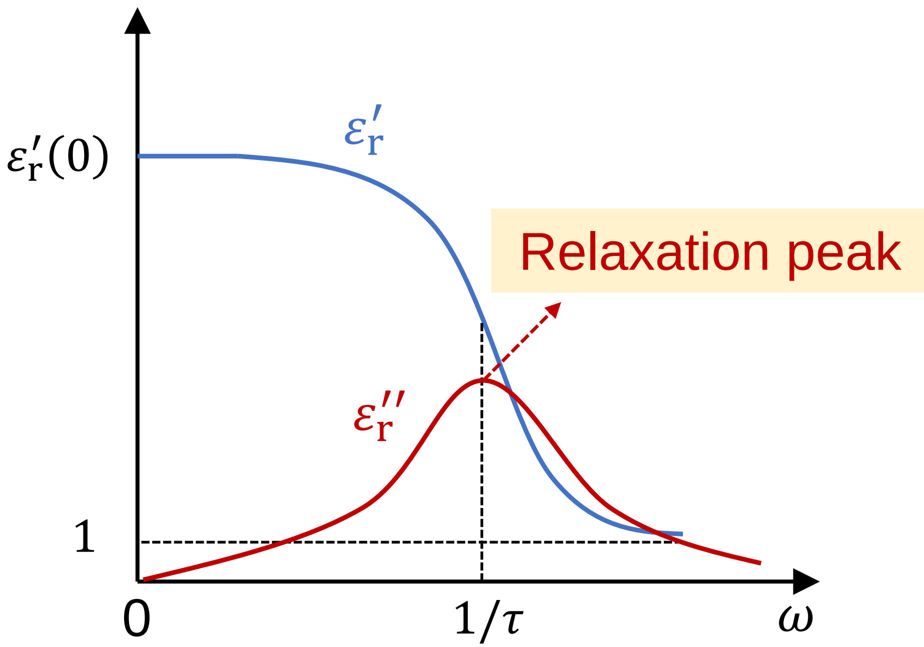
Energy stored:$\omega C'V^2$

Energy dissipated:$G_P V^2$

$$\begin{cases} C' = \dfrac{A\varepsilon_0\varepsilon_r'(\omega)}{d} \\[2ex] G_P = \dfrac{\omega A\varepsilon_0\varepsilon_r''(\omega)}{d} \end{cases}$$

Loss tangent (loss factor)
损耗角正切

$$\tan\delta = \frac{G_P V^2}{\omega C'V^2} = \frac{\varepsilon_r''}{\varepsilon_r'}$$



$$\begin{cases} C' = \dfrac{A\varepsilon_0\varepsilon_r'(\omega)}{d} \\ \\ G_P = \dfrac{\omega A\varepsilon_0\varepsilon_r''(\omega)}{d} \end{cases}$$

Energy dissipated per unit volume:

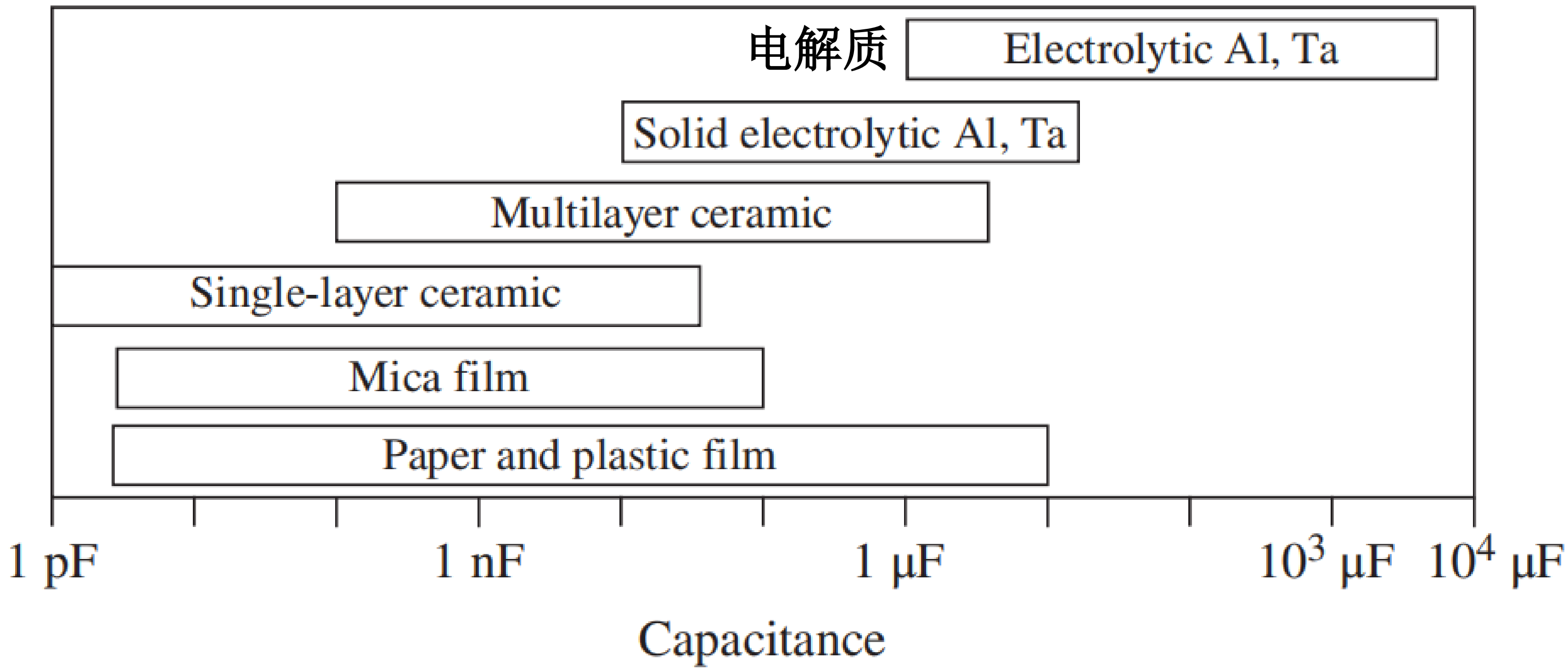
$$W_{vol} = \frac{\text{Power loss}}{\text{Volume}}$$

$$= \frac{V^2}{R_P} \times \frac{1}{dA}$$

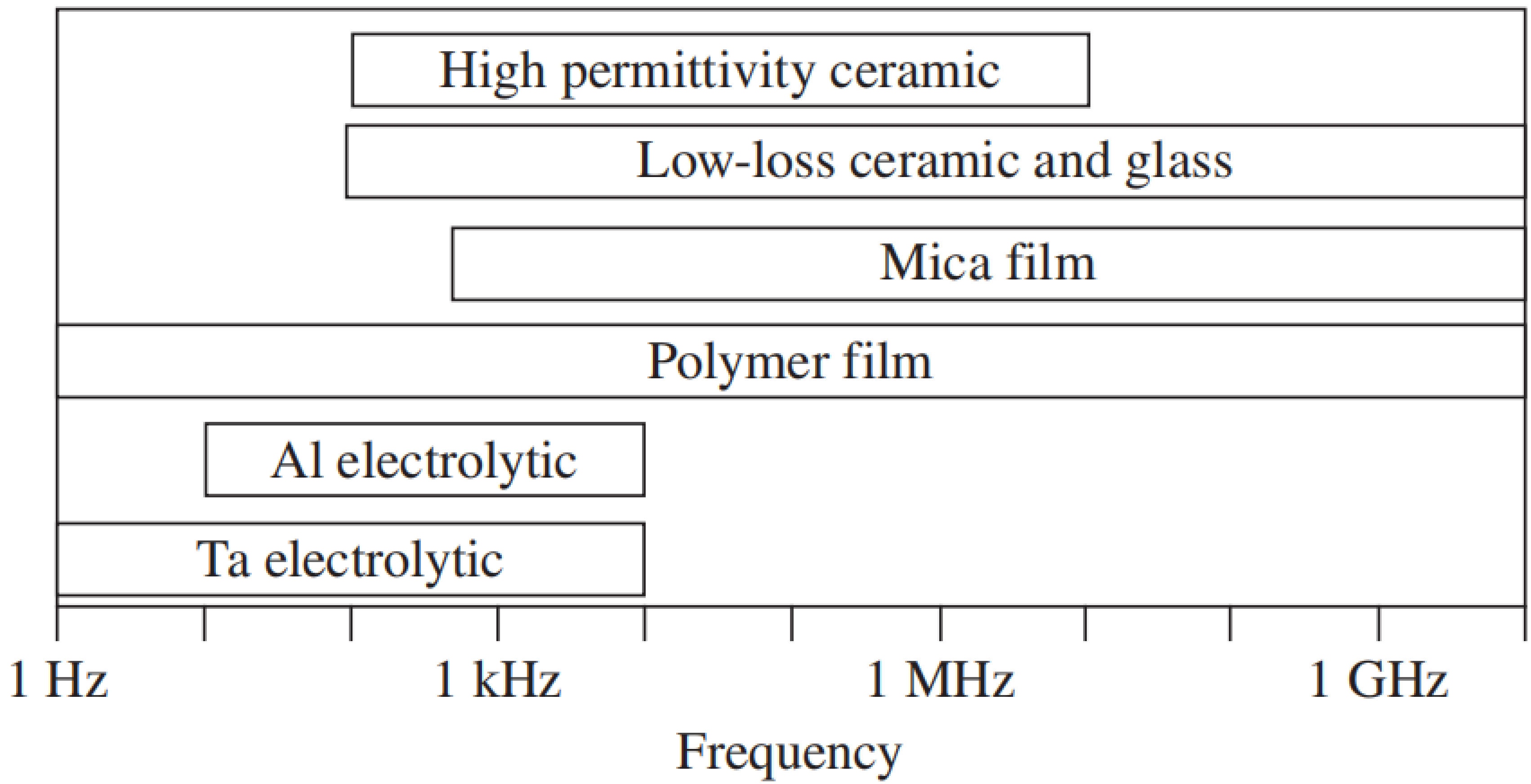
$$= \frac{V^2}{d^2}\omega\varepsilon_0\varepsilon_r''$$

$$= \omega E^2\varepsilon_0\varepsilon_r'\tan\delta$$

6.4 Capacitor dielectric materials

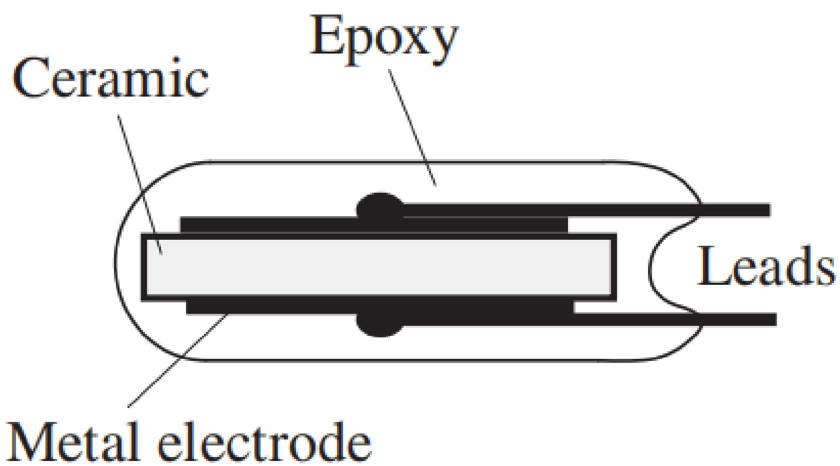


Energy dissipated per unit volume: $W_{\mathrm{vol}} = \omega E^2 \varepsilon_0 \varepsilon_r' \tan\delta$



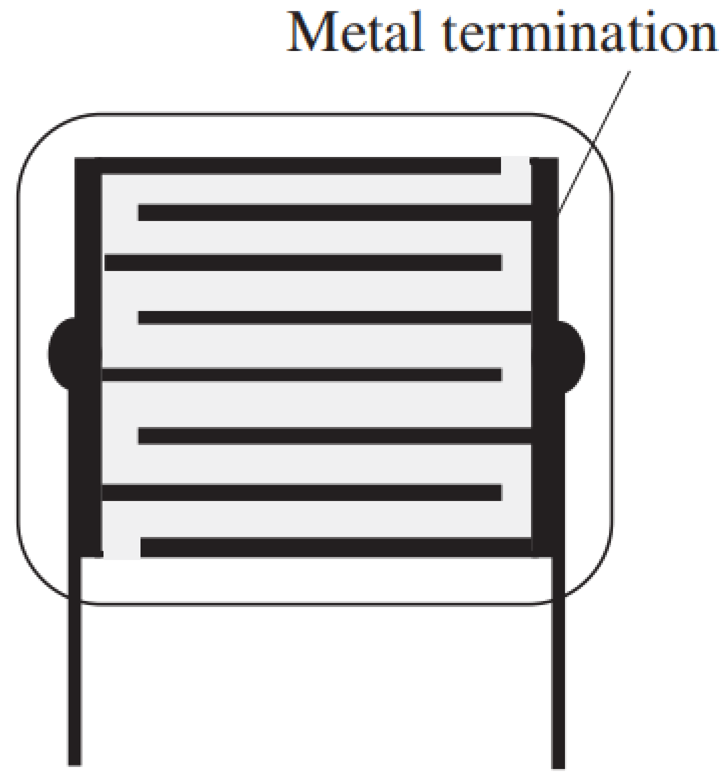
Ceramic parallel-plate capacitor 平行板陶瓷电容器

Single-layer ceramic capacitor

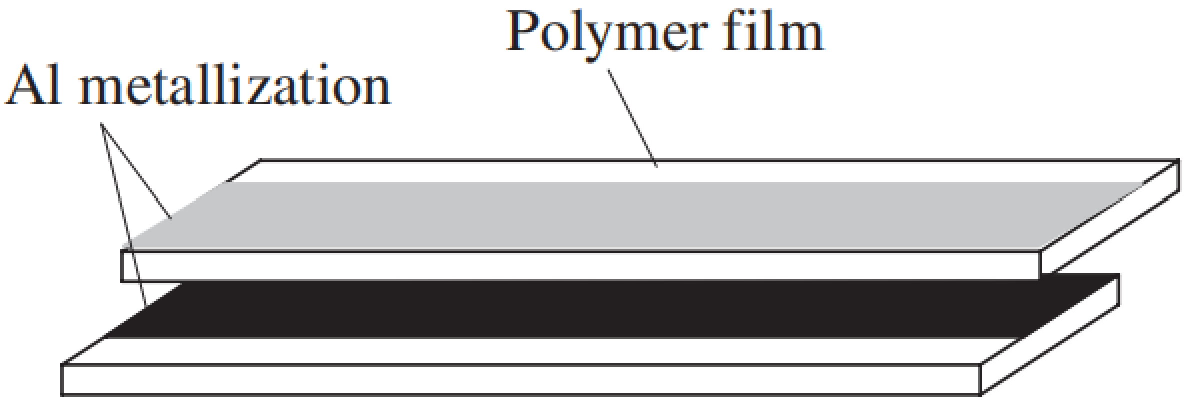


$$C = \frac{A\varepsilon_0\varepsilon_\mathrm{r}(\omega)}{d}$$

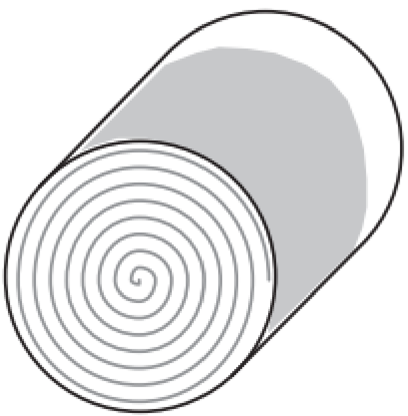
Multilayer ceramic capacitor

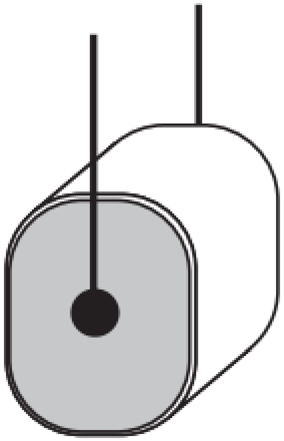


Polymer tape capacitor



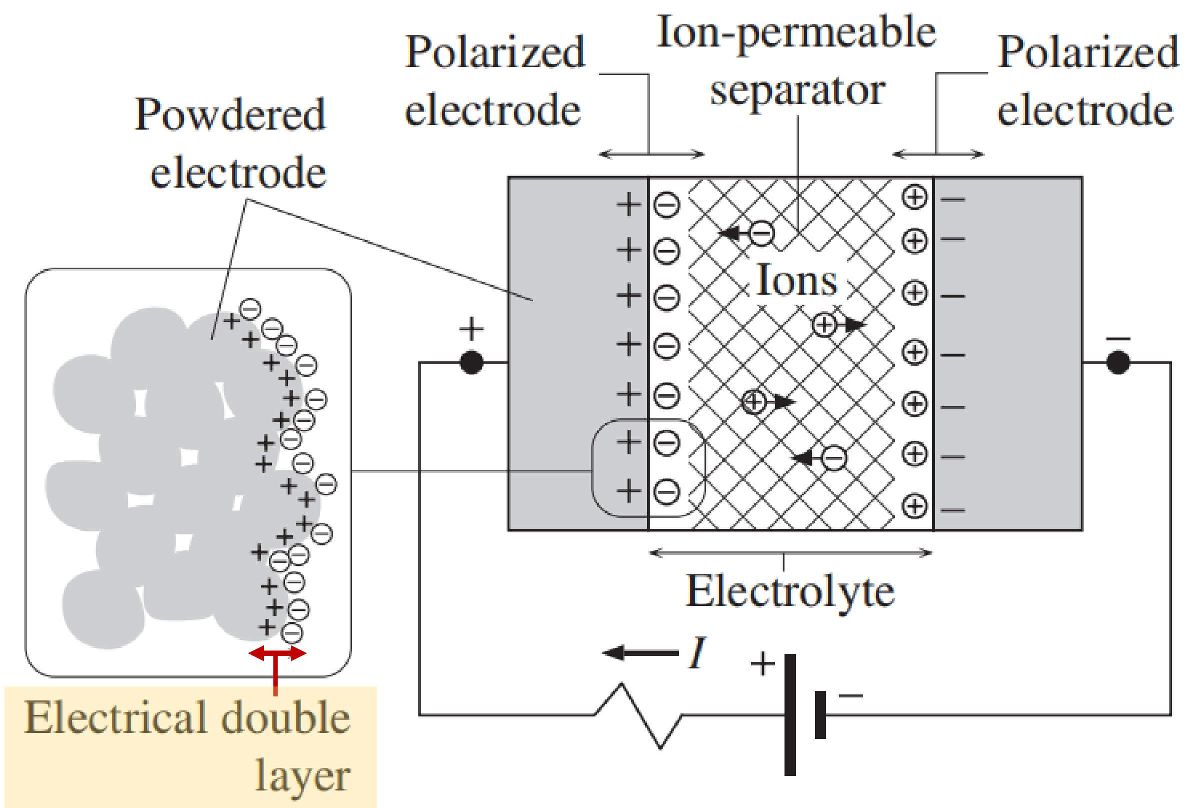
Since polymer tapes are flexible, the capacitor can be rolled together



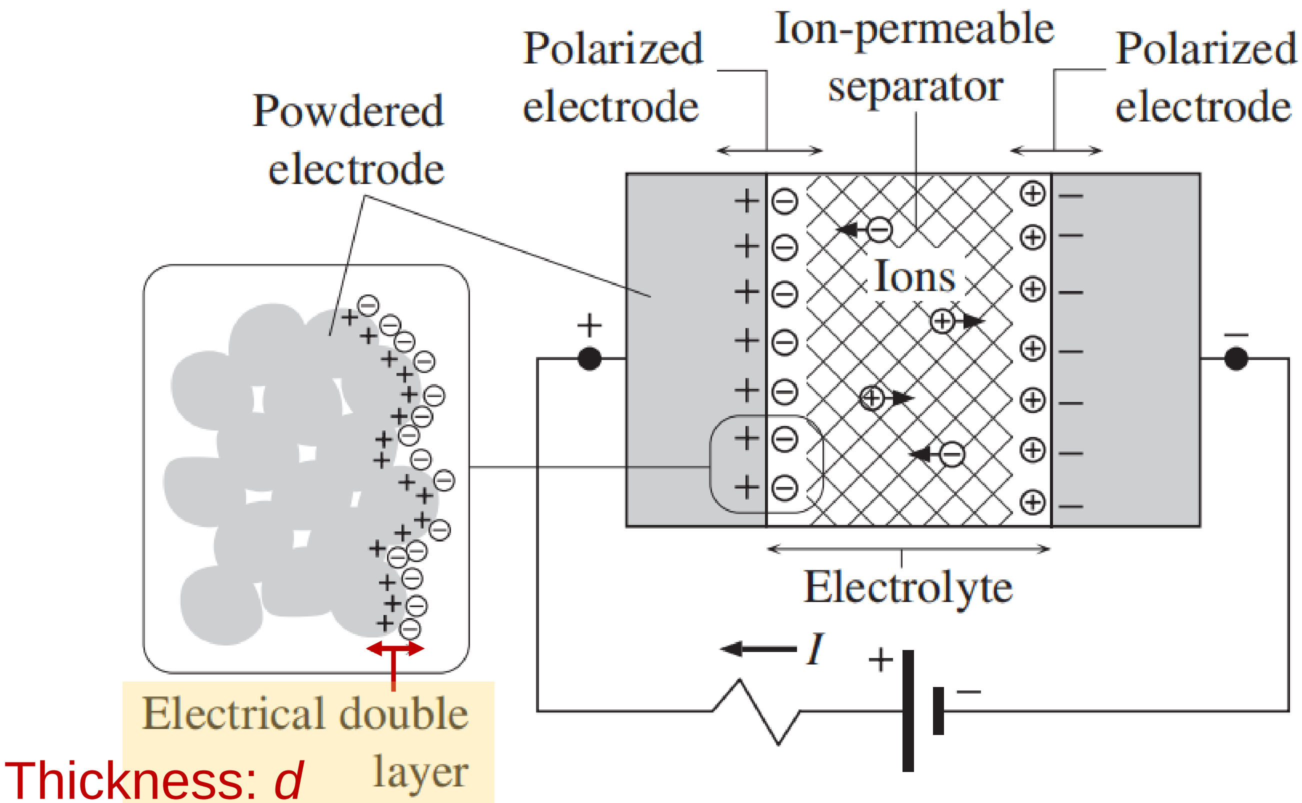


Supercapacitors 超级电容器

Capacitance is as high as 100 F or more



Thickness: *d*

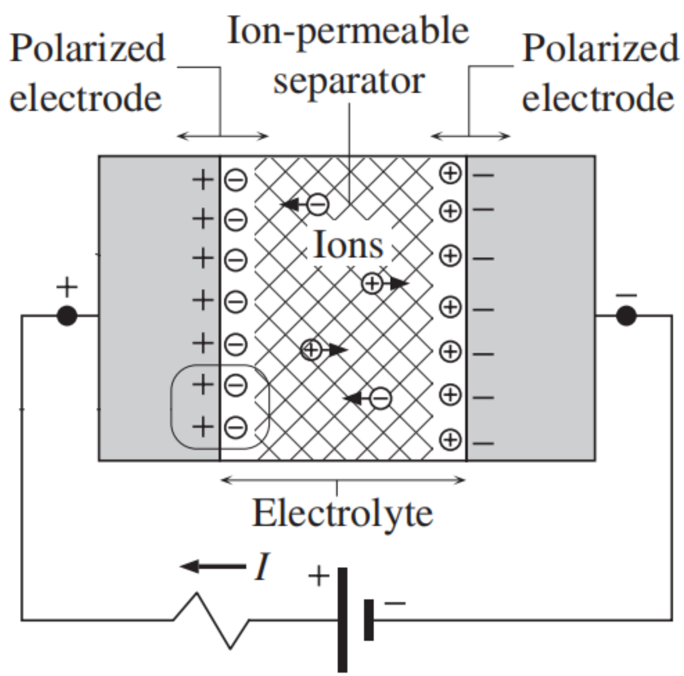


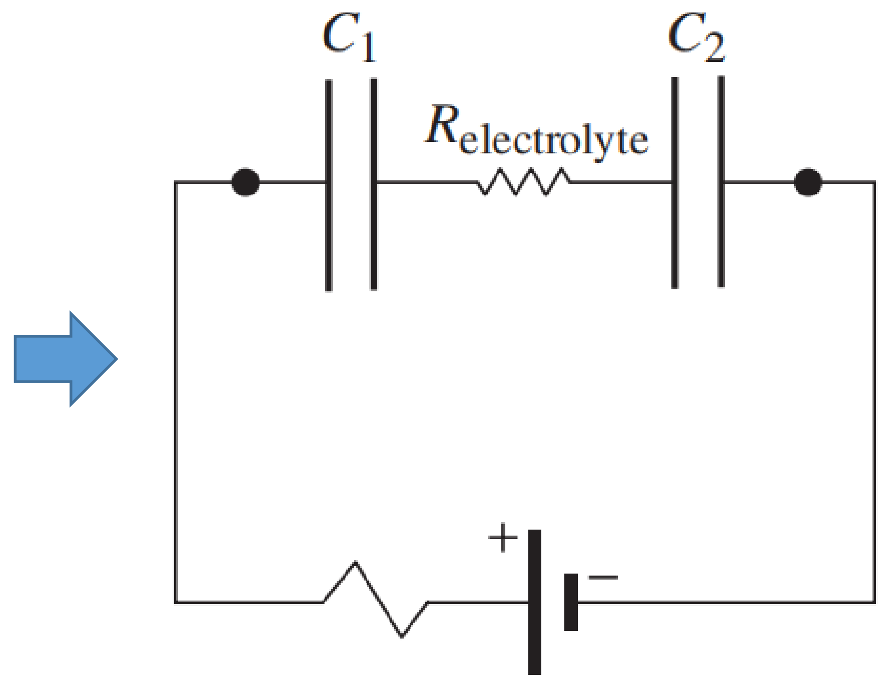
Electrolyte should not react with electrode.

Separation between electrical double layer is < 1nm

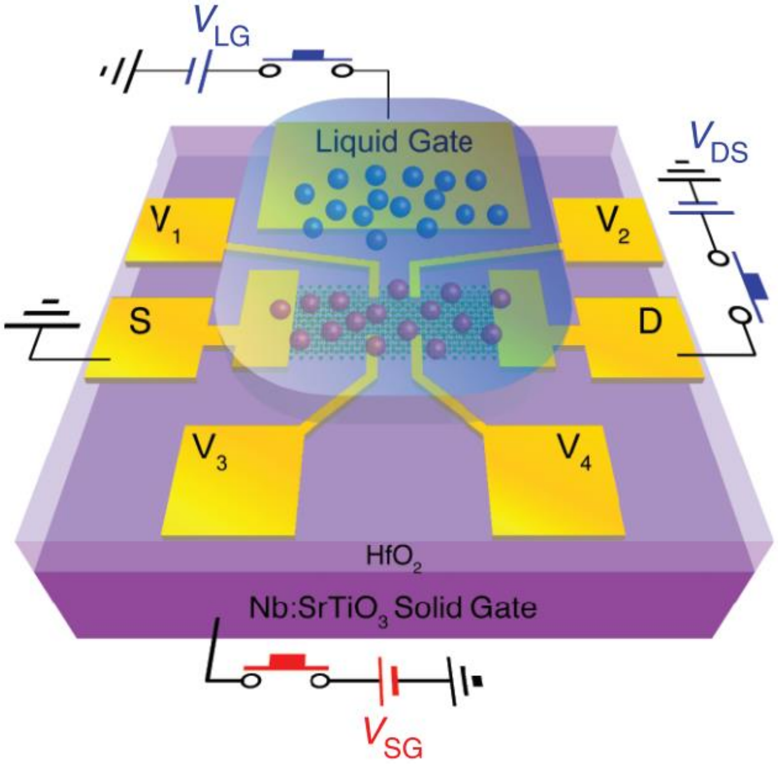
$$C = \frac{A\varepsilon_0\varepsilon_r(\omega)}{d}$$

Equivalent circuit





Electrolyte can use as gate electrode for transistors



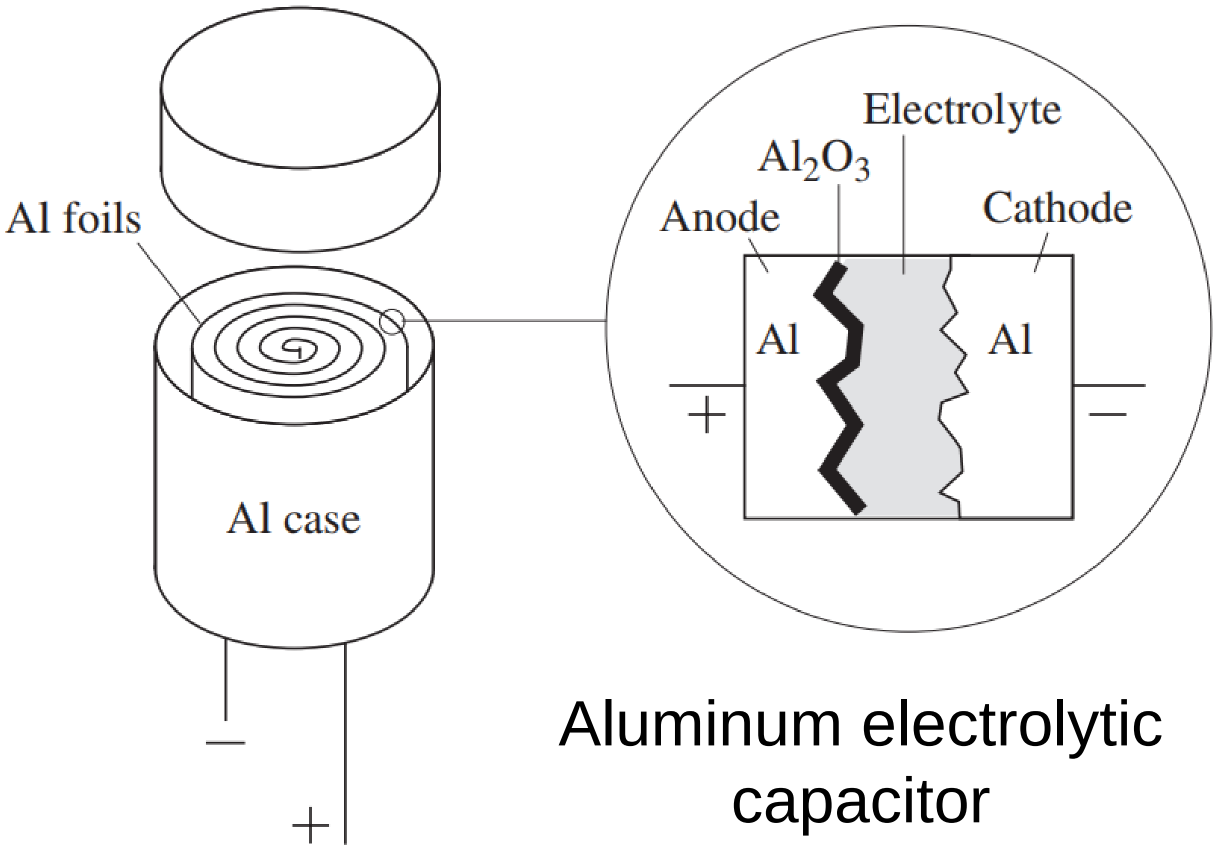
Merits:

- Very large gate capacitance
- Can effectively tune the Fermi energy of the channel material
- Can even tune the Fermi energy of metallic materials

Drawbacks:

- Slow response speed

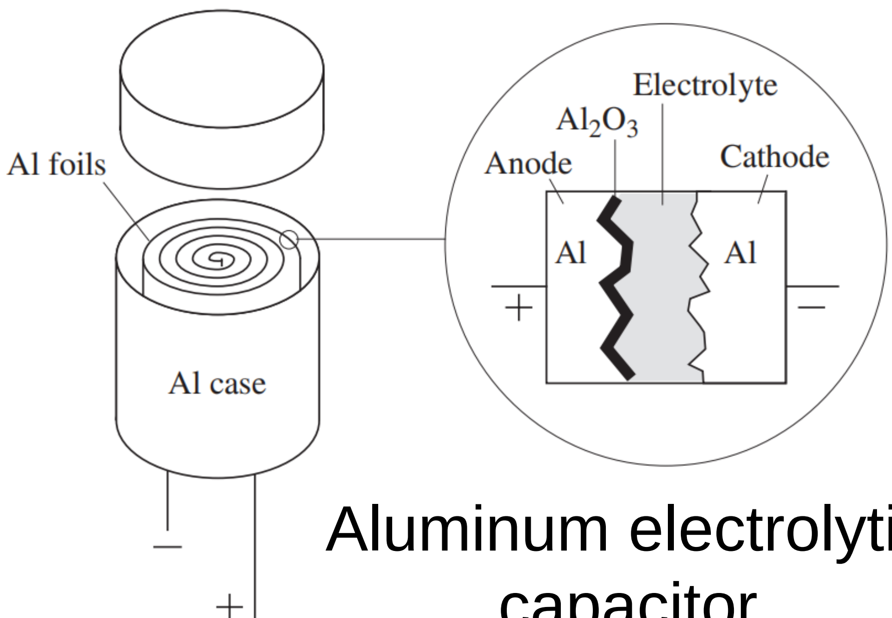
Electrolytic capacitors 电解电容器



Aluminum electrolytic capacitor

Dielectric material is a thin layer of Al_2O_3 (~100 nm)

Electrolytic capacitors 电解电容器

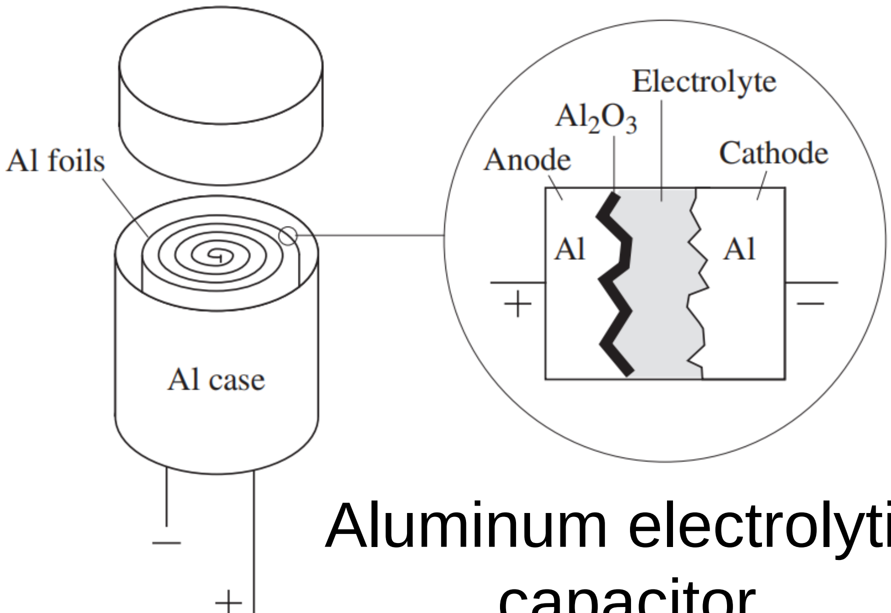


Aluminum electrolytic capacitor

- ◆ Positive voltage on anode: behave as capacitor
- ◆ Negative voltage on anode: conducting

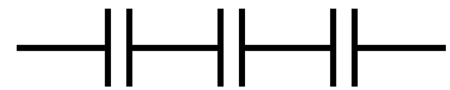
Behave as a rectifier

Electrolytic capacitors 电解电容器



Aluminum electrolytic capacitor

Capacitance:



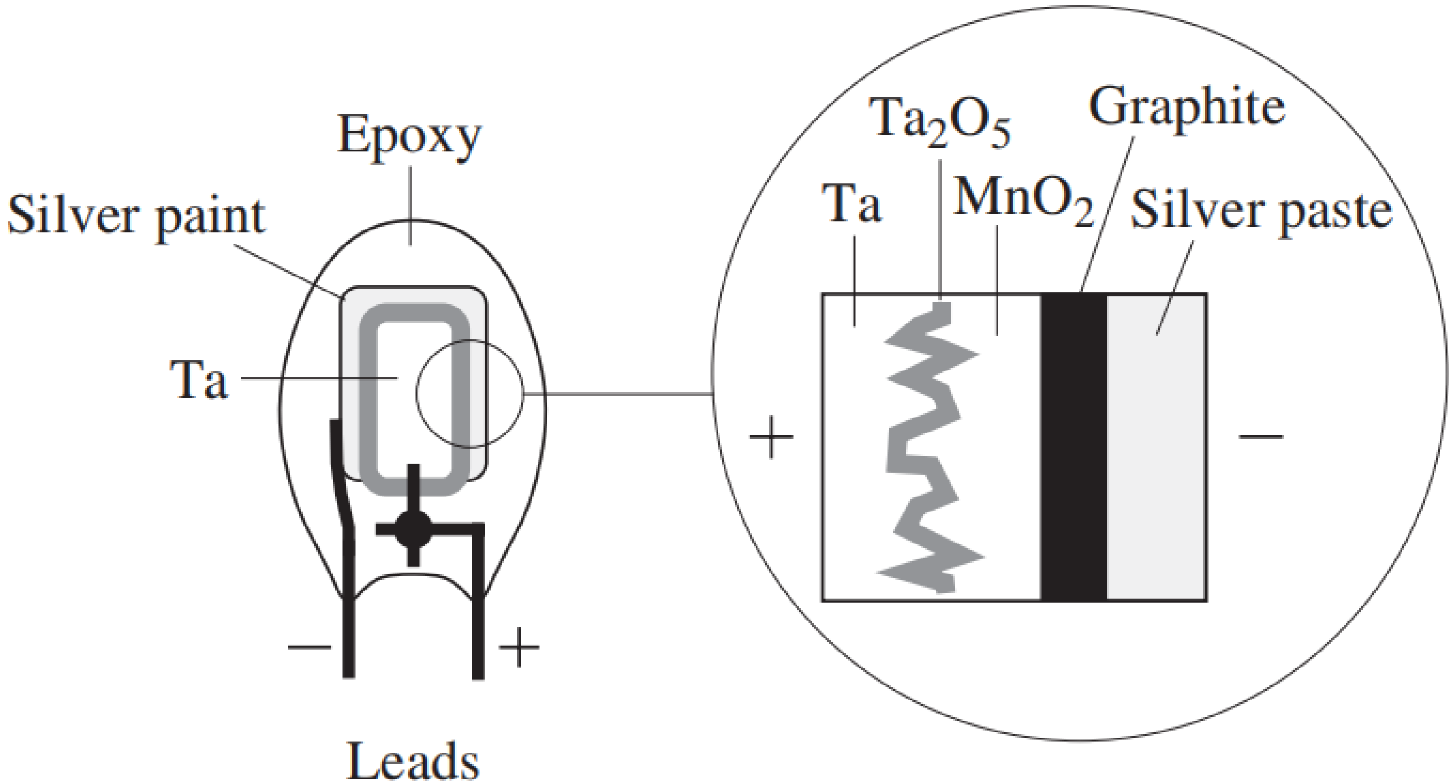
$$C_{\mathrm{Al2O3}} = \frac{A_1 \varepsilon_0 \varepsilon_{\mathrm{r\_Al2O3}}}{d_{\mathrm{Al2O3}}}$$

$$C_1 = \frac{A_1 \varepsilon_0 \varepsilon_{\mathrm{r\_Eletro}}}{d_{\mathrm{DL}}}$$

$$C_2 = \frac{A_2 \varepsilon_0 \varepsilon_{\mathrm{r\_Eletro}}}{d_{\mathrm{DL}}}$$

Total capacitance: $C = C_{\mathrm{Al2O3}} || C_1 || C_2 \approx C_{\mathrm{Al2O3}}$

Electrolytic capacitors 电解电容器



Solid electrolyte tantalum capacitor

6.5 Touchscreens

- Resistive touchscreen
- Infrared touchscreen
- Surface acoustic wave touchscreen
- Capacitive touchscreen

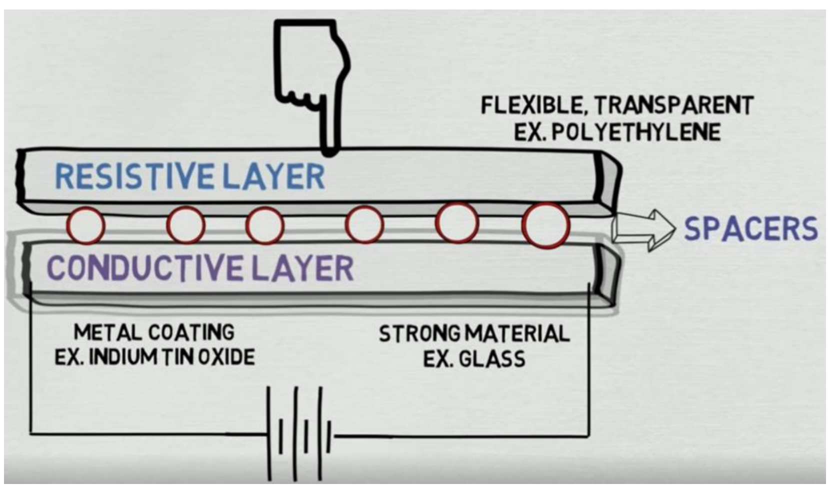
◆ Resistive touchscreen

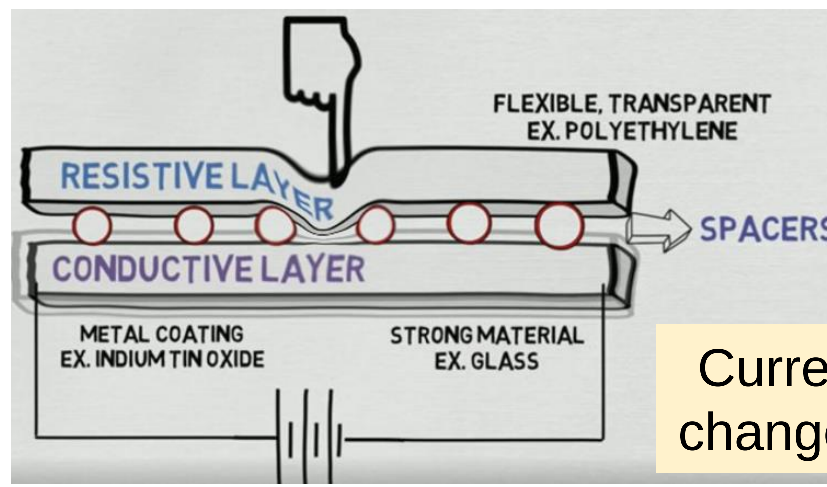
Advantages

- Cheap
- Strong

Disadvantages

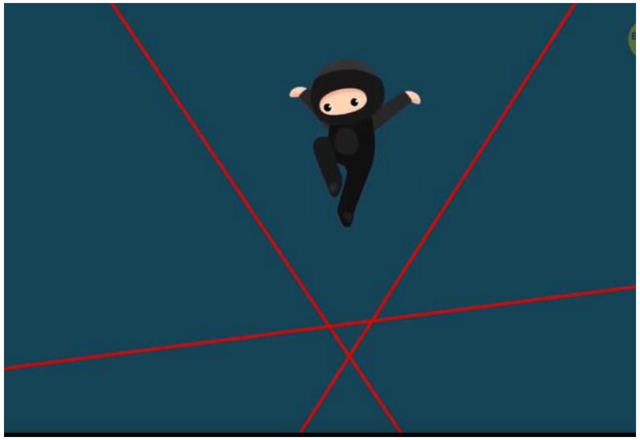
- Reflection
- No multitouch





Current changes!

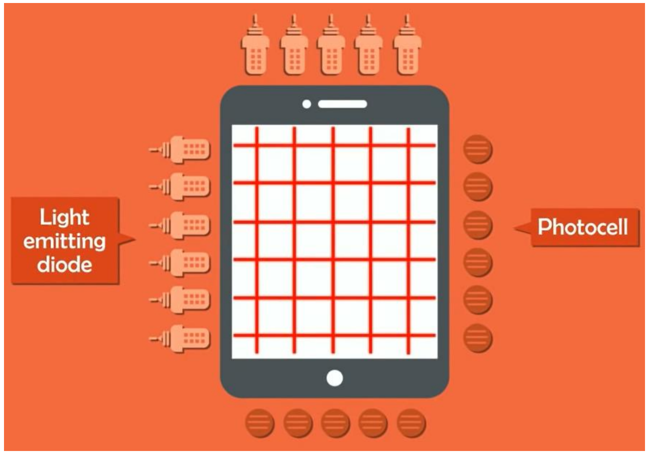
◆ Infrared touchscreen

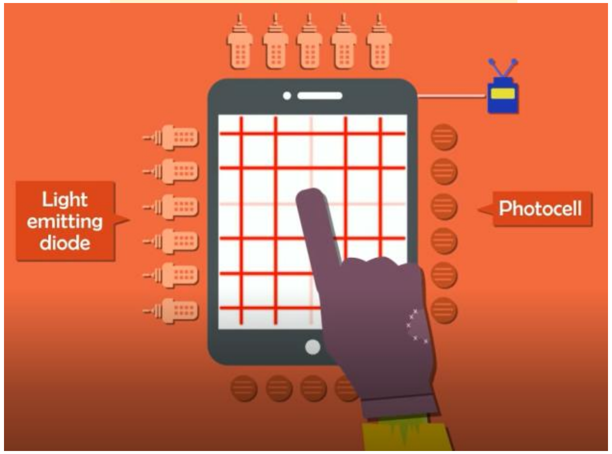


Some products:

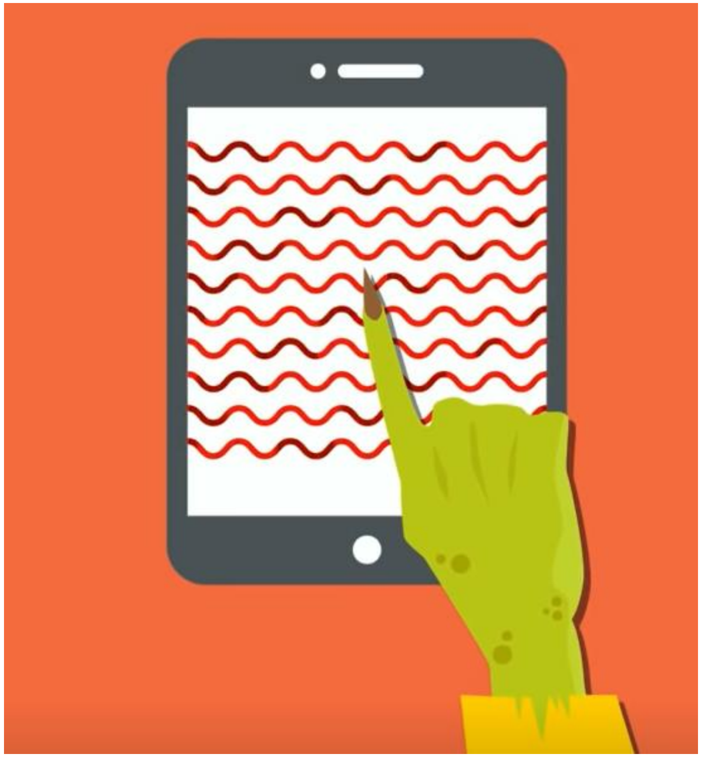
- Amazon kindle touch
- Sony ebook readers

Ware gloves!

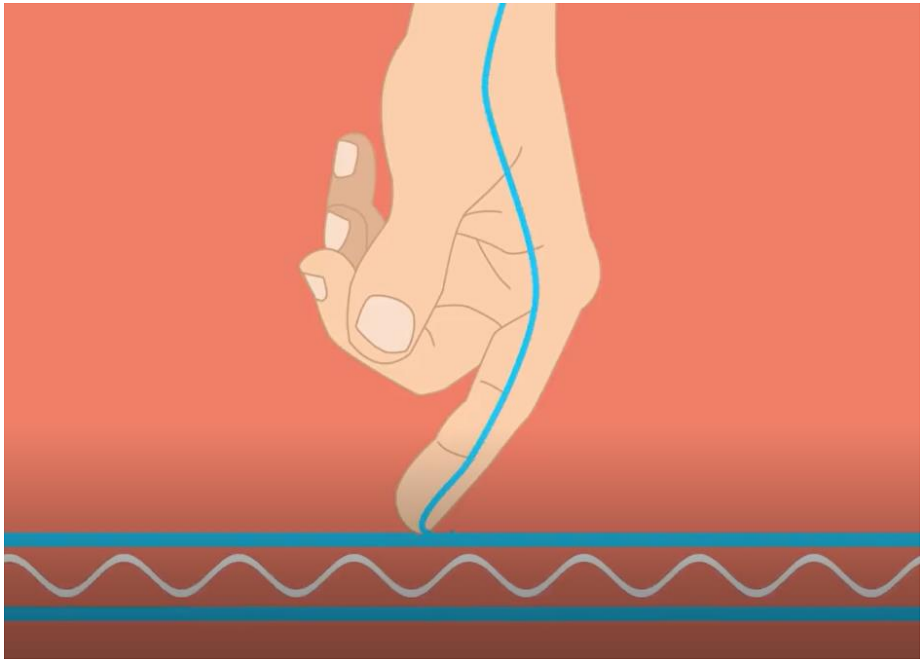




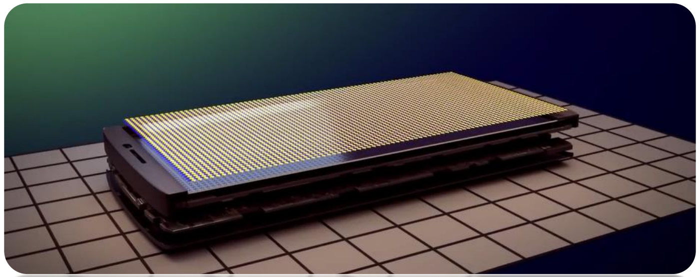
◆ Surface acoustic wave touchscreen

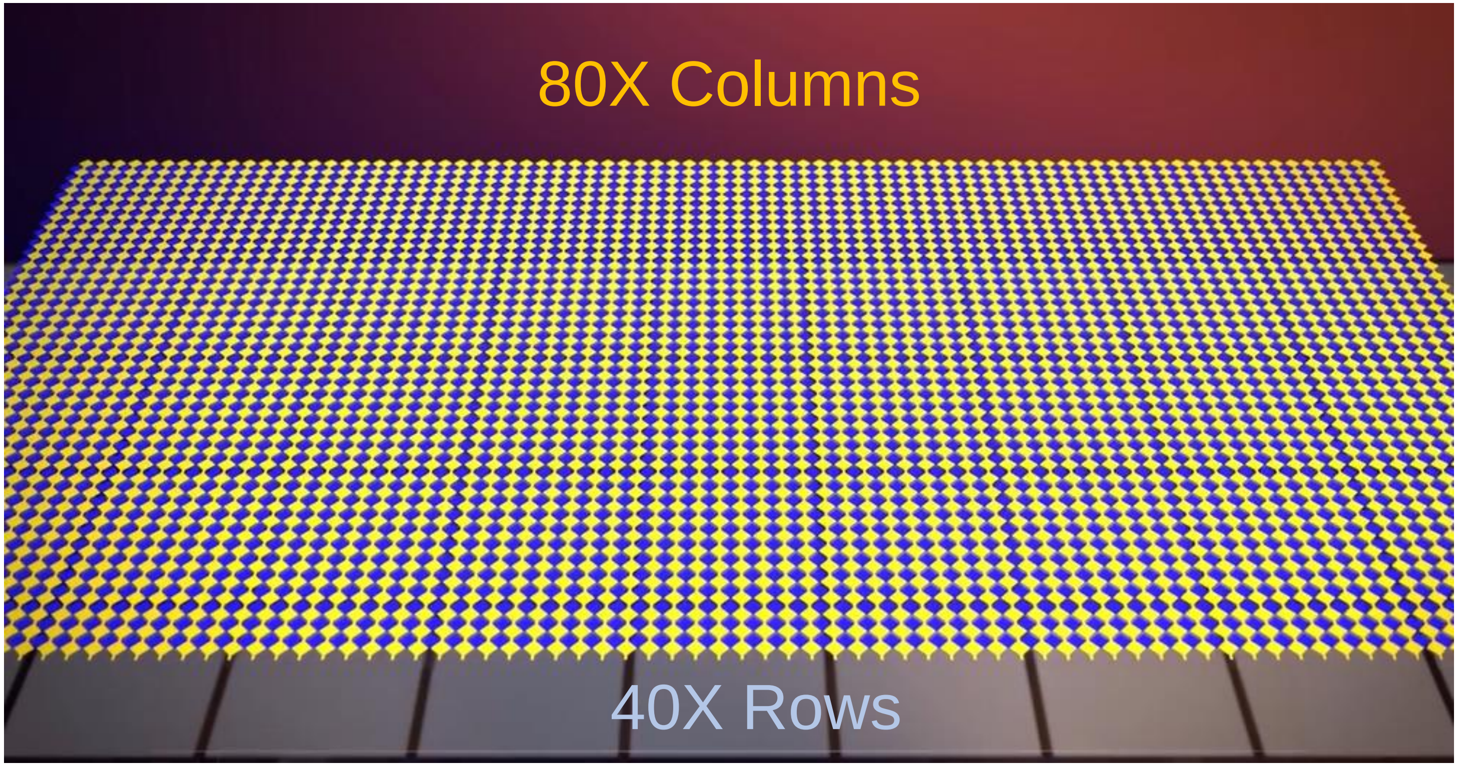


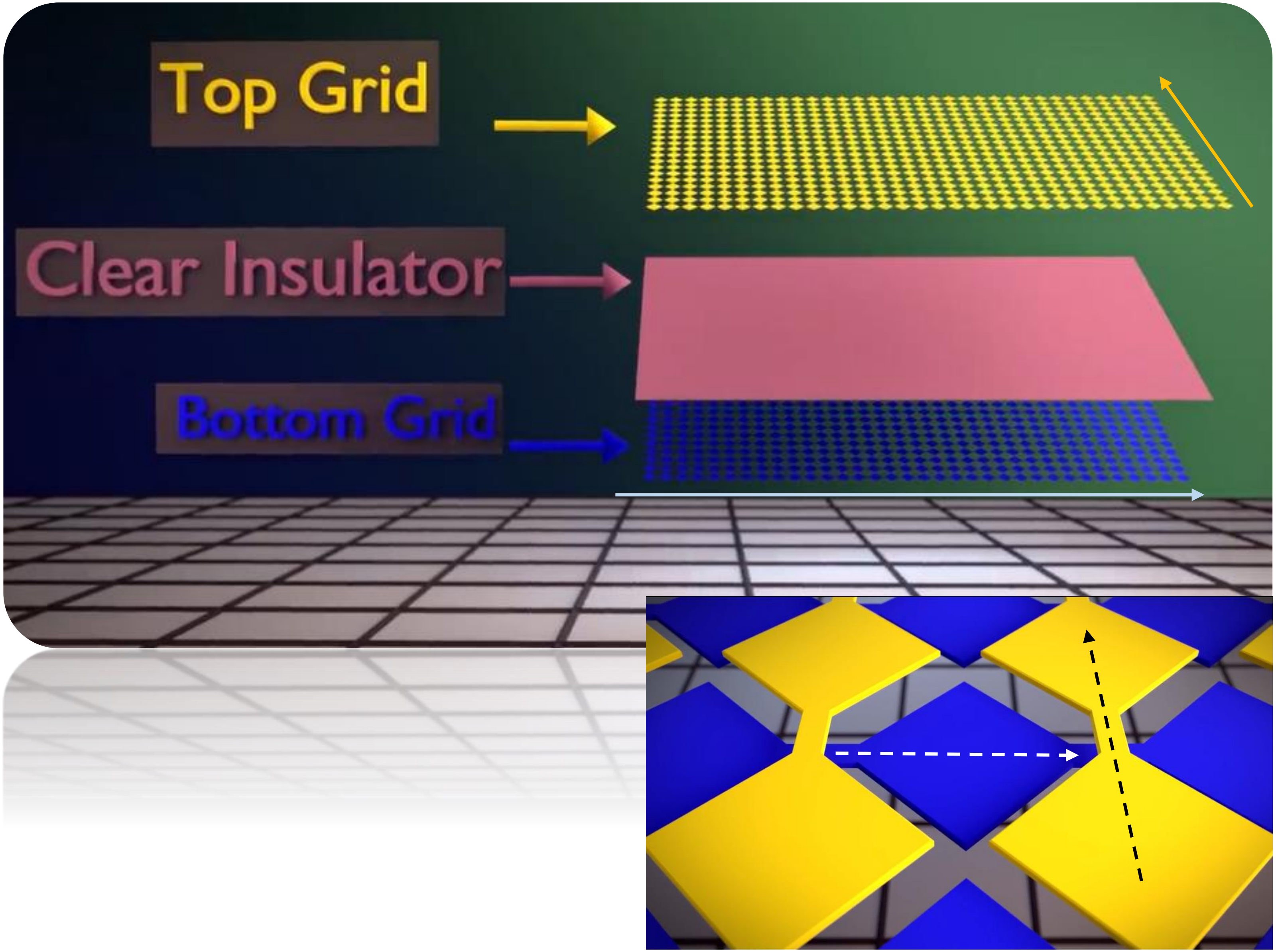
Use ultrasound wave to replace infrared light

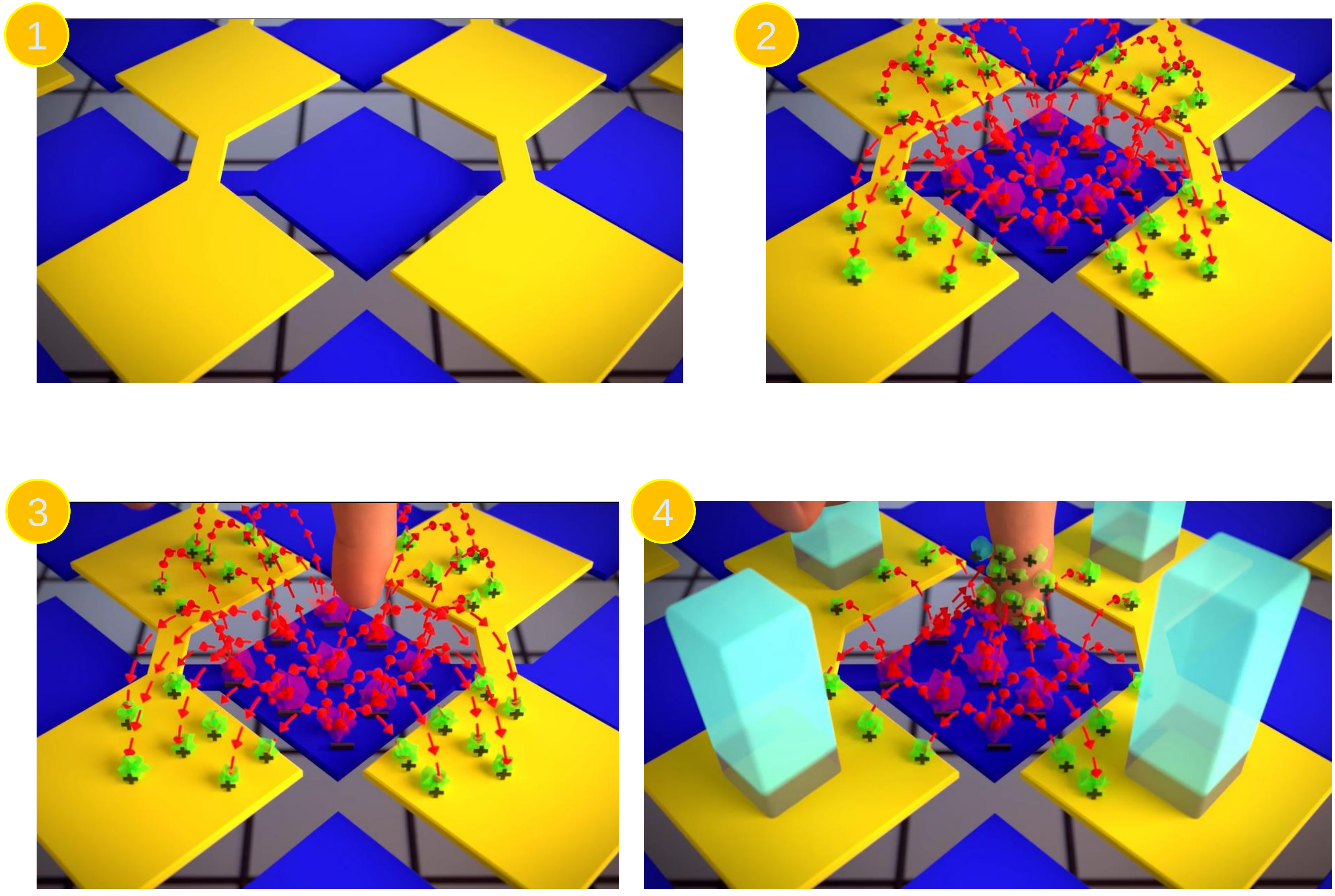


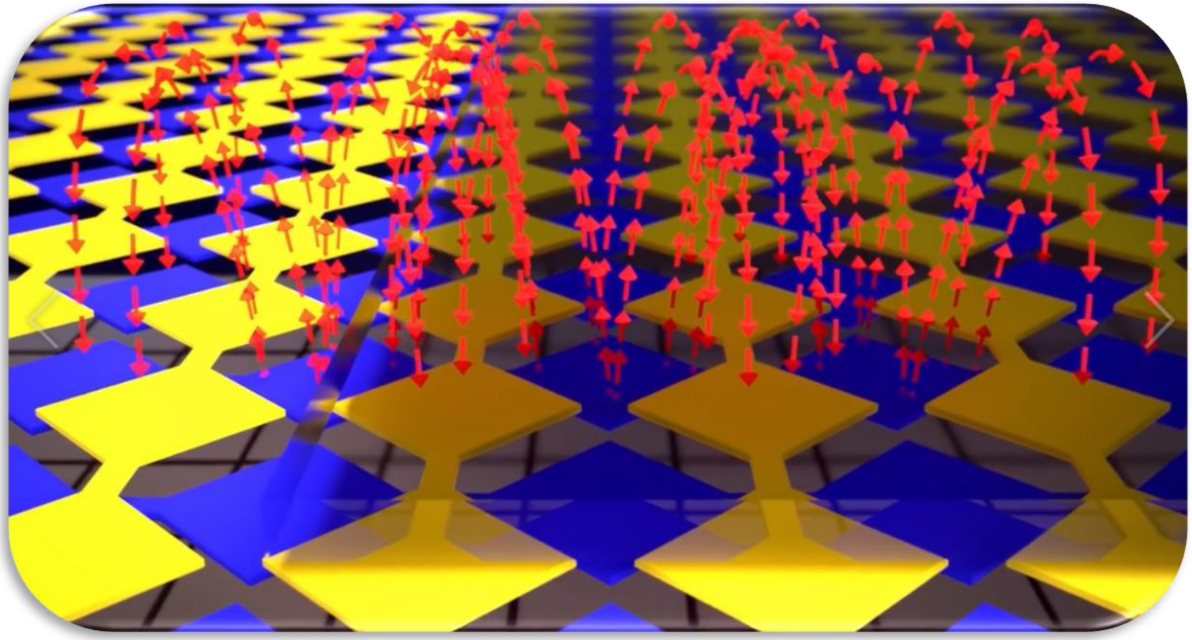
◆ Capacitive touchscreen (Projective-type)






Top Grid
Clear Insulator
Bottom Grid

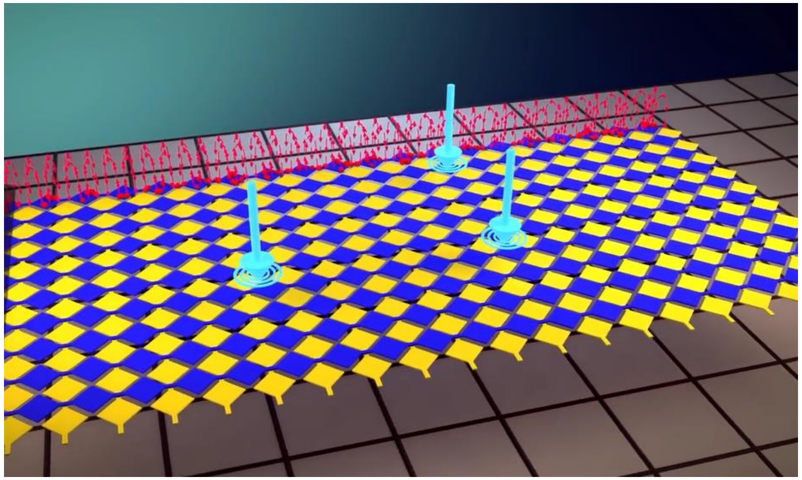

1
2
3
4

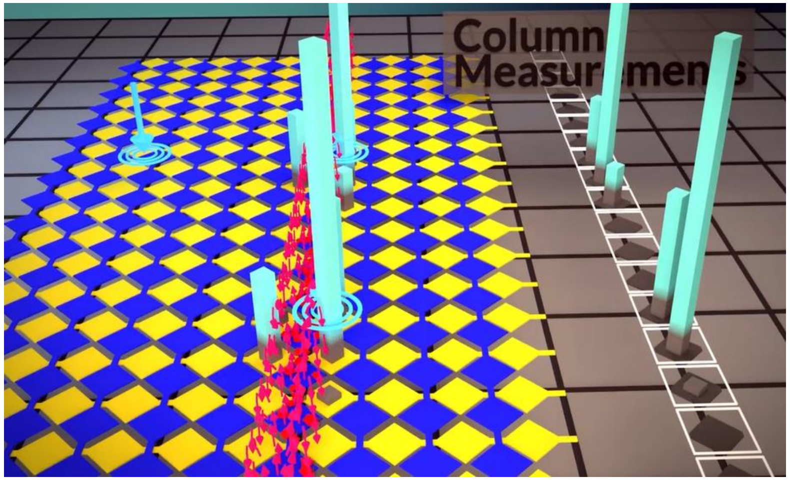


- Electric field can penetrate above the screen, so you even don’t need to touch the screen.

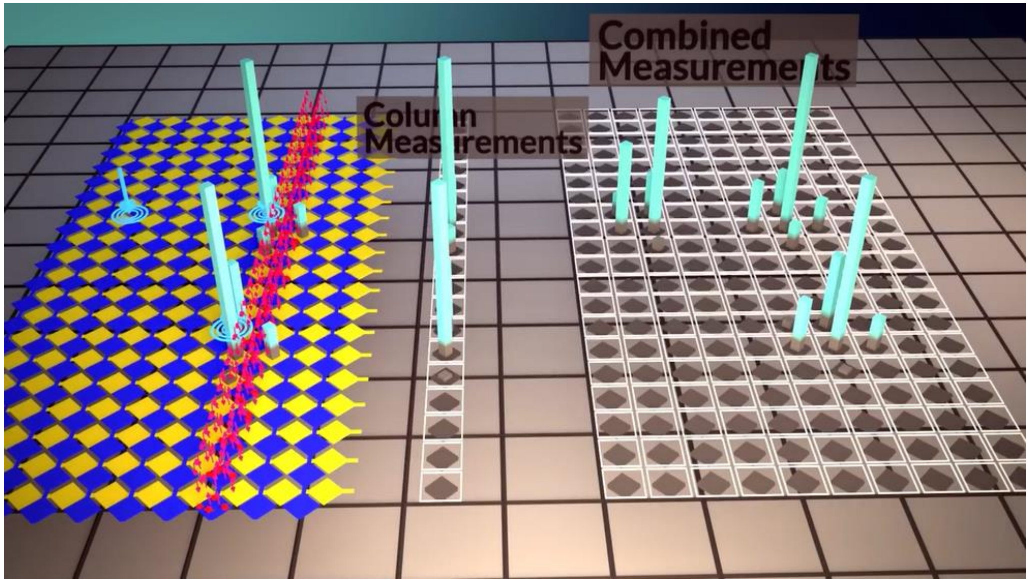
- Can do multitouch.

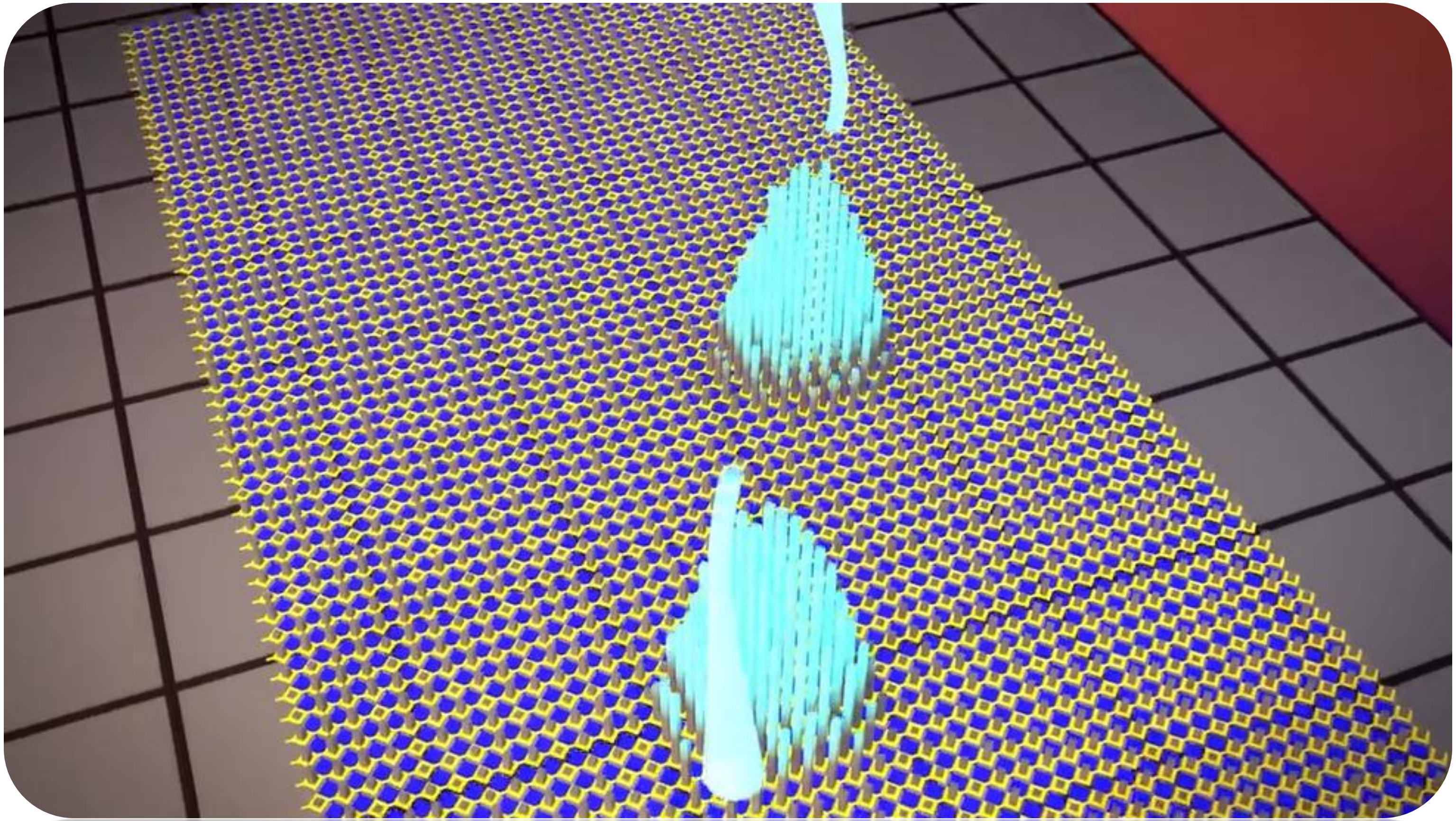
◆ Multitouch capability





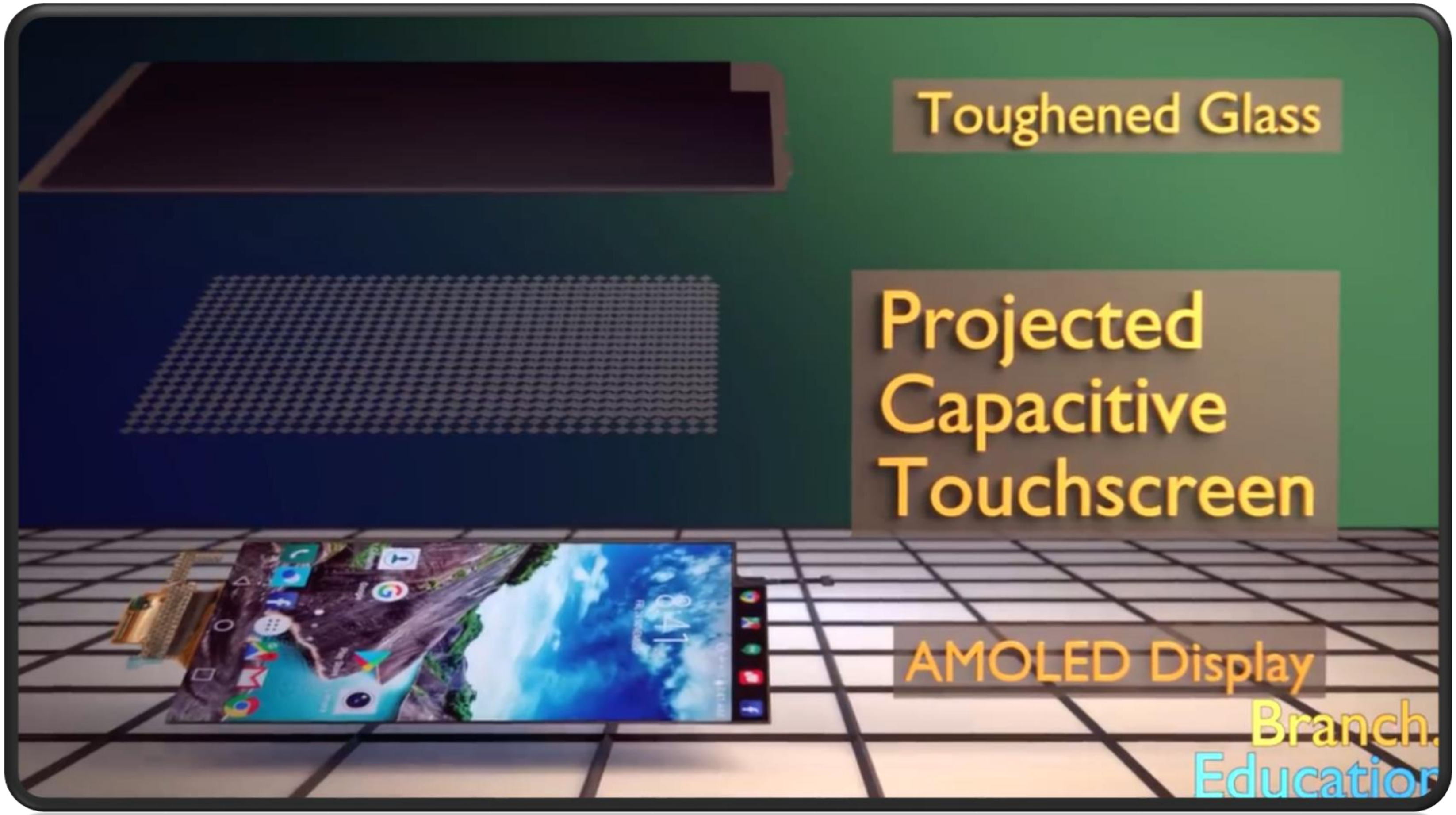
- 80 columns are electrically connected
- Scan each row within 10us

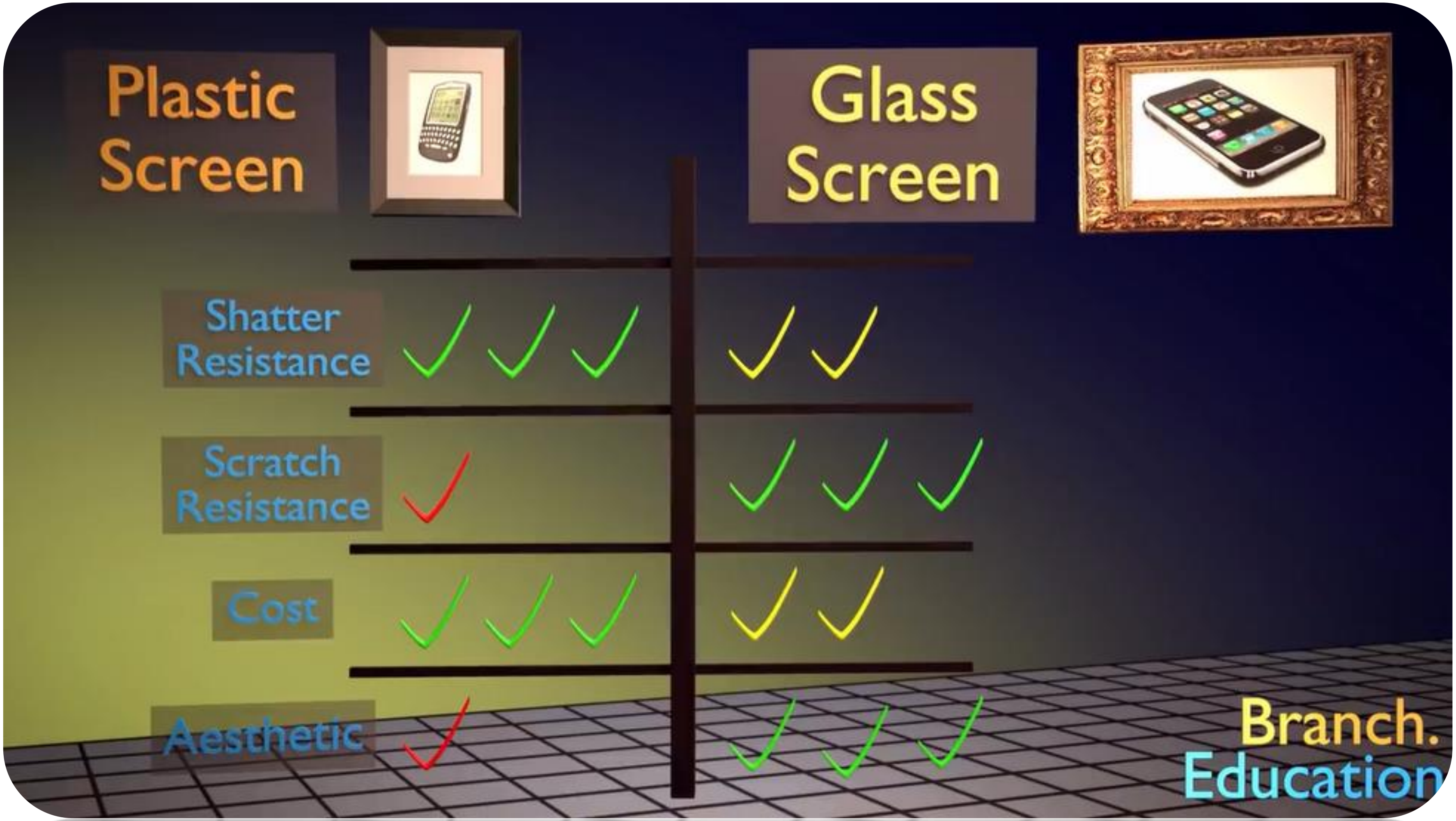




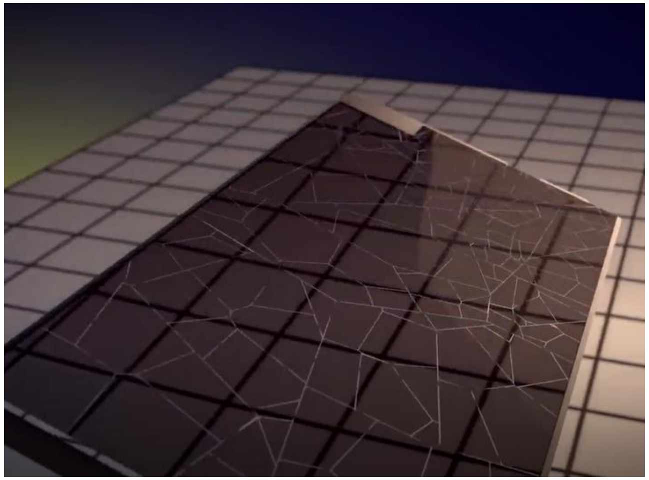
Let’s see a video

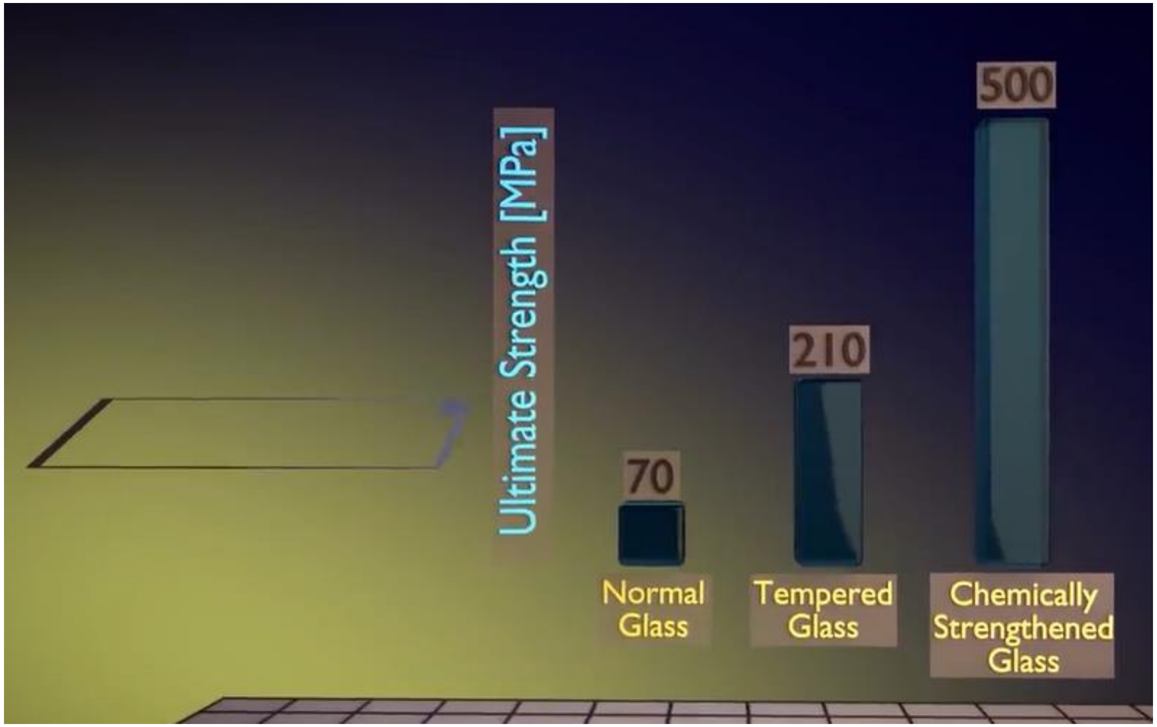
◆ Screen protector



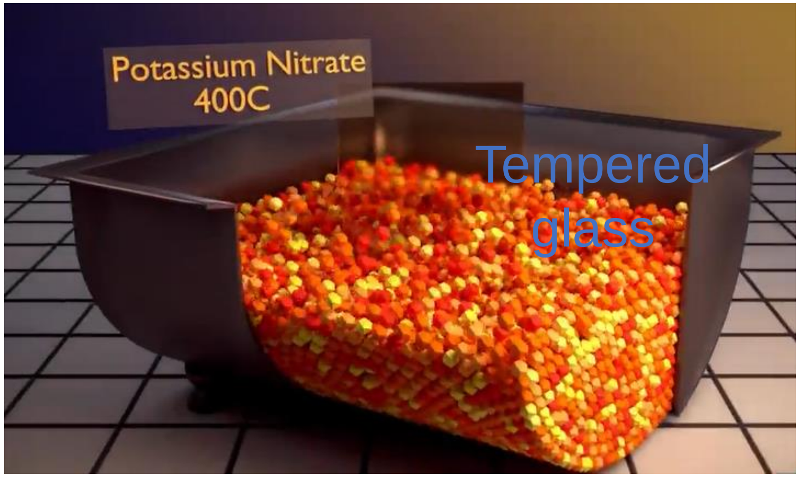

Plastic Screen
Glass Screen
Shatter Resistance
Scratch Resistance
Cost
Aesthetic
Branch. Education

Glass screen





Chemically strengthened glass 化学钢化/强化玻璃



Tempered glass