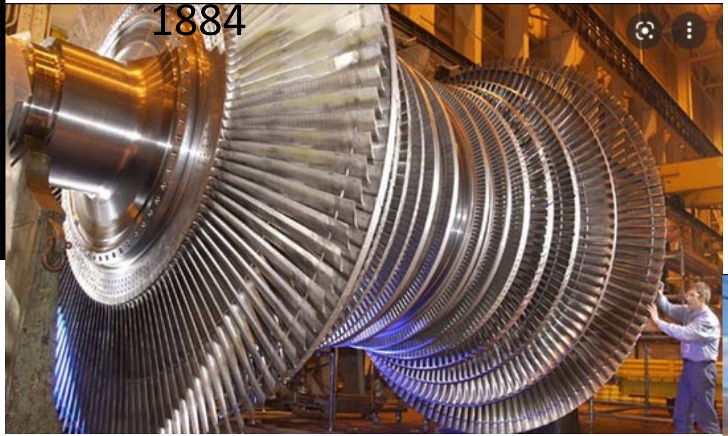
Introduction to Electronic Materials and Characterization

Electric Trains (1837)

1884



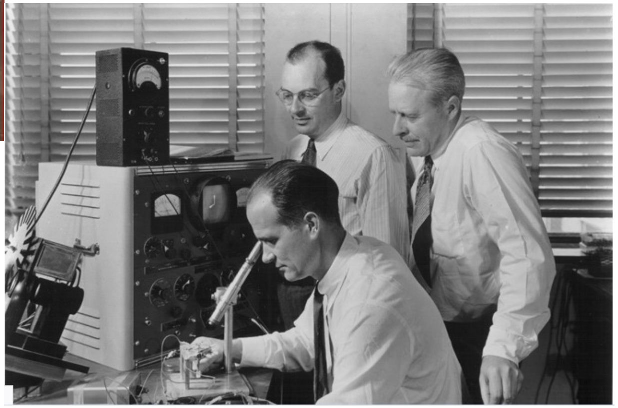
Steam Turbines, 1884

Electric Fans, appliances (1900)

Telephone lines
- The need for switching voltages – fast (1876)

Delhi-Faridabad Electric Sub-station 1885

Transmission-Line cables



Birth of Transistors, 1947

1973 – First handheld Motorola

Moto1973

Nokia 1987

Moto First Flip 1989

Nokia Communicator 1993

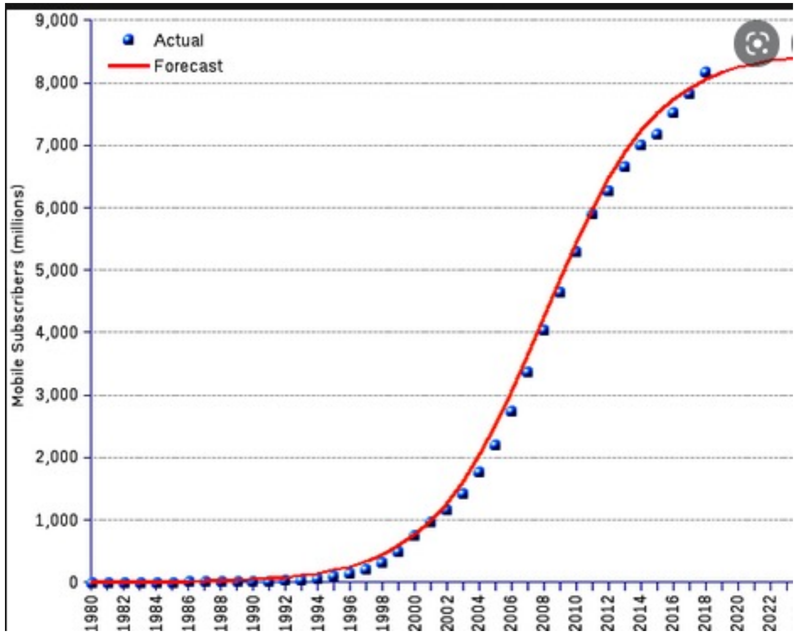
Seimens, Color Screen 1998

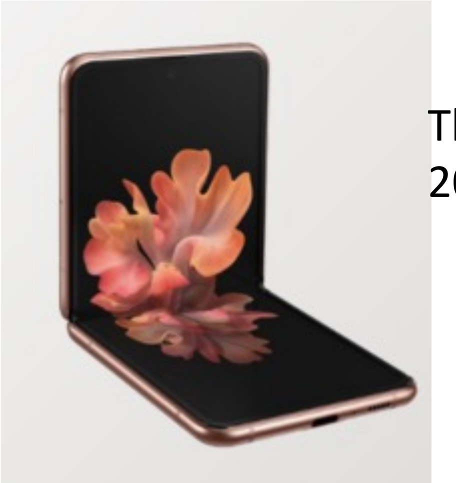
Nokia water proof 1999, 3G, GPS

First camera phone was a Selfie one!

Year 2K

First iPhone 2007





The fold again! 2020

Electrically ?

Soot

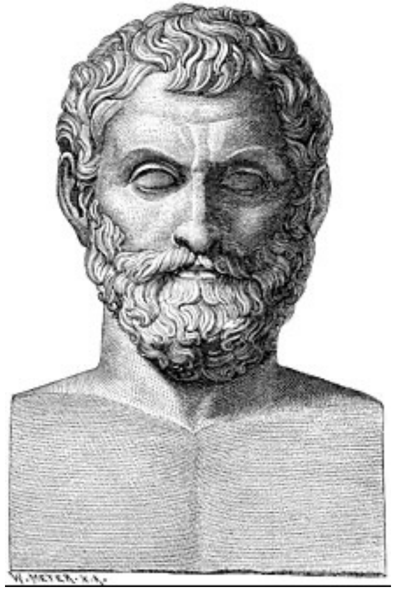
Graphite

Diamond

Structurally different!

What is electric charge ?

Charge (q): It is an indivisible physical property which bears a force upon interaction with an electric field. Electrons are taken to be negatively charged and protons positively charged (convention).



Thales Miletus 400 – 600 BC

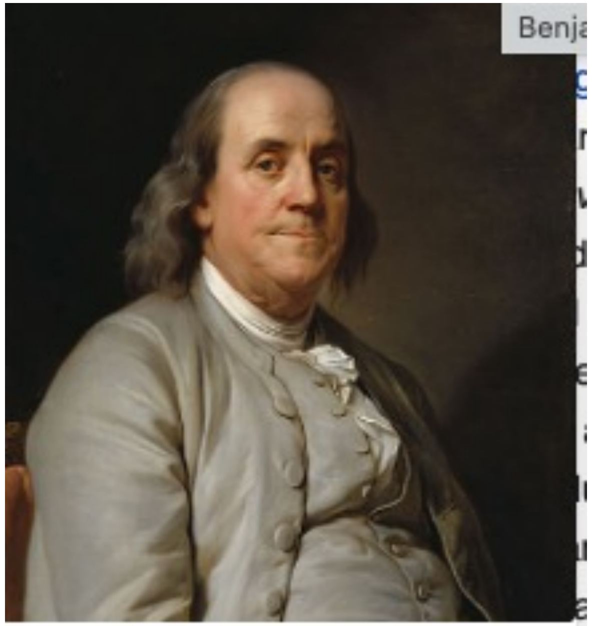
Amber and Fur are inanimate objects having soul

In 1600 **William Gilbert** coins the term electrica from Greek word electron for Amber

1729 The ‘electron’ in the Amber-fur flown across distances [Stephen Gray]

1733 Almost all materials can collect electrons by rubbing, other than metals! – C. Fay

Benjamin Franklin

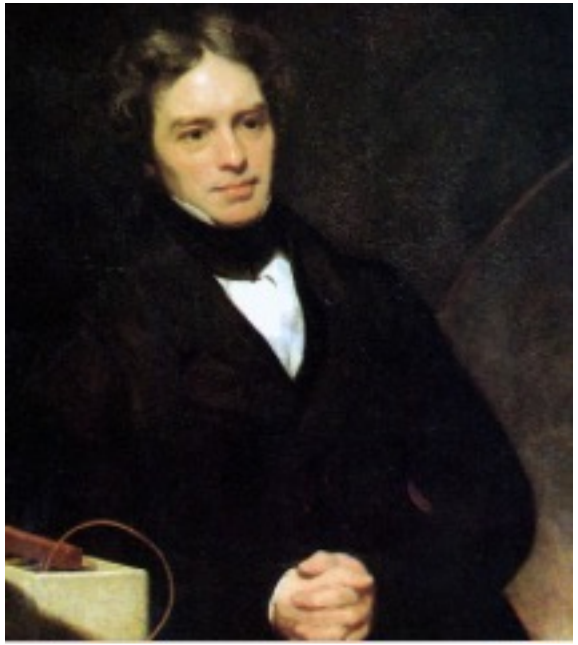


1750 – Rubbing glass with rubber develops equal ‘electrons’ on both and there exists attractive force. So two kinds of charges – B. Franklin

Alexandra Volta

1800 – Charges can be made to flow in a continuous loop. Alexander Volta

Michael Faraday

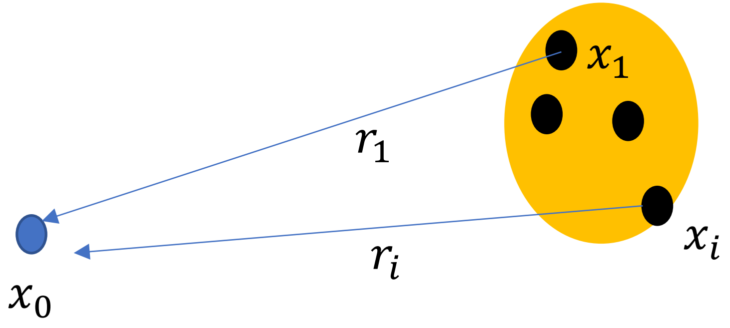


1833- 1838 There are only two kinds of charges.
They are independent on its prepared.
There is a force of attraction between the two kinds and they want to inter-mix in normal materials. When you rub one against other, the two types separate to different surfaces - M. Faraday

Charles Augustine Di Coulomb

In 1784:

- There exists a force between two charges
- The force was found to act on the line joining the charges, only either towards/away
  - Thereby giving only two kinds of charges
- The force is proportional to the number of charges
- The force is inversely proportional to the square of the distance between the two



Electric Field E: Force experienced by a unit positive charge

$$E = \frac{F}{q_0} \quad 1/4\pi\epsilon_0 \sum_i \frac{q_i}{(x_i - x_0)^2}\hat{r}_i$$

Ampere equations

Charge Dynamics

- Force on a charge $F = qE$
- Forces causes charges to move,
- moving charges are called current from hydrodynamics.
- One defines current density $J = \frac{d\rho}{dt}$

1820 – Orsted - flowing charge affects compass. There is an induced magnetic field.

- Magnetic field lines encircle the wire carrying current
- lie perpendicular to the plane of the wire.

Ampere also introduced the equations for the magnetic field and current density called as the circuital law:

Forms of the original circuital law written in SI units

	Integral form	Differential form
Using **B**-field and total current	$\oint_C \mathbf{B} \cdot \mathrm{d}\boldsymbol{l} = \mu_0 \iint_S \mathbf{J} \cdot \mathrm{d}\mathbf{S} = \mu_0 I_{\mathrm{enc}}$	$\nabla \times \mathbf{B} = \mu_0 \mathbf{J}$
Using **H**-field and free current	$\oint_C \mathbf{H} \cdot \mathrm{d}\boldsymbol{l} = \iint_S \mathbf{J}_{\mathrm{f}} \cdot \mathrm{d}\mathbf{S} = I_{\mathrm{f,enc}}$	$\nabla \times \mathbf{H} = \mathbf{J}_{\mathrm{f}}$

James Clarke Maxwell

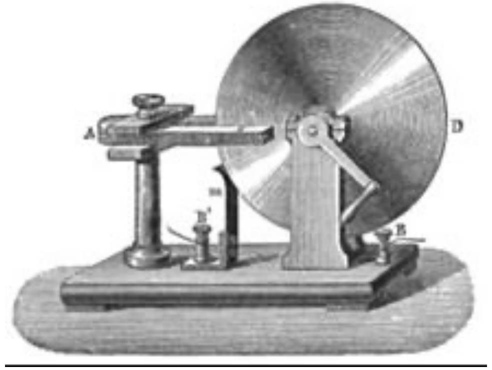
In dynamical theory of electromagnetic fields (1865)

Name	Integral equations	Differential equations
Gauss's law	$\oiint_{\partial\Omega} \mathbf{E} \cdot \mathrm{d}\mathbf{S} = \frac{1}{\varepsilon_0} \iiint_{\Omega} \rho \, \mathrm{d}V$	$\nabla \cdot \mathbf{E} = \frac{\rho}{\varepsilon_0}$
Gauss's law for magnetism	$\oiint_{\partial\Omega} \mathbf{B} \cdot \mathrm{d}\mathbf{S} = 0$	$\nabla \cdot \mathbf{B} = 0$
Maxwell–Faraday equation (Faraday's law of induction)	$\oint_{\partial\Sigma} \mathbf{E} \cdot \mathrm{d}\boldsymbol{\ell} = -\frac{\mathrm{d}}{\mathrm{d}t} \iint_{\Sigma} \mathbf{B} \cdot \mathrm{d}\mathbf{S}$	$\nabla \times \mathbf{E} = -\frac{\partial \mathbf{B}}{\partial t}$
Ampère's circuital law (with Maxwell's addition)	$\oint_{\partial\Sigma} \mathbf{B} \cdot \mathrm{d}\boldsymbol{\ell} = \mu_0 \left(\iint_{\Sigma} \mathbf{J} \cdot \mathrm{d}\mathbf{S} + \varepsilon_0 \frac{\mathrm{d}}{\mathrm{d}t} \iint_{\Sigma} \mathbf{E} \cdot \mathrm{d}\mathbf{S} \right)$	$\nabla \times \mathbf{B} = \mu_0 \left(\mathbf{J} + \varepsilon_0 \frac{\partial \mathbf{E}}{\partial t} \right)$

Electrical Components

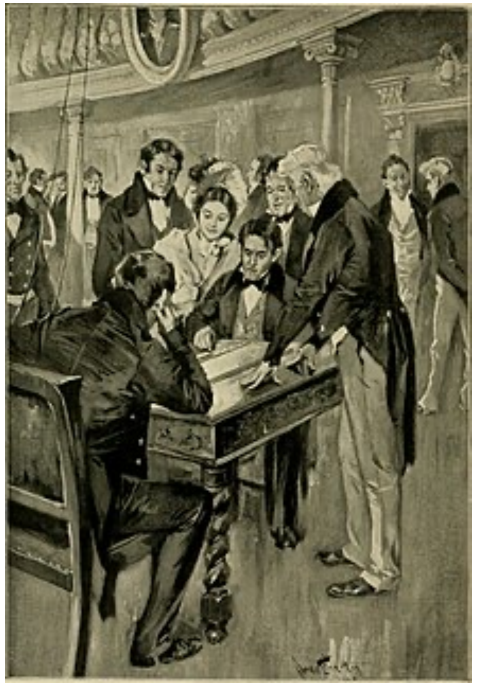
Leiden Jar, 1745

First notion of storage of charges,
First unit of capacitance was Jar.



Faraday's Motor, 1820

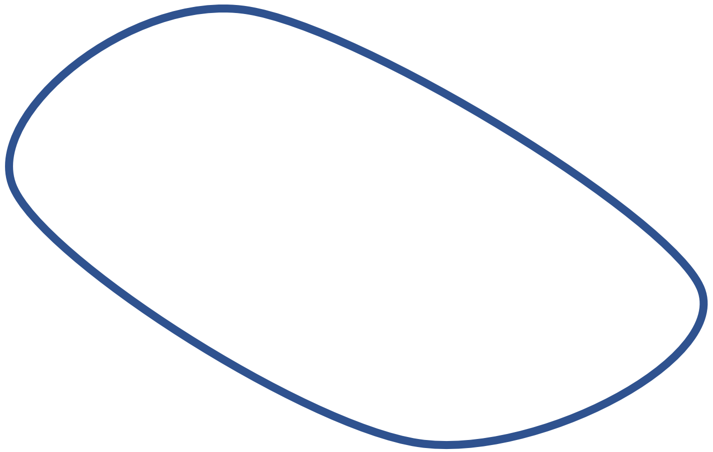
Faraday thought a wave will flow between two coils wound on an iron core when one of them is carrying current. He also saw that current can flow in the coil as the magnet/iron rod can be moved fast enough. Hence he name inductance, where the wave is induced.



Morse code, 1844
Transmission of electric signals on long wires to communicate information.

Marconi,
Bose Radio waves
1886-1888

What is Potential/ Voltage ?



Consider a system with a large collection of chargeble particles.

The entire collection is entirely neutral – always!

A battery is a special system in which the work is done to separate the charges.

However, some work can be done on the system to locally separate the charges.

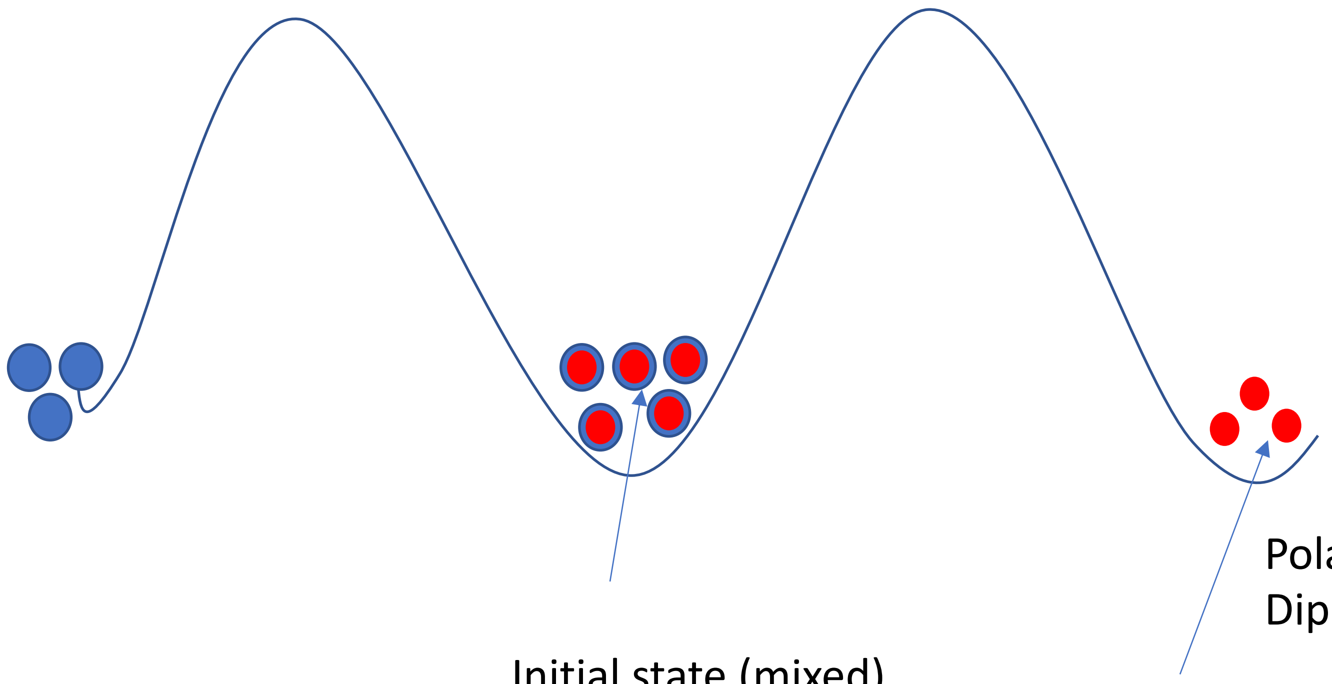
Since work is done on the system, its total energy (potential) energy increases!

Remember, just separation is not enough!

Remember a low energy state with increasing entropy exists in which the charges are mixed! .

So, if there exists a pathway for the charges to recombine, the system will recombine and reduce to lowest energy.

Excess energy will be delivered as heat!



A battery, potential source has the capacity to separate charges and retain the separation for enough time

Useful work can be done if the charges are allowed to recombine in a controllable fashion

Capacitor/ Charge accumulator

A charge density ρ separated by a distance d [m] develops a potential difference

$$V = \frac{d\rho}{\epsilon}$$

Defining a capacitance density C = ϵ/d [F/m]

Current – defined as the rate of flow of charges

Current through the plates: $i = C\frac{dV}{dt} = C\int \frac{dE}{dt}dl$

Resistor

If there exists a current density (j) due to a potential difference V

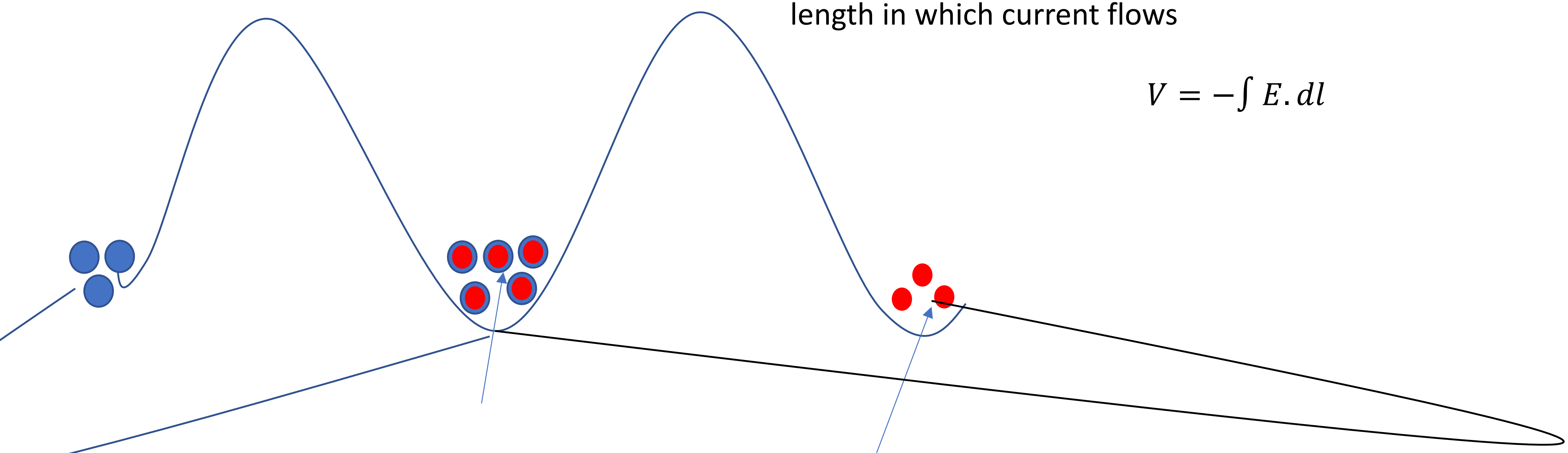
It was experimentally observed that

$$I = V\sigma$$

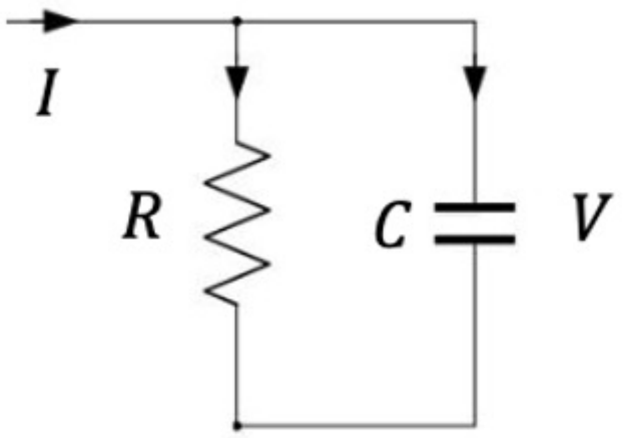
Where σ is the conductivity [Sm^{-1}]

we define an electric field E such that it varies smoothly over the length in which current flows

$$V = -\int E.dl$$

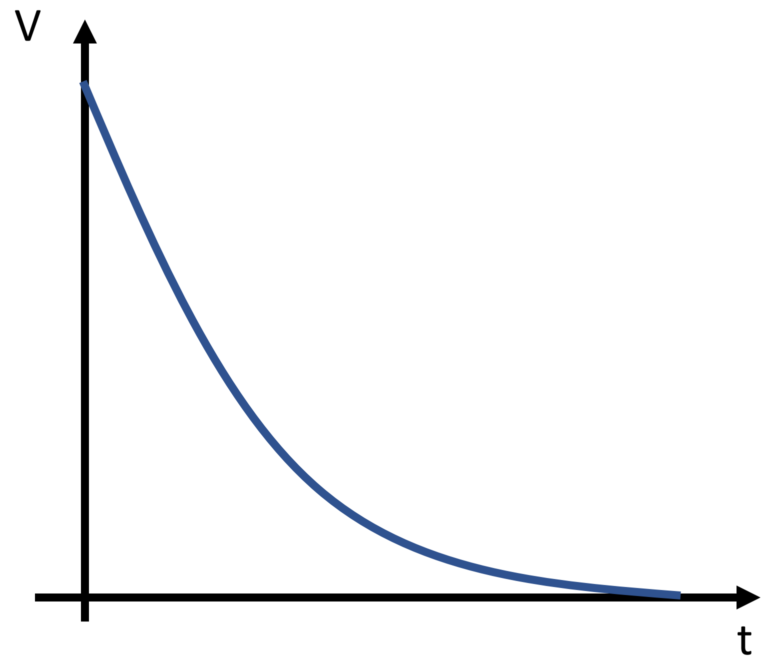


At what rate will the charges now be recombined ?



$$I = \frac{V}{R} + C\frac{dV}{dt}$$

$$\frac{I}{C} = \frac{V}{RC} + \frac{dV}{dt}$$



Solution to the D.E $\quad V(t) = V_0 e^{-\frac{t}{RC}}$

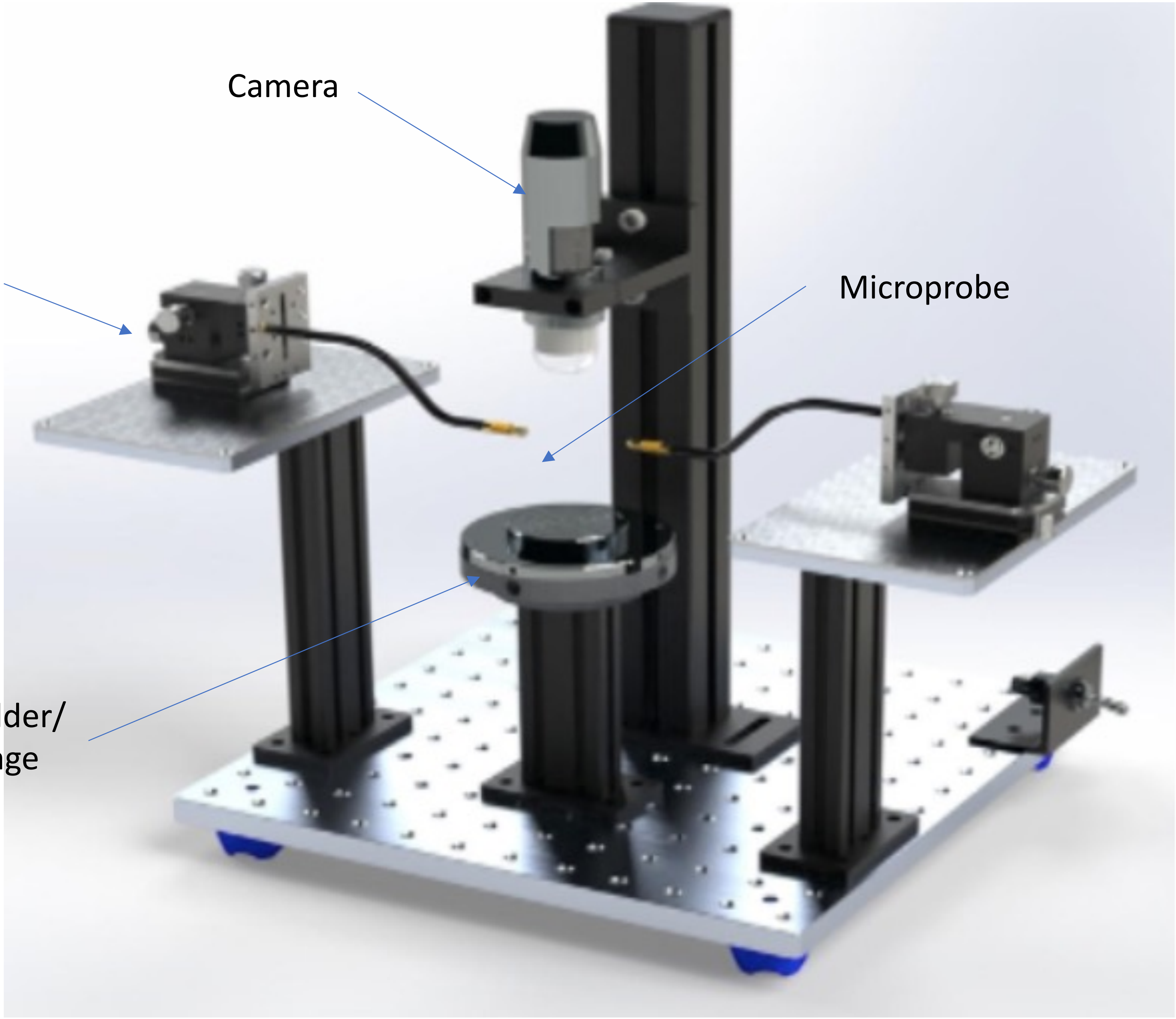
The potential will drop to 1/e times the initial value in a time determined by its time constant RC

Electrical Characterization of Materials

The following properties are usually measured.

1. Electrical conductivity
2. Dielectric constant/Strength
3. Ferro-electricity
4. Piezoelectricity
5. Pyroelectricity
6. Photosensitivity

Probestation



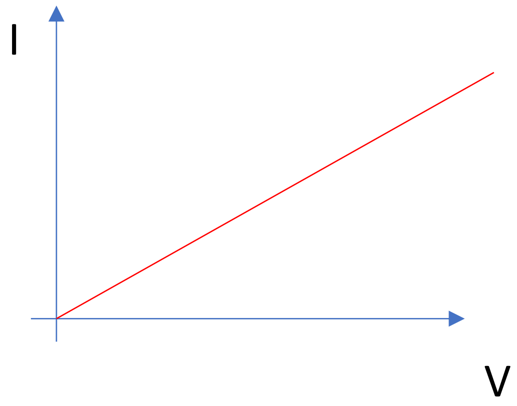
Resistivity Measurement

Two wires are connected to a material of a well-defined geometry.
Preferably with a constant cross section.

Two methods:

1. Constant potential:-

   In this method, a constant voltage source is connected to the terminals and the current is measured.

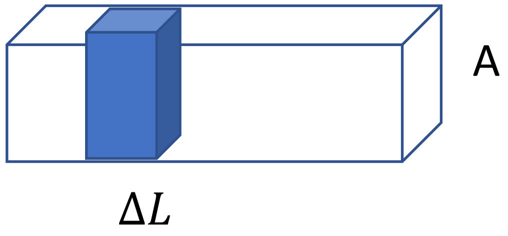


Under such circumstances, we obtain the material resistance $R = \frac{V}{I}$

Typically, a series of measurements are taken such that the resistance is extracted as the slope

Resistance $R = \frac{dV}{dI}$

However, also remember, that the resistance is proportional to the geometry



$$\rho = R * \frac{A}{L}$$

Is an intrinsic material property

Resistance is measured in Ohms (Ω)

Length, and area in m and m^2 respectively.

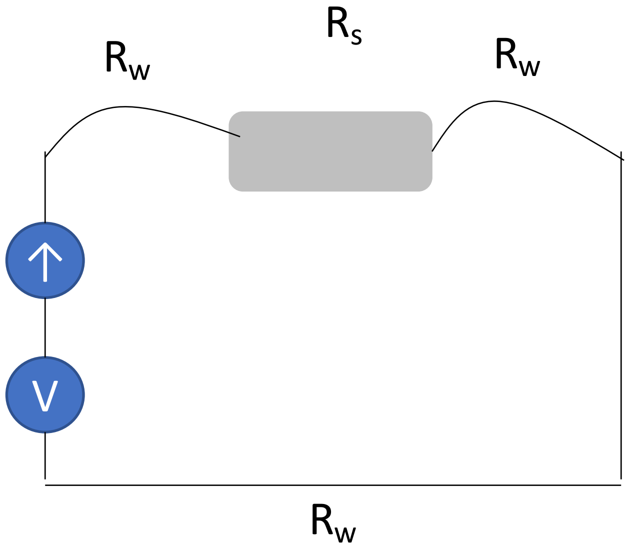
The resistivity has the units of $\Omega - m$

At room temperature the measured resistances are given here.

Sl. No.	Element	Resistivity at 20°C in Ω – m
1	Silver	1.59×10^{-8}
2	Copper	1.7×10^{-8}
3	Gold	2.44×10^{-8}
4	Aluminum	2.82×10^{-8}
5	Tungsten	5.6×10^{-8}
6	Iron	1.0×10^{-7}
7	Platinum	1.1×10^{-7}
8	Lead	2.2×10^{-7}
9	Manganin	4.82×10^{-7}
10	Constantan	4.9×10^{-7}
11	Mercury	9.8×10^{-7}
12	Carbon (Graphite)	3.5×10^{-5}
13	Germanium	4.6×10^{-1}
14	Silicon	6.4×10^{2}
15	Glass	10^{10} to 10^{14}
16	Quartz (fused)	7.5×10^{17}

There is a problem here!

In an actual experiment, the system is like this



Therefore, the total resistance of the circuit is

$$R_M = R_S + n * R_W$$

In situations where the sample resistance is very small (particularly in metals), This method over-estimates the resistance

The solution is Via Kirchhoff's law.

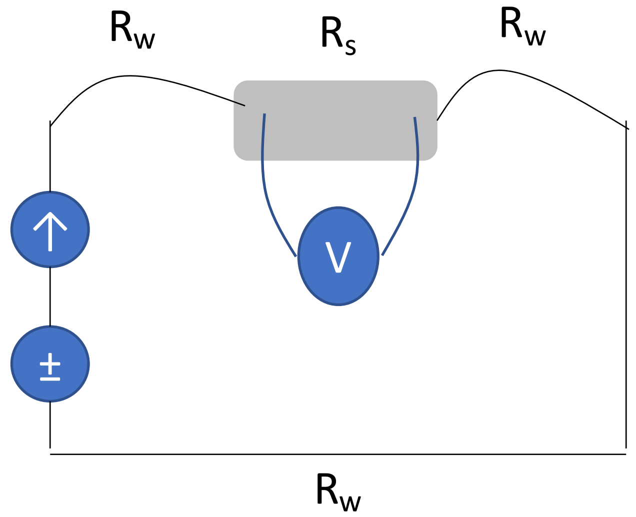
By Kirchhoff, all the resistive components give independent potential drops, which should sum up to the supply potential

$$V_T = V_S + n * V_W$$

Thus the solution to the problem is near! .

Since the current that passes through the wires and the samples is the same. All you need is to measure the potential difference on the sample

This method of measurement is called as four-probe Resistance measurement



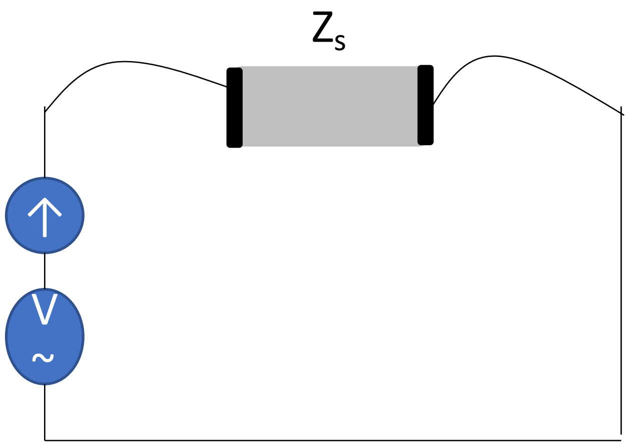
Measure of Capacitance

For a class of materials that do not conduct current so well, resistance tends to very high values

No proper current sensor can measure such tiny currents

$R \to \infty$ as $I \to 0$ for some known small potential.

How do we characterize these materials ?

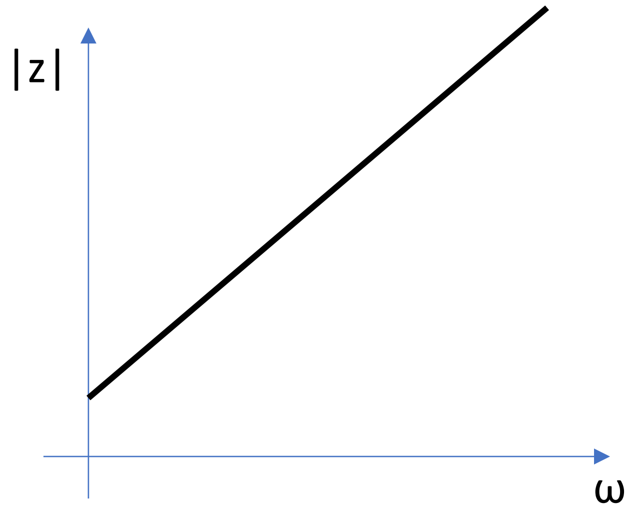


Since the resistance goes to ∞ for a steady DC potential,

We can measure the capacitance of the structure.

This is done by imposing an alternating potential of freq ω

Once again, the actual capacitance is measured by sweeping the frequency



The slope of the impedance vs frequency plot gives the capacitance.

The Y-intercept gives the resistance!

For a typical device

$$Z = R + j\omega C$$

The impedance is complex as there is phase difference between the potential and the current.

The capacitance is once again a geometric parameter.

A fundamental property of the material, dielectric constant ϵ is then obtained by

$$\epsilon = \frac{CA}{d}$$

Where C is measured slope, A – cross section of the capacitor and d is the separation between the plates

A general table of dielectric constants

Material	Dielectric constant
Air (dry)	1.0
Bakelite	4.9
Mylar	3.2
Nylon	3.4
Paper	3.7
Paraffin-impregnated paper	3.5
Polypropylene	2.2
Polystyrene	2.6
Polyvinyl chloride	3.4
Porcelain	6.0
Pyrex glass	5.6
Strontium titanate	233.0
Water	80.0

For a general unknown material:

Suppose, I have an excitation signal such as

$$v = v_0 \sin \omega t$$

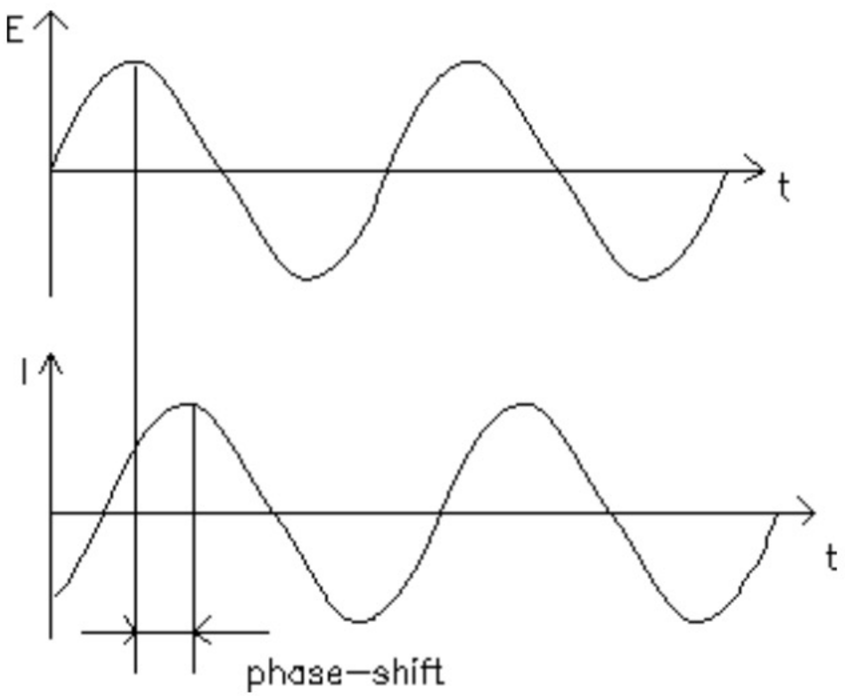
$\omega(\frac{rad}{sec}) = 2\pi f$ – f being the frequency (hertz)

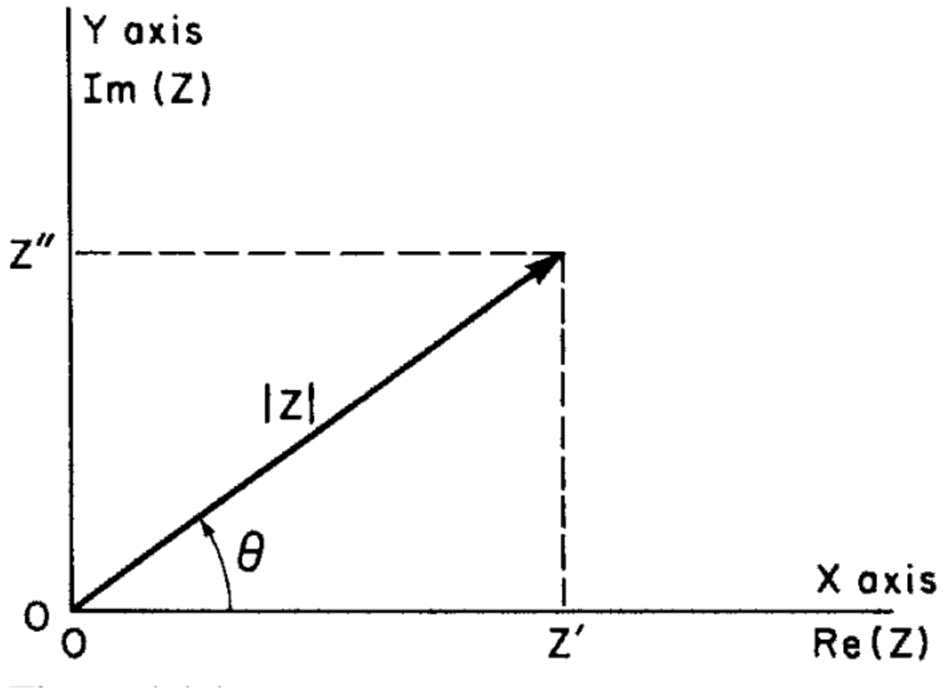
In a linear system, the output current is of the form

$$I = I_0 \sin \omega t + \phi$$

An impedance $Z = \frac{v}{I} = \frac{v_0}{I_0} \frac{sin\omega t}{\sin \omega t + \phi}$

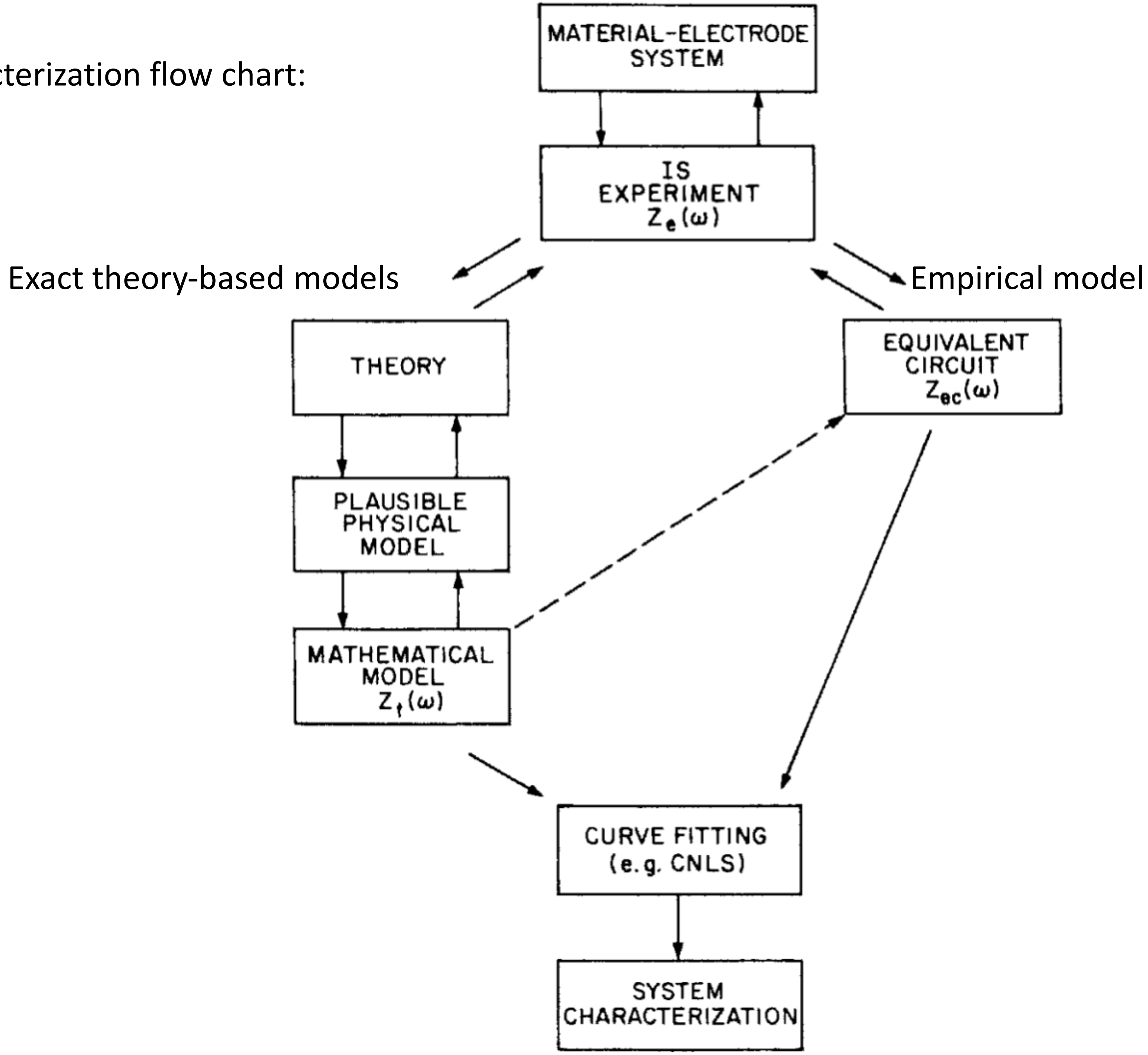
Thus, impedance is typically specified as Z_0, ϕ at ω



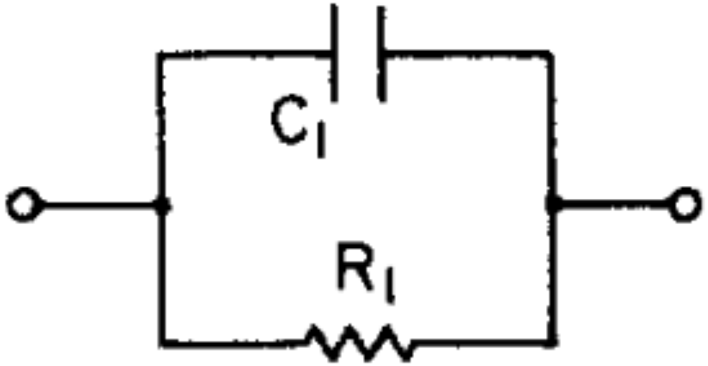


The impedance is a complex value $R(Z) = |Z|\cos\theta \; and \; Im(Z) = |Z|\sin\theta$

General characterization flow chart:

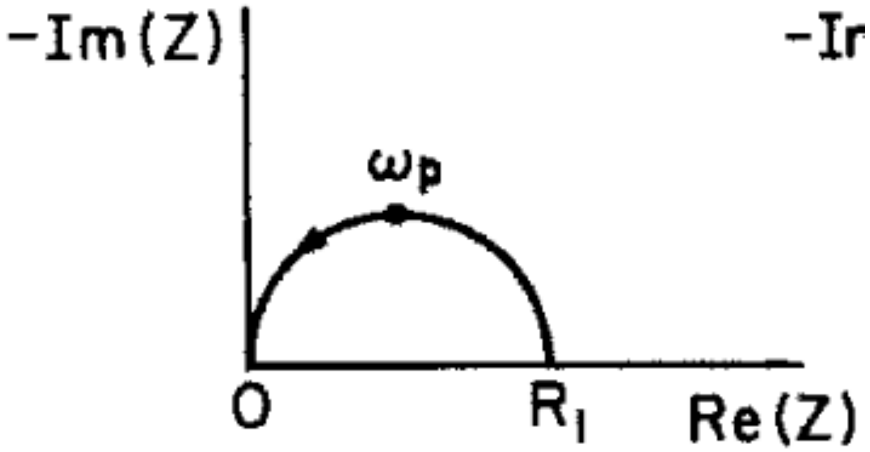


Simple equivalent circuit



(a)

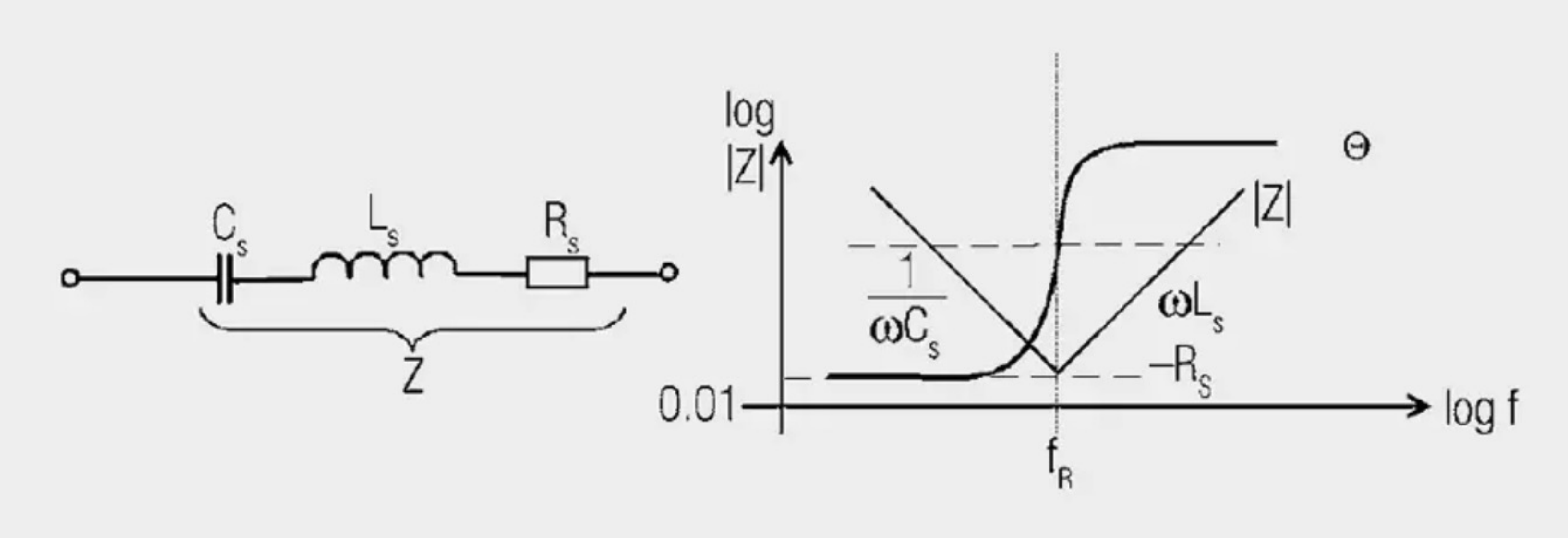
Nyquist plot

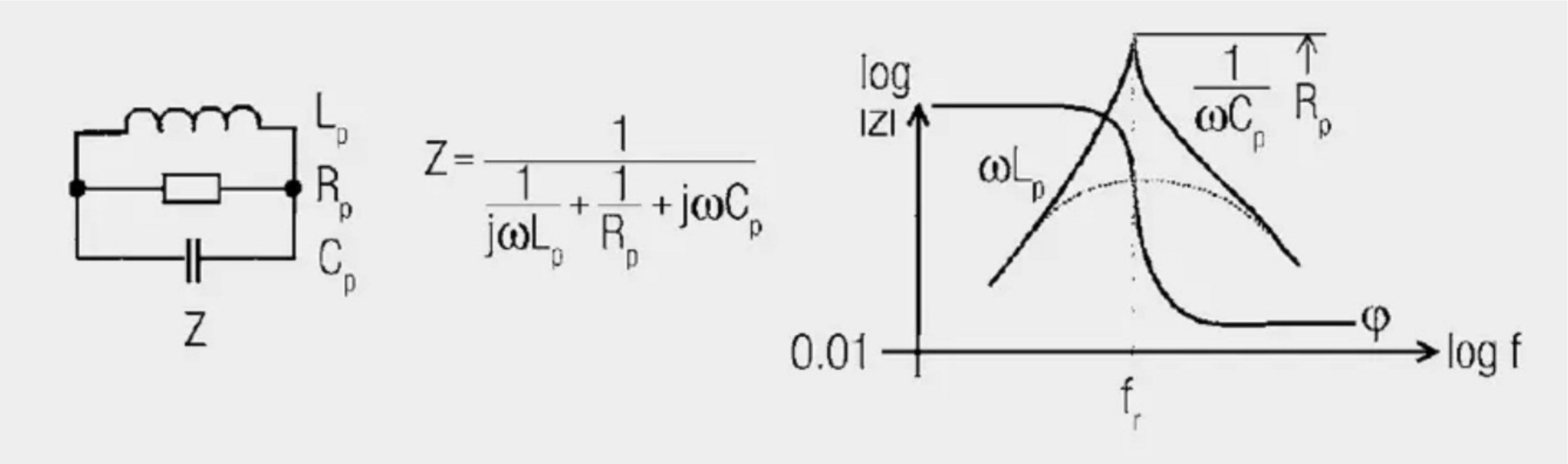


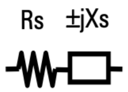
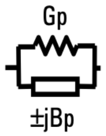
(b)

Maximal impedance frequency ω_p - associated with minimum time constant $\tau_D = 1/\omega_p$

Alternate equivalent circuits





<table>
<tr><th colspan="2">Series mode</th><th colspan="2">Parallel mode</th></tr>
<tr><td>
</td><td>$|Z| = \sqrt{Rs^2 + Xs^2}$
$\theta = \tan^{-1}(Xs/Rs)$</td><td>
</td><td>$|Y| = \sqrt{Gp^2 + Bp^2}$
$\theta = \tan^{-1}(Bp/Gp)$</td></tr>
<tr><td colspan="2">Rs: Series resistance
Xs: Series reactance
(XL = wLs, XC = –1/(wCs))
Ls: Series inductance (= XL/w)
Cs: Series capacitance (= –1/(wXC))
D: Dissipation factor
(= Rs/Xs = Rs/(wLs) or wCsRs)
Q: Quality factor
(= Xs/Rs = wLs/Rs or 1/(wCsRs))</td><td colspan="2">Gp: Parallel conductance (= 1/Rp)
Bp: Parallel susceptance
(BC = wCp, BL = –1/(wLp))
Lp: Parallel inductance (= –1/(wBL))
Cp: Parallel capacitance (= BC/w)
D: Dissipation factor (= Gp/Bp = Gp/(wCp)
= 1/(wCpRp) or wLpGp = wLp/Rp)
Q: Quality factor (= Bp/Gp = wCp/Gp
= wCpRp or 1/(wLpGp) = Rp/(wLp))</td></tr>
</table>

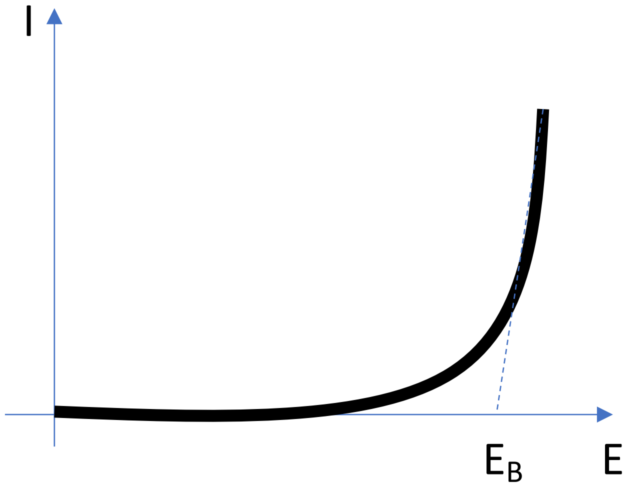
Dielectric Breakdown

All the measurements before are true before a certain limit is reached.

A true dielectric blocks DC current and allows AC current to flow with a known impedance.

However, this blocking capacity is not infinite.

A typical current density vs DC potential for dielectrics look like



The field at which the current density increases drastically is called as the breakdown potential and the dielectric no longer blocks the DC potential

This property is important for insulators used in HV transmission, microelectronic devices and control systems

Some example dielectric strength of polymers

Dielectric strength in kilovolts per inch (kV/in):

Material*	**Dielectric strength**
Vacuum	20
Air	20 to 75
Porcelain	40 to 200
Paraffin Wax	200 to 300
Transformer Oil	400
Bakelite	300 to 550
Rubber	450 to 700
Shellac	900
Paper	1250
Teflon	1500
Glass	2000 to 3000
Mica	5000

Effect of Temperature

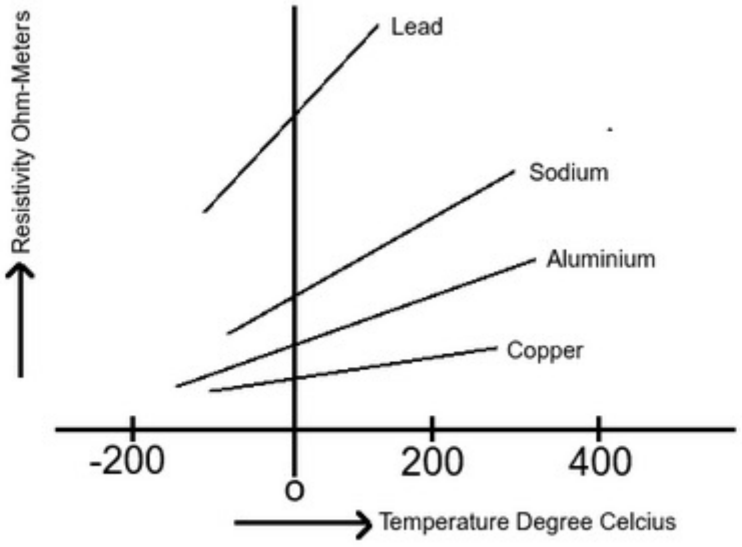
Temperature has an interesting effect on electrical properties

Experimentally, for many materials, if the resistance (R_{ref}) is measured at a reference temperature T_{ref}

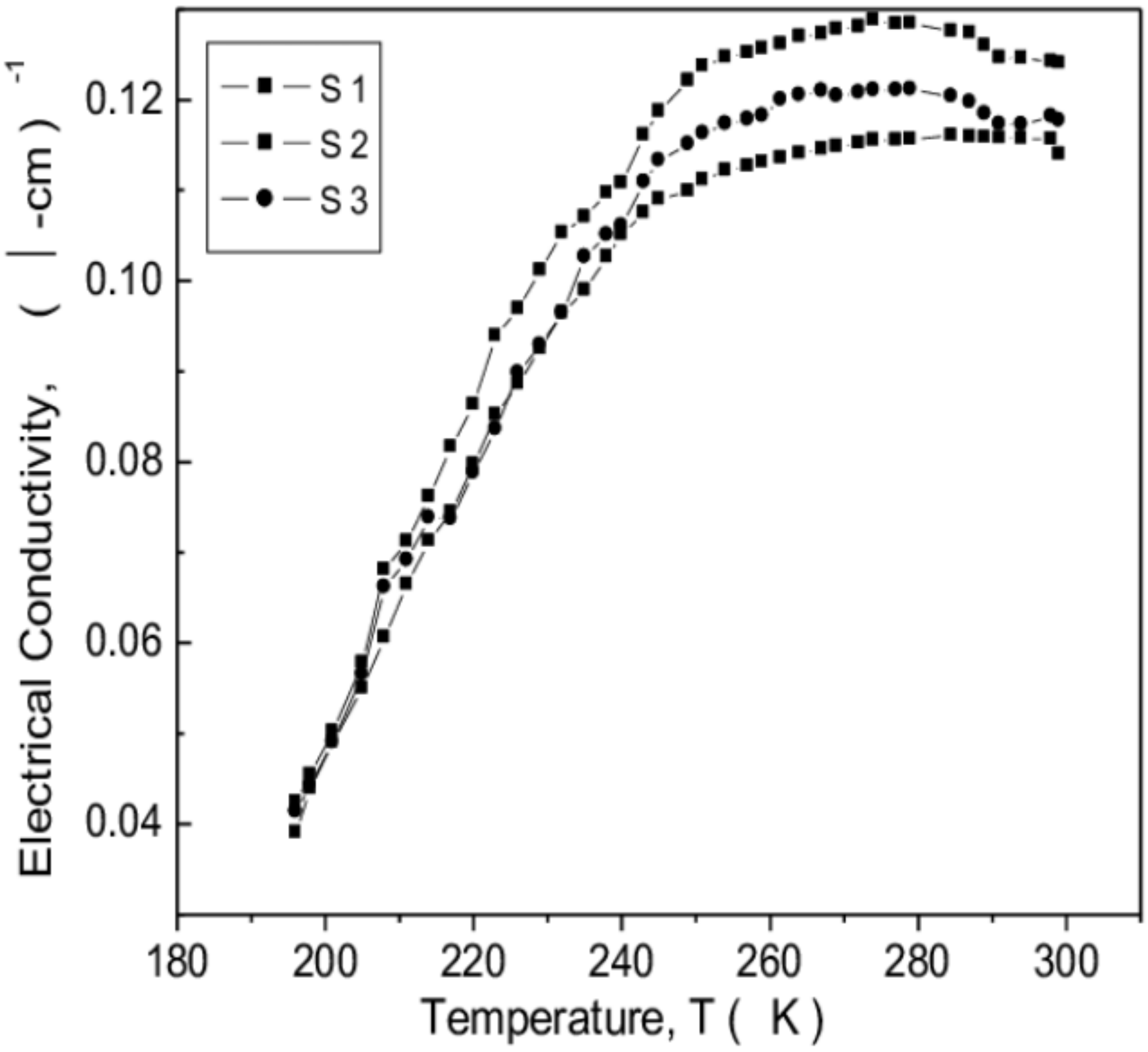
At any other temperature T, the resistance can be obtained from the expression

$$R = R_{ref}\left[1 + \alpha\left(T - T_{ref}\right)\right]$$

Metals seems to have a positive temperature coefficient α



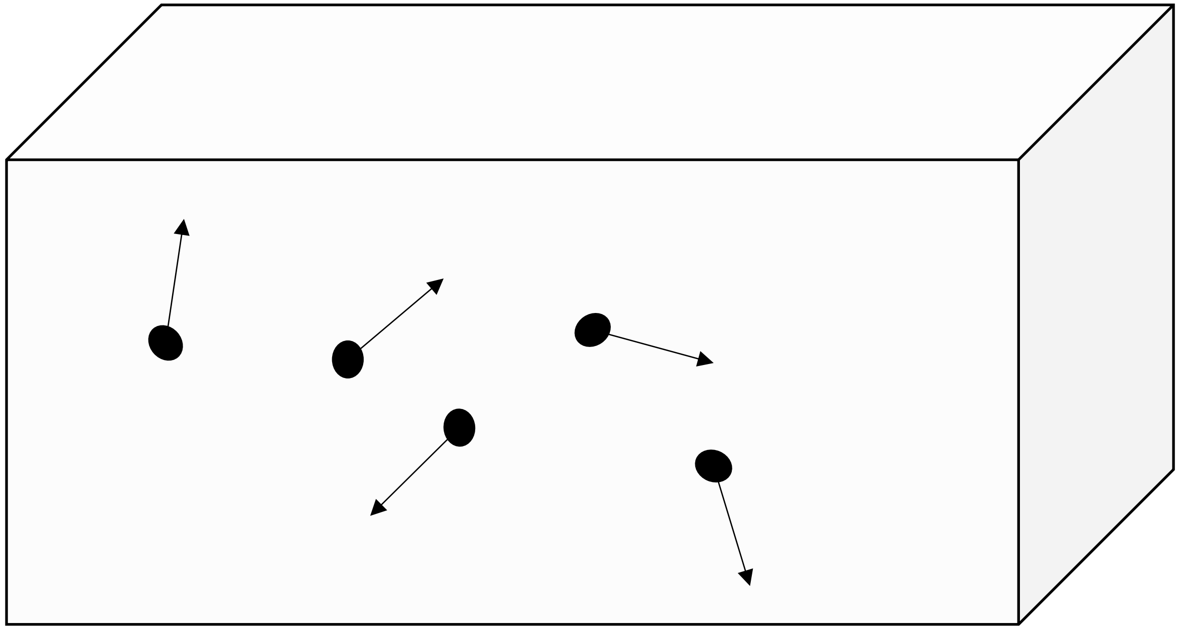
However, for another class of materials - Semiconductors



Experimental Temperature Co-efficient of Resistance

Material	Resistivity, ρ ($\Omega \cdot m$)	Temperature Coefficient, α $(C°)^{-1}$
Conductors		
Silver	1.59×10^{-8}	0.0061
Copper	1.68×10^{-8}	0.0068
Gold	2.44×10^{-8}	0.0034
Aluminum	2.65×10^{-8}	0.00429
Tungsten	5.6×10^{-8}	0.0045
Iron	9.71×10^{-8}	0.00651
Platinum	10.6×10^{-8}	0.003927
Mercury	98×10^{-8}	0.0009
Nichrome (Ni, Fe, Cr alloy)	100×10^{-8}	0.0004
Semiconductors‡		
Carbon (graphite)	$(3\text{–}60) \times 10^{-5}$	−0.0005
Germanium	$(1\text{–}500) \times 10^{-3}$	−0.05
Silicon	0.1–60	−0.07
Insulators		
Glass	$10^{9}\text{–}10^{12}$	
Hard rubber	$10^{13}\text{–}10^{15}$	

What is Resistance ?



Assume a material having n free electrons.

Electrons move in material like ideal gas in containers.

Only difference: Electrons scatter with ions in solids.

If mean scattering time is τ

Under these assumptions, one can extract resistivity $\frac{1}{\rho} = \frac{ne^2\tau}{m}$

This is the Drude's model for conductivity in metals

$$\frac{1}{\rho} = \frac{ne^2\tau}{m}$$

If the electron masses is assumed to be constant in all materials, the only variable then is

$$n * \tau$$

Thus, materials with higher number of electrons or those with longer scattering times have lower resistivity

Along the same lines: If temperature is increased, if the number of electrons is not changing, a increased resistance is observed because of reduction in the mean scattering time.

This is can be due to stronger ion oscillations at higher temperatures!

However, this is just the beginning! The story is not complete!