Physics 209, Lecture 9

Today’s Topics

- Current And Resistance (Ch. 25)
- Motion of Charged Particle In Electric Field (brief review)
- Current: Macroscopic and Microscopic Views
- Resistance: Macroscopic and Microscopic Views
- Electrical Power

- Reminder, Midterm 1, Oct 5th, 5:30-7PM
- See your email for details
- Yes there is homework due next Monday
Motion Of Charged Particle In The Electric Field

- Fundamental Formulas:
  - \( F = qE \)
  - \( a = \frac{F}{m} = \frac{qE}{m} \)
  - \( v = v_i + at \rightarrow \text{if } v_i = 0, \text{ then } v = at \)

If initially at rest
Subsequent Motion of \( +q \):
Same dir. as \( E \)
From high \( V \) to low \( V \)

Motion of \( -q \):
Opposite dir. as \( E \)
From low \( V \) to high \( V \)
Charge Motion in a Conductor

- Without electric field:
  - electrons move randomly (thermal motion) \(|v_{av}|=0, |v|_{av} >0\)

- With electric field applied:
  - electron motion = thermal + drift (directional): \(|v_{av}| = v_{drift} >0, |v|_{av} >0\)
  - i.e. a net charge \(\Delta Q\) is moving directionally

- Average current: \(I = \frac{\Delta Q}{\Delta t}\)
- Instantaneous current: \(i = \frac{dQ}{dt}\)

“direct current (DC)”
\(I = \text{constant}\)


**Current: Macroscopic View**

- **Definition:** $I = \frac{dQ}{dt}$
- **Unit:** 1 Ampere = 1 Coulomb/1 sec
- **Current is directional:** Follows positive charge $+q$ moving in $+x$ direction $\leftrightarrow -q$ in moving $-x$ direction

- The following pictures represent the same current

- **Charge conservation $\rightarrow$ Current conservation**

$$I_{in} = I_{out}$$

\[ V \]

\[ A \]
Current: Microscopic View

- Current $\leftrightarrow$ motion of charged particles

Then:

- Current density $J = \frac{I}{A} = nqv_d$
  
(vector)

$\Delta x$:

$v_d$: average drift velocity

$n$: number density

$I_{\text{average}} = \frac{\Delta Q}{\Delta t} = nq v_d A = I$

Note: $v_d \propto E$ (why?)

$v = at = \left(\frac{F}{m}\right)t = \left(\frac{Eq}{m}\right)t$

where $t$ is the time till the charge hits something
Ohm’s Law: Resistance

- It can be shown (experimentally and theoretically) that for many material, the electric current is proportional to $\Delta V$

\[ I \propto V \]

note: $I \propto v_d \propto E \propto V$

- For a fixed material and geometry

\[ I = \frac{V}{R} \quad \text{or} \quad V = RI \]

R will have something to do with the time till the charges hit something (or how much the material resists the motion of the charges) and distance l

⇒ R: resistance
Conductivity And Resistance

- Ohm’s Law (microscopic): \( J = \sigma E \)
  - \( \sigma \) is called conductivity
  - also: \( \rho = 1/\sigma \) is called resistivity
- Ohm’s Law (macroscopic): \( \Delta V = RI \)
- \( R \): Resistance. (unit: Ohm \( \Omega = \text{Volt}/\text{Amper} \))
- Relating \( R \) to \( \rho \), \( I = JA = (1/\rho)AE = (1/\rho)A(\Delta V/I) \)

\[
R = \rho \frac{l}{A}
\]
# Resistors

## Resistivity For Various Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Resistivity (a) (\Omega \cdot m) )</th>
<th>Temperature Coefficient (b ) ([\text{C}^{-1}])</th>
</tr>
</thead>
<tbody>
<tr>
<td>Silver</td>
<td>(1.59 \times 10^{-8})</td>
<td>(3.8 \times 10^{-3})</td>
</tr>
<tr>
<td>Copper</td>
<td>(1.7 \times 10^{-8})</td>
<td>(3.9 \times 10^{-3})</td>
</tr>
<tr>
<td>Gold</td>
<td>(2.44 \times 10^{-8})</td>
<td>(3.4 \times 10^{-3})</td>
</tr>
<tr>
<td>Aluminum</td>
<td>(2.82 \times 10^{-8})</td>
<td>(3.9 \times 10^{-3})</td>
</tr>
<tr>
<td>Tungsten</td>
<td>(5.6 \times 10^{-8})</td>
<td>(4.5 \times 10^{-3})</td>
</tr>
<tr>
<td>Iron</td>
<td>(10 \times 10^{-8})</td>
<td>(5.0 \times 10^{-3})</td>
</tr>
<tr>
<td>Platinum</td>
<td>(11 \times 10^{-8})</td>
<td>(3.92 \times 10^{-3})</td>
</tr>
<tr>
<td>Lead</td>
<td>(22 \times 10^{-8})</td>
<td>(3.9 \times 10^{-3})</td>
</tr>
<tr>
<td>Nichrome(^c)</td>
<td>(1.50 \times 10^{-6})</td>
<td>(0.4 \times 10^{-3})</td>
</tr>
<tr>
<td>Carbon</td>
<td>(3.5 \times 10^{-5})</td>
<td>(-0.5 \times 10^{-3})</td>
</tr>
<tr>
<td>Germanium</td>
<td>(0.46)</td>
<td>(-48 \times 10^{-3})</td>
</tr>
<tr>
<td>Silicon</td>
<td>(640)</td>
<td>(-75 \times 10^{-3})</td>
</tr>
<tr>
<td>Glass</td>
<td>(10^{10}) to (10^{14})</td>
<td></td>
</tr>
<tr>
<td>Hard rubber</td>
<td>(\sim 10^{13})</td>
<td></td>
</tr>
<tr>
<td>Sulfur</td>
<td>(10^{15})</td>
<td></td>
</tr>
<tr>
<td>Quartz (fused)</td>
<td>(75 \times 10^{16})</td>
<td></td>
</tr>
</tbody>
</table>

\(^a\) All values at \(20^\circ\)C.

\(^b\) See Section 27.4.

\(^c\) A nickel–chromium alloy commonly used in heating elements.

\[ R = \rho \frac{l}{A} \]
Resistance And Temperature

- Resistivity is usually temperature dependent.

Normal Metal
(See demo)

Semiconductor

Superconductor
Ohmic and non-Ohmic Materials

- **Ohmic:**
  - Linear I-V relationship

- **non-Ohmic:**
  - Non-linear I-V

For the rest of the course, we assume ohmic for all materials
Superconductivity

- **Superconductors**: temperature \( T < T_c \), resistivity \( \rho = 0 \)
  - Superconductivity is a quantum phenomenon.
  - Superconductors have special electric and magnetic features

![Graph showing critical temperature \( T_c \) vs. resistance \( R(\Omega) \)]

<table>
<thead>
<tr>
<th>Material</th>
<th>( T_c )(K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>HgBa(_2)Ca(_2)Cu(_3)O(_8)</td>
<td>134</td>
</tr>
<tr>
<td>Tl–Ba–Ca–Cu–O</td>
<td>125</td>
</tr>
<tr>
<td>Bi–Sr–Ca–Cu–O</td>
<td>105</td>
</tr>
<tr>
<td>YBa(_2)Cu(_3)O(_7)</td>
<td>92</td>
</tr>
<tr>
<td>Nb(_3)Ge</td>
<td>23.2</td>
</tr>
<tr>
<td>Nb(_3)Sn</td>
<td>18.05</td>
</tr>
<tr>
<td>Nb</td>
<td>9.46</td>
</tr>
<tr>
<td>Pb</td>
<td>7.18</td>
</tr>
<tr>
<td>Hg</td>
<td>4.15</td>
</tr>
<tr>
<td>Sn</td>
<td>3.72</td>
</tr>
<tr>
<td>Al</td>
<td>1.19</td>
</tr>
</tbody>
</table>

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Electric Power

Electric Power:

\[ P = \frac{dU}{dt} = \frac{d(Q\Delta V)}{dt} = I\Delta V \]

For resistors (ohmic):

\[ P = I\Delta V = I^2R = \frac{(\Delta V)^2}{R} \]

Power unit: watts (W=J/s)
Energy unit: kWh

1 kWh = 3.6 MJ
Example: Battery Connected To A Resistor

- Show the energy flow of this battery-resistor set-up

- Chemical Process $\rightarrow \Delta V = 1.5V$
- $\Delta V$ on Resistor $\rightarrow$ Current $I = \Delta V/R$

Charge flow through the resistor in $\Delta t$: $Q = I\Delta t = (\Delta V/R)\Delta t$

Electrical potential energy released: $U = Q\Delta V = (\Delta V/R)\Delta t\Delta V = ((\Delta V)^2/R)\Delta t$

Power: $P = U/\Delta t = (\Delta V)^2/R$

Energy Flow: Chemical $\rightarrow$ Electrical $U \rightarrow K_E \rightarrow$ thermal/light
Demo 1: Consumption of Electric Power On Resistors

A voltage is applied to a wire of length \( L \). When \( L \) increases, does power consumed increase or decrease?

1. Increases
2. Decreases
3. Same

\[
\text{Ni} \quad \Delta V
\]
Demo 2: Consumption of Electric Power On Resistors

- When a current passes through serially connected wire segments made of copper and nichrome, which metal: copper or nichrome, consume more energy?

\( \rho_{\text{Cu}} \sim 10^{-8} \, \Omega m, \rho_{\text{Ni}} \sim 10^{-6} \, \Omega m, \text{All segments have about the same length and diameter.} \)

1. Copper
2. Nichrome
3. Same