Physics 209, Lecture 9

Today's Topics

- Current And Resistance (Ch. 27)
- Motion of Charged Particle In Electric Field (review)
- Current: Macroscopic and Microscopic Views
- Resistance: Macroscopic and Microscopic Views
- Electrical Power

- Expected from Preview:
  - Current, current density, drift velocity, Ohm, Ampere, power, ...

Motion Of Charged Particle
In The Electric Field

Fundamental Formulas:

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

A Picture to remember

Motion of \( +q \):
- From high \( V \) to low \( V \)
- Same dir. as \( E \)

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

Charge Motion in a Conductor

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

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

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

Current: Macroscopic View

- Definition: \( I = \frac{dQ}{dt} \)
- Unit: 1 Ampere = 1 Coulomb/1 sec
- Current is directional: Follows positive charge
- Equivalence Principle:
  - \( +q \) moving in \( +x \) direction \( \leftrightarrow \) \( -q \) in moving \( -x \) direction
  - The following pictures represent the same current

- Charge conservation \( \rightarrow \) Current conservation

If initially at rest
- Motion of \( +q \):
  - Same dir. as \( E \)

- Motion of \( -q \):
  - Opposite dir. as \( E \)

From high \( V \) to low \( V \)

From low \( V \) to high \( V \)
Current: Microscopic View

- Current $\leftrightarrow$ motion of charged particles
- $I = \int_{S} n \cdot q \cdot v \cdot dA$
- $v_d$: average drift velocity
- $n$: number density
- $\eta$: density of charge carriers
- $q$: charge
- $\tau$: relaxation time

Show that: $I_{av} = \frac{\Delta Q}{\Delta t} = \eta q v_d A = I$

Current density $J = I / A = n q v_d$ (vector)

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

Ohm’s Law: Resistance

- It can be shown experimentally and theoretically that for many materials, the electric current is proportional to $\Delta V$:
  $I \propto V$

- For a fixed material and geometry:
  $I = \frac{V}{R}$ or $V = RI$

$R$: 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 ($\Omega = \text{Volt/Ampere}$)

- Exercise: relate $R$ to $\rho$

Resistivity For Various Materials

<table>
<thead>
<tr>
<th>Material</th>
<th>Resistivity ($\Omega \cdot \text{m}$)</th>
<th>Temperature Coefficient ($% / \degree C$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Al</td>
<td>$1.3 \times 10^{-6}$</td>
<td>$-0.4 \times 10^{-4}$</td>
</tr>
<tr>
<td>Cu</td>
<td>$1.7 \times 10^{-8}$</td>
<td>$0.0 \times 10^{-4}$</td>
</tr>
<tr>
<td>Sn</td>
<td>$9.0 \times 10^{-7}$</td>
<td>$-0.6 \times 10^{-4}$</td>
</tr>
<tr>
<td>Pt</td>
<td>$1.0 \times 10^{-6}$</td>
<td>$-0.1 \times 10^{-4}$</td>
</tr>
<tr>
<td>Ta</td>
<td>$1.4 \times 10^{-6}$</td>
<td>$-0.2 \times 10^{-4}$</td>
</tr>
<tr>
<td>C</td>
<td>$1.5 \times 10^{-6}$</td>
<td>$-0.3 \times 10^{-4}$</td>
</tr>
<tr>
<td>Al2O3</td>
<td>$1.0 \times 10^{-4}$</td>
<td>$-0.4 \times 10^{-4}$</td>
</tr>
</tbody>
</table>

- $\rho_{o}$ is the intrinsic resistivity
- $\rho_{e}$ is the extrinsic resistivity
- $\rho_{m}$ is the mixture resistivity
- $\rho_{e} \approx \rho_{o}$

Resistors

$R = \frac{\rho \ell}{A}$

Resistors

- Resistors are used to control the flow of current in a circuit.
- They are used in various applications such as heaters, relays, and dimmers.
- Resistors are classified into two types:
  - Fixed resistors
  - Variable resistors

- Fixed resistors are made of materials with a constant resistivity.
- Variable resistors can be adjusted to change their resistance.

- Resistors are also classified by their color code.
- The color code is a system of stripes and bars that indicate the resistance value.

- Resistors are used to protect electronic components from damage.
- They are used to limit the current flow in a circuit.

- Resistors are used to divide voltage.
- They are used to change the current flow in a circuit.

- Resistors are used to control the power supply.
- They are used to limit the current flow in a circuit.

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- They are used to limit the current flow in a circuit.
Resistance And Temperature

- Resistivity is usually temperature dependent.

![Graph showing resistivity vs temperature for Normal Metal, Semiconductor, and Superconductor](image)

Normal Metal
(See demo)

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 $\rho = 0$
  - Super conductivity is a quantum phenomenon.
  - Super conductors have special electric and magnetic features

![Graph showing superconductivity](image)

Electrical Power

- Electric Power:
  - For resistors (ohmic):
    \[ P = I^2R = \frac{(\Delta V)^2}{R} \]
    - Power unit: watts (W=WJ/s)
    - Energy unit: kWh
    - 1 kWh = 3.6 MJ

![Graph showing electrical power](image)

Table 27.5

<table>
<thead>
<tr>
<th>Material</th>
<th>$T_C$ (K)</th>
</tr>
</thead>
<tbody>
<tr>
<td>High-Tc Bi2212</td>
<td>135</td>
</tr>
<tr>
<td>HiBaCaCu2O8</td>
<td>125</td>
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<tr>
<td>Bi-2212</td>
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<tr>
<td>YBaCu3O7</td>
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<tr>
<td>NbSe</td>
<td>18.05</td>
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<td>Nb</td>
<td>9.46</td>
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<tr>
<td>Pd</td>
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<td>Hg</td>
<td>4.13</td>
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<tr>
<td>Sn</td>
<td>3.72</td>
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<tr>
<td>Al</td>
<td>1.19</td>
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</tbody>
</table>
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:
  - $U = Q \Delta V = \Delta V^2/R \Delta t$

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

Energy Flow: Chemical $\rightarrow$ Electrical $U$ $\rightarrow$ $K_e$ $\rightarrow$ thermal/light

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Demo/ Quiz 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

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Demo/ Quiz 2: Consumption of Electric Power On Resistors

- When a current passes through a wire made of copper and nichrome, which metal: copper or nichrome, consumes more energy?
  ($\rho_{Cu} \sim 10^{-8} \, \Omega m, \rho_{Ni} \sim 10^{-6} \, \Omega m$, All segments have about the same length and diameter.)
  1. Copper
  2. Nichrome
  3. Same

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I $\rightarrow$ Cu Ni Cu Ni