Electrical Quantities

AS Level Physics 9702

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By the end of this topic I can. . .

- use charge, current and $I = nAvq$
- define p.d., e.m.f., resistance and resistivity
- calculate electrical power
- interpret I–V graphs for wires, lamps, thermistors and diodes

Charge

Quantised charge

Charge comes in whole multiples of the elementary charge $e = 1.60 \times 10^{-19}$ C.

- charge is conserved

$$Q = Ne$$

Example: lost electrons

Example: lost electrons

The sphere is positively-charged, so it has lost some of its electrons.

The number of lost electrons: $N = \frac{Q}{e} = \frac{2.4 \times 10^{-9}}{1.60 \times 10^{-19}} \quad \Rightarrow \quad N = 1.5 \times 10^{10}$

Electric current

Current

Charge flow per unit time.

- unit: ampere
- conventional current: positive to negative
- area under I–t graph = charge

$$I = \frac{\Delta Q}{\Delta t}$$

Example: electrons in a wire

Example: electrons in a wire

Charge flow: $Q = It = 25 \times 10^{-3} \times 3600 \quad \Rightarrow \quad Q = 90$ C

Number of electrons: $N = \frac{Q}{e} = \frac{90}{1.60 \times 10^{-19}} \quad \Rightarrow \quad N \approx 5.6 \times 10^{20}$

Example: rising current

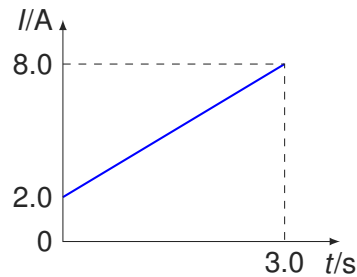
The current in a lamp is increased uniformly from 2.0 A to 8.0 A over 3.0 s. What is the charge flow?

Example: rising current

The current in a lamp is increased uniformly from 2.0 A to 8.0 A over 3.0 s. What is the charge flow?

Average current during this time is: $\bar{I} = \frac{2.0+8.0}{2} = 5.0$ A
charge flow is then: $Q = \bar{I}t = 5.0 \times 3.0 = 15$ C
we can also use area under *I*-*t* graph

$$Q = \frac{1}{2} \times (2.0 + 8.0) \times 3.0 = 15 \text{ C}$$



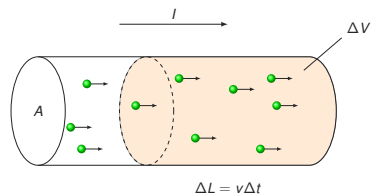
Drift velocity

Microscopic current

n carriers per unit volume, charge q, drift velocity v.

- metals: large n, tiny drift speed

$$I = nAvq$$



Example: silver wire

Example: silver wire

$$v = \frac{I}{nAe} = \frac{I}{n \cdot \frac{1}{4}\pi d^2 \cdot e} \quad \Rightarrow$$

$$\frac{2.0}{5.9 \times 10^{28} \times \frac{1}{4}\pi \times (1.2 \times 10^{-3})^2 \times 1.60 \times 10^{-19}} \approx 1.9 \times 10^{-4}\ \mathrm{m\,s^{-1}}$$

This calculation shows that each free electron actually travel at very low speeds in a wire

Example: metal and semiconductor

Example: metal and semiconductor

The same current and same cross section, so mean drift speed $v = \frac{I}{nAe} \propto \frac{1}{n}$

The metal has larger n, so free electrons move at relatively lower speeds

The semi-conductor has smaller n, so charge carriers move at relatively higher speeds

P.d. and e.m.f.

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P.d.: energy converted *from* electrical per unit charge. **E.m.f.**: energy converted *to* electrical per unit charge.

- unit: volt = J C^{-1}

$$V = \frac{W}{Q}$$

$$\mathcal{E} = \frac{W}{Q}$$

Example: heater

Example: heater

$$V = \frac{W}{Q} \quad \Rightarrow \quad W = VQ = 25 \times 10 = 250 \text{ J}$$

Example: car battery

Example: car battery

total charge that can be supplied: $Q_{\text{total}} = \frac{W}{\mathcal{E}} = \frac{0.90 \times 10^6}{12} = 75000$ C
charge needed for each start: $Q = It = 150 \times 2.0 = 300$ C
number of starts possible: $N = \frac{Q_{\text{total}}}{Q} = \frac{75000}{300} = 250$

Example: electron beam

Example: electron beam

electrical potential energy is transformed into kinetic energy of electrons:

$$qV = \frac{1}{2}mv^2 \quad \Rightarrow$$

$$v = \sqrt{\frac{2qV}{m}} = \sqrt{\frac{2 \times 1.60 \times 10^{-19} \times 40}{9.11 \times 10^{-31}}} \approx 3.75 \times 10^6 \text{ m s}^{-1}$$

Resistance and resistivity

Resistance

P.d. divided by current; for a uniform wire:

- unit: ohm; resistivity unit: Ω m

$$R = \frac{V}{I}$$

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

Example: heater wire

Example: heater wire

$$R = \frac{V}{I} = \frac{220}{0.10} \quad \Rightarrow \quad R = 2200\ \Omega$$

$$R = \frac{\rho L}{A} \quad \Rightarrow \quad L = \frac{RA}{\rho} = \frac{2200 \times \pi \times (0.12 \times 10^{-3})^2}{1.8 \times 10^{-5}} \quad \Rightarrow \quad L \approx 5.5\ \text{m}$$

Example: stretched wire

Example: stretched wire

volume: $V = LA = \text{constant}$, so $A \propto \frac{1}{L}$, hence doubling L means A would become halved

resistance: $R = \frac{\rho L}{A} \propto \frac{L}{A} \quad \Rightarrow \quad \frac{R'}{R} = \frac{L'}{L} \times \frac{A}{A'} = 2 \times 2 \quad \Rightarrow \quad R' = 4R$

Electrical power

Power

Rate of energy transfer.

- unit: watt

$$P = IV$$

$$P = I^2 R$$

$$P = \frac{V^2}{R}$$

Example: toaster

Example: toaster

current: $I = \frac{P}{V} = \frac{900}{220} \quad \Rightarrow \quad I \approx 4.09$ A

resistance: $R = \frac{V}{I} = \frac{220}{4.09}$, or alternatively, $R = \frac{V^2}{P} = \frac{220^2}{900} \quad \Rightarrow \quad R \approx 53.8\ \Omega$

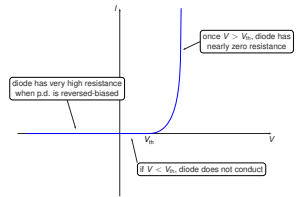
Example: two cylinders

Example: two cylinders

for either cylinder, electrical power: $P = I^2 R = I^2 \cdot \frac{\rho L}{A} = I^2 \cdot \frac{4\rho L}{\pi d^2}$
same current I, same diameter d, same resistivity ρ, so power:
$P \propto L \quad \Rightarrow \quad \frac{P_X}{P_Y} = \frac{L_X}{L_Y} = 2$

I–V characteristics

- ohmic conductor: straight line, constant R
- filament lamp: curves, R increases with temperature
- NTC thermistor: R falls as temperature rises
- diode: conducts one way above threshold (0.6 V)



Key equations

current	$I = \dfrac{\Delta Q}{\Delta t}$	resistance	$R = \dfrac{V}{I}$
drift	$I = nAvq$	resistivity	$R = \dfrac{\rho L}{A}$
p.d.	$V = \dfrac{W}{Q}$	power	$P = IV$