Episode 110: Resistance and temperature

This episode looks at the resistance of a metal and a semiconductor, giving a microscopic explanation of the variation with temperature. There is also a brief look at superconductivity and its applications.

Summary

Demonstration + discussion: Resistance and temperature. (10 minutes)
Discussion: Free-electrons in metals. (10 minutes)
Student experiment: Thermistor behaviour. (20 minutes)
Discussion + demonstration: Conduction in semiconductors. (5 minutes)
Discussion: Superconductivity. (20 minutes)
Student activity: Researching superconductivity. (30 minutes + time for reporting back)
Student questions: Using these ideas. (20 minutes)

Demonstration + discussion:

Resistance and temperature

This episode picks up on the variation of resistance of the filament lamp. Students’ own results should show that the resistance increases with current. Link this to the change of temperature of the wire and remind them that metals obey Ohm’s Law if the temperature is constant. (When they measured the resistance of the constantan wire in Episode 109, the current was always small, so temperature was almost constant.) You can reinforce the idea of resistance change in metals by cooling a wire and showing that its resistance decreases. This can be done using a cooling spray or, more dramatically, using liquid nitrogen (if this is available).

TAP 110-1: Metal resistance decreases as temperature falls.

Discussion:

Free-electrons in metals

It is worth pausing at this point to discuss the mechanism of metallic resistance. Remind students of the model whereby as temperature increases the thermal vibrations in the lattice increase causing more electron scattering. (Be aware that there is more here than meets the eye in terms of quantum, as opposed to classical, free electron theory.) This increases the rate of transfer of electrical energy by heating and increases the electrical resistance.

Next consider semiconductors. Students are unlikely to know much about semiconductors so it may be worth giving a brief introduction by saying that, compared to metals, they have only a few free electrons, so resistance (resistivity is the more appropriate term here, but they have not yet met it) is much higher. However, semiconductors such as silicon are central to the electronics industry so it is well worth considering their electrical characteristics. For example, how does their resistance depend on temperature?
Student experiment:

Thermistor behaviour

Students can investigate the temperature dependence of the resistance of a thermistor for themselves.

The results should show a clear decrease of resistance with increasing temperature. This is the opposite of what happened with the metal.

NB These thermistors are n.t.c. types (negative temperature coefficient). Other types exist which have a non-linear positive temperature coefficient.

TAP 110-2: Calibration of a thermistor

Discussion + demonstration:

Conduction in semiconductors

Ask whether the atoms in the semiconductor vibrate more at higher temperature. Of course they do - so this contribution to resistance must increase in the same way as for a metal. So what else could make the semiconductor conduct better? The answer is: more charge carriers. Whereas the number of free electrons in a metal is constant the effect of heating a semiconductor frees additional electrons (and holes, but it’s probably not worth mentioning them yet!). For silicon in this temperature range the effect of additional charge carriers outweighs the effect of additional vibrations.

An interesting additional demonstration can be done using a different semiconductor (carbon). This shows that the two effects compete with each other. At lower temperatures the increase in resistance due to vibration dominates, as temperature rises, more and more electrons are freed and the resistance begins to fall.

Discussion:

Superconductivity

Having introduced the idea that metallic resistance is caused by electron scattering from ions as they vibrate with thermal energy you should return to what happens as a metal is cooled down.

You are looking for an argument that runs along the lines of: less thermal energy, smaller amplitude of vibration so reduced scattering and therefore reduced resistance. Refer back to the initial demonstration.

How low can we go?

The students ought to predict that thermal vibrations will eventually stop (at absolute zero on a simple mechanical model). This implies a very low resistance at low temperatures (but not necessarily zero).
Lead into Kammerlingh Onnes’s work and his surprise that mercury’s resistance disappears at a very low temperature (a few degrees above absolute zero: 4.15 K).

![Graph showing resistivity vs temperature]

This sudden transition was unexpected and is a quantum effect. It occurs for some but not all metals. It has also been observed at much higher temperatures (around 150 K) in certain ceramics. These are called ‘high temperature’ superconductors (even though we are still talking about temperatures more than 100 degrees below zero Celsius! The mechanism for high temperature superconductivity is not fully understood and it is hoped that in future we may be able to manufacture room temperature superconductors.

Rather than lecture them about superconductors this would be a good opportunity to set them some research tasks which can be reported back to the class. Here is a work sheet that could be used:

**TAP 110-3: Researching Superconductivity**

**Student questions:**

Using these ideas

**TAP 110-4: Filament lamp and thermistor in series**
TAP 110-1: Metal resistance decreases as temperature falls.

You could simply use a freeze spray on a coil of constantan wire and show that the resistance decreases as temperature falls. However, it is more satisfying (and makes a bigger impression) if you show how current increases when a metal resistor is cooled.

Apparatus:

- Coil of constantan wire.
- Filament lamp.
- Power supply.

You will need to try this first. Connect all three components in series. Make sure the constantan wire is tightly coiled up (but that its coils don't touch each other) and that the lamp lights dimly when the wire is at room temperature.

If the freeze spray is applied directly onto the constantan wire the light should noticeably increase in brightness.

If you have some liquid nitrogen available the effect is even greater but request the CLEAPSS Special Risk Assessment for safety procedures when using liquid nitrogen. You could use a coil of fine copper wire instead of the constantan.

(Another neat demonstration involving reduced resistance at low temperatures is the famous 'jumping ring experiment’. This involves the induced emf and current in an aluminium ring suspended above an electromagnet. When the electromagnet is switched on there is a sudden induced emf and current which, by Lenz’s law, results in a repulsive force. The ring ‘jumps’. If the ring is then cooled in liquid nitrogen and used before it warms back to room temperature the jump is much bigger. The drawback of using this at this stage is that weaker groups will not appreciate the role of electromagnetic induction.)
TAP 110-2: Calibration of a thermistor

Data and graphs show the difference in electrical behaviour of metals and semiconductors. This experiment gives direct evidence for the effect of temperature on the resistivity of a semiconductor.

You will need
- Thermistor e.g. disc type 4.7 kΩ at 25°C
- Digital multimeter set on resistance range
- Two crocodile clips
- 4 mm connecting leads
- 250 ml beaker
- Source of hot water – an electric kettle is simplest
- Thermometer
- Ice cubes
- Clamp, stand and boss

What to do
1. Place the thermistor in the beaker. Use crocodile clips and leads to attach the multimeter, which should be set on the 10 kΩ range. Pour in hot water.
2. Record temperature and resistance in a table. Cool the thermistor by steps by adding cold water. You should obtain ten or more pairs of readings as temperature is taken down near 0°C.

Data analysis
1. Plot a graph of resistance against temperature in Kelvin. Write in words the pattern you have found.

Practical advice
Encourage students to plot the graph while the data are collected. To establish a range of values, they will need to note the thermistor resistance and room temperature before starting.

The resistance will rise as temperature falls, given an n.t.c. (negative temperature coefficient) thermistor!

More able students may be asked to check whether the curve displays equal ratios of resistance changes over equal intervals of temperature. Point out that this pattern is called 'exponential'.

Second-year students might return to this activity, to plot ln(R) versus temperature / K and check whether it produces a straight line.

This is a good practice exercise for the making sense of data task.

Note that the exponential relationship is only approximately correct.
Alternative approaches
If you cannot afford the teaching time for students to do their own experiment, you could either do it as a demonstration or simply provide raw data, as tabulated below:

<table>
<thead>
<tr>
<th>Temperature / K</th>
<th>Resistance /</th>
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<tbody>
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<tr>
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</tbody>
</table>

Social and human context
Because thermistors are cheap and they have a low thermal capacity, they can be used in temperature sensors, e.g. to make a disposable thermometer.

External references
This activity is taken from Advancing Physics Chapter 5, 320E
Student instructions

You are to use books, articles or websites to research superconductivity. At the end of this you should summarise your findings on a single sheet of A4 that must be handed to your teacher by .......... (some time in advance of the feedback session). This will be checked, photocopied and distributed to the class. In the lesson you will be asked to talk us through your findings (be prepared to speak for up to 5 minutes - by all means prepare some PowerPoint slides to illustrate your points). Your research should focus on (one of the questions below):

- How did Kammerlingh Onnes discover superconductivity?
- How can the low temperatures for superconductivity be reached?
- What are typical transition temperatures for metals and high temperature superconductors? Include a table and explain why high temperature superconductors are exciting.
- Why are superconductors used in strong magnets? (Find at least two examples and explain how superconductivity is maintained).
- Superconductors can be used to store energy. How?
- How would room temperature superconductors change the world?
- How are superconducting materials used in electronics and what advantages do they have over conventional conductors?

Useful websites:

Superconductivity:  
http://superconductors.org/  
http://hyperphysics.phy-astr.gsu.edu/hbase/solids/scond.html
Superconducting magnets:  
http://www.google.co.uk/search?hl=en&q=superconducting+magnets&btnG=Search&meta=  
http://en.wikipedia.org/wiki/Superconducting_magnet
High temperature superconductors:  
http://www.eapen.com/jacob/superconductors/chapter5.html
Make your own! http://www.webcom.com/cfsc/scpart1.html
Applications: http://www.physnet.uni-hamburg.de/home/vms/reimer/htc/pt4.html
Energy storage: http://www.doc.ic.ac.uk/~mpj01/ise2grp/energystorage_report/node8.html
Before starting

Make sure you are familiar with the characteristic graphs of the filament lamp and the thermistor.

Surge current protection

1. Sketch graphs of current vs. potential difference for a filament lamp rated 230 V; 25 W. Explain the shape of the graph in terms of the effect of temperature on the conductance / resistance of the lamp.

2. Sketch graphs of current vs. potential difference for a thermistor whose resistance decreases with temperature. Explain the shape of the graph in terms of the effect of temperature on the conductance / resistance of the thermistor.

3. This circuit contains a filament lamp and thermistor in series with a 230 V supply. When the switch is closed, the lamp glows dimly at first, but then gets brighter and brighter until the lamp is lighting normally. Explain these observations.

4. How does connecting a filament lamp in series with a thermistor protect the components from a surge current?
Practical advice

This question can follow activities on electrical characteristics. The student is expected to remember the shape of the characteristics. It is important for students to relate the characteristics to the change in conductance / resistance with temperature. The observations in question 3 can be demonstrated using a torch bulb of high resistance connected to a low voltage supply. It is not wise, for safety reasons, to use the mains voltage for laboratory demonstrations of the effect. A pair of circuits, one with and one without a thermistor in series and switched on together, neatly shows the delay.

Social and human context

Many devices, from modern lighting systems to computers, need protection against surges in current, particularly when turning them on.

Answers and worked solutions

1. With current on the $y$-axis and pd on the $x$-axis, the graph should slope steeply for low currents (low resistance, high conductance), and then curve to become flatter at high currents (higher resistance, lower conductance).

2. With current on the $y$-axis and pd on the $x$-axis, the curve should have a small slope to begin with (high resistance, low conductance at small currents), and then start to rise more steeply (lower resistance, higher conductance, as the thermistor becomes hotter).

3. As the filament wire gets hot the conductance decreases and the resistance increases. As the thermistor gets hotter its conductance increases and the resistance decreases.

4. When the switch is closed both components are cold. The thermistor has a high resistance which limits the current. Most of the potential difference is across the thermistor and so most of the power is dissipated in the thermistor. This heats up the thermistor so its conductance increases and more of the potential difference is applied across the filament lamp. More power is dissipated by the lamp which now glows brighter. The bulb glows more and more strongly as the thermistor's conductance increases. As the filament gets hotter its resistance increases. Eventually the situation stabilises when the resistance of the filament is far greater than that of the thermistor, so that nearly all the power is dissipated by the lamp.

5. Surge currents often occur when circuits are turned on and this large initial current, although only lasting for a fraction of a second, can still overload a component. The high resistance of the lamp (when cold) limits the size of the surge current.

External references

This activity is taken from Advancing Physics Chapter 2, 280X