Conductivity of solids: Temperature dependence

Time required: 40-50 min

Aims of the experiment

- Learn that the conductivity of solids changes with temperature.
- Learn about semiconductor properties.
- Heat metals to a red glow.

Principles

In solid materials, current transport is performed by electrons (1st order conductors). Hence, the conductivity depends on the mobility of the electrons. Since the mobility of the electrons depends on the temperature, conductivity (or conductance) is also temperature-dependent.

In this experiment, the temperature dependence of conductivity will be evaluated using a current flow. To measure a current flow, a known voltage will be applied to a solid and the current transport through an amperemeter will be determined in order to draw conclusions on the conductivity of the solid. However, the conductivity itself can be calculated from the current and applied voltage (see on the right):

The inverse of conductivity is resistance. Resistance and conductivity are temperature-dependent. How this dependency takes effect depends on the algebraic sign of the temperature coefficient. A negative sign means that the conductivity increases as the temperature increases or as the resistance decreases.

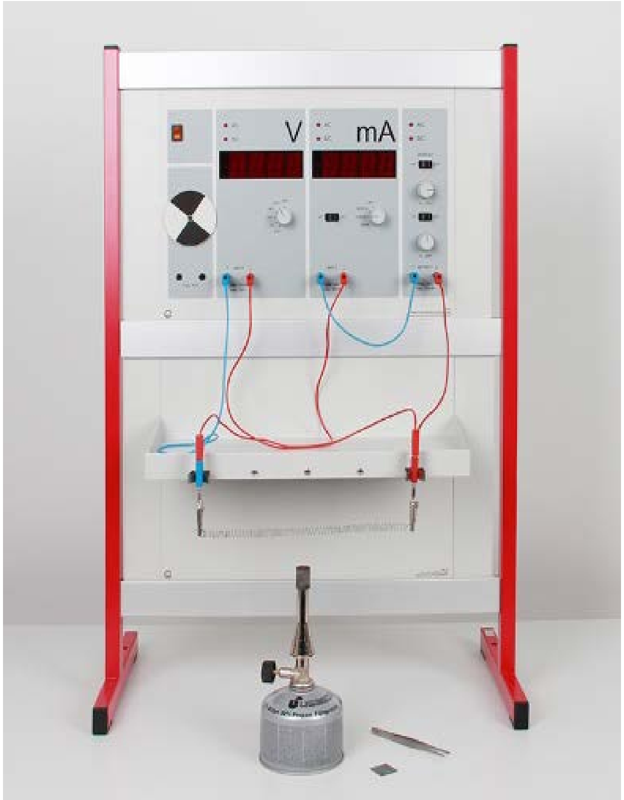

Fig. 1: Set-up of experiment and materials.

According to Ohm's law $U = R \cdot I$

U = Voltage [V]

I = Current [A]

Then, $R = \frac{U}{I}$

R = Resistance (Ω)

and the conductivity (conductance) $G = \frac{1}{R} = \frac{I}{U}$

G = Conductivity (S)

Temperature dependence of the resistance $R(T) = R(T_0) \cdot \left(1 + \alpha(T - T_0)\right).$

α = Temperature coefficient (1/K)

T = Temperature (K)

Risk assessment

In using the electrochemistry demonstration unit, the only voltages allowed are those not dangerous to the touch.

CAUTION! Do not select a higher voltage, since the maximum allowable current of 2000 mA will be exceeded and a short circuit may occur.

Iron wires and silicon discs can become very hot. RISK OF BURNS!

Equipment and chemicals

1	Electrochemistry demonstration unit, CPS	664 4071
1	Panel frame C50, two-level, for CPS	666 425
1	Electrochemistry table, CPS	666 472
1	Clip plugs, small, set of 2	59002ET2
1	Electrochemistry accessories set	664 401
2	Connecting leads, 50 cm	from 664 401
2	Connecting leads, 25 cm	from 664 401
1	Connecting leads, 10 cm	from 664 401
1	Cartridge burner	666 714
1	Tweezers, blunt	from 664 401
2	Crocodile clips	from 664 401
1	Iron wire, 2m	from 664 401
1	Silicon disc	from 664 401

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Set-up and preparation of the experiment

Set-up of the experiment

The 2 m long iron wire is wound onto a pencil or the like to make an approx. 20 cm long coil.

Insert one clip plug into each of the outermost sockets of the demonstration unit table. The crocodile clips are attached to the clamps of the clip.

Preparation of the experiment

Since the metal wires have a very low resistance, the internal resistance of the amperemeter, which would otherwise taint the measurement results, must in this case be uncoupled using the following circuit in Figure 3.

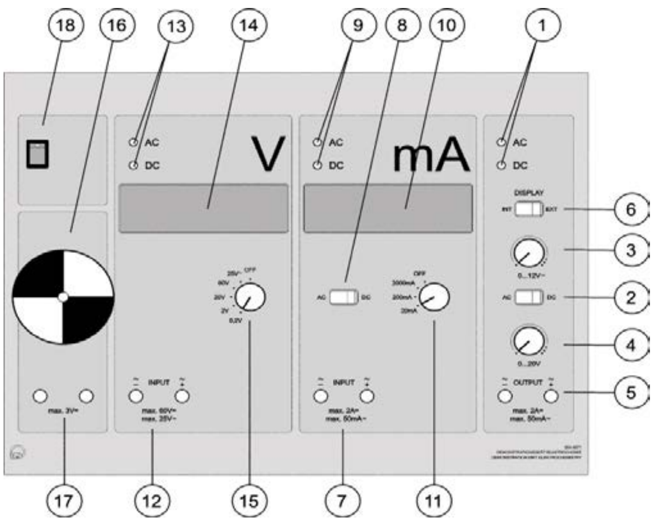

Fig.2: Sketch of the demonstration unit.

The changeover switches (2) and (8) on the demonstration unit (see Fig. 2) are placed in the “DC” position (direct current). The measurement of the external power source is turned on using the selector switch (6).

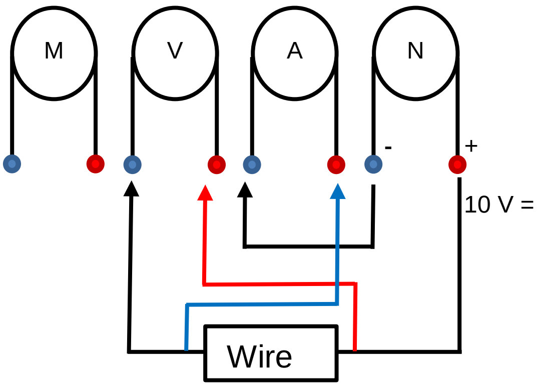

Fig. 3: Demonstration unit circuit for decoupling the internal resistance.

Performing the experiment

The brittle silicon disc must be clamped in place very carefully so as not to break it.

*Note: The copper wire included should **not** be heated since it is easily oxidised and can become brittle as a result. Also, the plastic samples (coated and uncoated) must **not** be heated.*

To investigate the temperature dependence of conductivity, the iron wire is placed between the clamps under tension, 0.5 V is applied at the demonstration unit and the wire is heated to a weak red glow using a burner. If necessary, readjust the voltage to 0.5 V. The resulting current is noted and tabulated. However, it can fluctuate considerably during adjustment since the wire cannot be heated evenly.

Note: While heating the samples, make sure that the experiment table, cable and the like do not get exposed to too much heat. The plate and the wire are fixed in a way that allows maximal distance to the table. If necessary, use a separate stand set-up for fixing the samples.

Silicon is heated as the second sample. Here, a clamp is unclipped since the silicon plate is too small to be correctly clamped (see Fig. 4). The silicon disc should be carefully moved using tweezers.

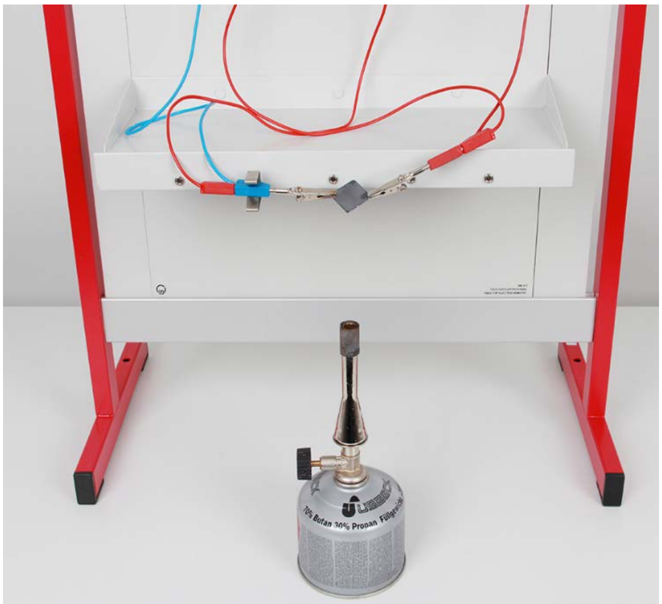

Fig. 4: Arrangement for stable fastening of the silicon disc.

Proceed in the same manner with silicon. Record two measurements for silicon (once when hot, once when hot and glowing red).

Observation

The iron wire begins to glow quickly. The silicon disc needs much more time to glow red.

In Table 1, the values for the indicated currents are given.

Tab. 1: Measurement results of the temperature-dependent measurement.

Materials	Current [mA] at 0.5 V
Fe wire, hot	51
Si disc, hot	~90
Si disc, hot and glowing red	300

Evaluation

The measurement results from the experiment can be used to determine the temperature of the metal, if the temperature coefficient of the material is given (see Tab. 2).

Tab. 2: Temperature coefficients for Iron and Silicon (lit.).

Material	Temperature coefficient in K^{-1}
Iron	6.57×10^{-3}
Silicon	-75×10^{-3}

From the measurements of conductivity at higher temperatures, the resistance *R* and the conductivity *G* of iron and silicon can now be determined using the voltage *U* and the current *I* (see fundamentals).

The resistance for iron becomes

$$R = \frac{500\,mV}{51\,mA} = 9.8\,\Omega$$

And the conductivity for iron becomes

$$G = \frac{1}{9.8\,\Omega} = 0.102\,S = 102\,mS$$

Similarly, this also applies to silicon and provides the following resistances *R* and conductivities *G* (see Tab. 3).

Tab. 3: Calculated resistances and conductivities for hot silicon and values for cold substances.

Material	Resistance [Ω]	Conductivity [mS]
Iron, room temperature	2.28	438
Iron, hot	9.8	102
Silicon, room temperature	1420	0.7
Silicon, hot	5.6	178
Silicon, hot, glowing red	1.7	588

With these values, the temperatures of iron and silicon can now be determined. For iron,

$$R(T) = R(T_0) \cdot (1 + \alpha(T - T_0))$$

where *R(T)* is the determined resistance during heating, $R(T_0)$ is the resistance at room temperature and α is the specific temperature coefficient. Therefore, the temperature *T* is what is sought. The converted formula is as follows

$$T = \frac{\frac{R}{R_0} - 1}{\alpha} + T_0$$

Using the values for iron results in

$$T = \frac{\frac{9.8}{2.28} - 1}{6.57 \cdot 10^{-3}} + 293 = 797.8\,K \approx 1071\,°C$$

Do the same for the two silicon temperatures.

Thus, the following temperatures can be calculated (please note: -273.15 °C = 0 K).

Results

In this experiment, the temperature behaviour of conductors and semiconductors was investigated.

Material	Calculated temperature [°C]
Silicon, hot	446
Silicon, glowing red	552
Iron, hot	1071

Tab. 4: Calculated temperature for silicon.

Classical behaviour of conductors

Iron belongs to the class of conductors. The good conductivity of metals is based on metallic bonding. This is characterised by the existence of freely-moving (delocalised) electrons. They are not bound to a specific atomic nucleus, but distributed across the entire atomic matrix (as an “electron cloud”). The electrons can shift relative to the atoms, allowing the electrical impulse to be better transferred.

Classical behaviour of semiconductors

Silicon belongs to the class of semiconductors. These have very low conductivity at low temperatures and room temperature. The reason is in the electronic structure of semiconductors in the crystal structure. The energetic difference between the valence band and the conduction band is not very high in semiconductors, but the energy at room temperature is usually not enough to excite electrons to cross the *band gap*. To overcome the band gap energy must be added to the system. For example, thermal or photonic energy or energy from increased pressure would suffice.

Temperature behaviour of conductors

The property of good conductivity decreases with temperature. The reason for this is that the valence electrons in conductors are easier to remove. Almost all electrons are in the conduction band. By raising the temperature, elevated electron motion is in fact expected, which would by definition increase conductivity.

However, by raising the temperature and speed, the number of collisions is much higher, which causes electrons to move more slowly on average in a limited space. On the other hand, Ohm’s resistance decreases as the temperature drops in conductors. Therefore, such metals are often called cold conductors.

Temperature behaviour of semiconductors

Semiconductors exhibit very different temperature behaviour. Where in a conductor such as iron the conductivity decreases when it is heated, it increases drastically in semiconductors. The explanation is that there is now enough energy in the system to force the electrons from the valence band across the *band gap* into the conduction band. In the conduction band, the electrons are now delocalised and can conduct an electric current by the electron cloud.

In this experiment, silicon was successfully classified as a semiconductor. Silicon has elevated conductivity with increased temperature. Iron, on the other hand, has a lower conductivity.

Application

This phenomenon of decreased or increased conductivity in conductors and semiconductors has many applications. In order to measure high temperatures (T > 300°C), alloyed nickel temperature sensors are frequently used, where commercially-available mercury thermometers or other thermometers fail. Here, the temperature is very precisely measured using the property of decreased conductivity or increased resistance of the alloy.