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Solid State Physics

Electrical Conductivity

The Aim

The aim of this laboratory is to deepen your understanding of different types of solids, such as a superconductor or metal, in terms of their electrical conductivity. Furthermore, you should get an insight in the usage of vacuum systems for the generation of low temperatures (cryogenic equipment). You will also see how a computer can be used to control temperature and measure electrical quantities.

The Task

Your task in this laboratory is to study and to explain the temperature dependence of the electrical conductivity of a superconductor, a semiconductor and a metal in the temperature range from 10 to 300 K.

1. Equipment

- Cryogenic equipment (compressor, cooling head, flexible pressure tubes).
- Two vacuum pumps: a coarse vacuum pump and a turbo-molecular pump.
- Temperature control.
- Control for the turbo-molecular pump including a pressure indicator.
- Samples of three different materials (metal, semiconductor, and superconductor).
- "4-pole resistance measurement system" (electronics, multimeter, computer, program "Elledn").
- Compendium with excerpts from various "Solid State Physics" books.

2. Cryogenic equipment

The cryogenic equipment consists of a **compressor** (HC-2D), **a two-stage cooling head** (DE-202, Fig. 1) and flexible pressure tubes. The cooling system has two cooling stages. The **cooling capacity** of the second stage is approximately 2 W at 20 K and diminishes quickly towards lower temperatures until close to 0 W at 10 K (Fig. 2).

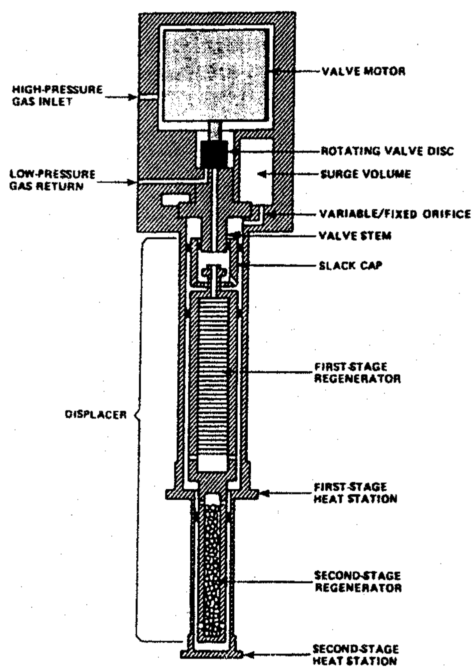

Fig. 1: The cooling head DE-202. The drawing is **up side down** with respect to the position of the cooling head in the experimental setup!

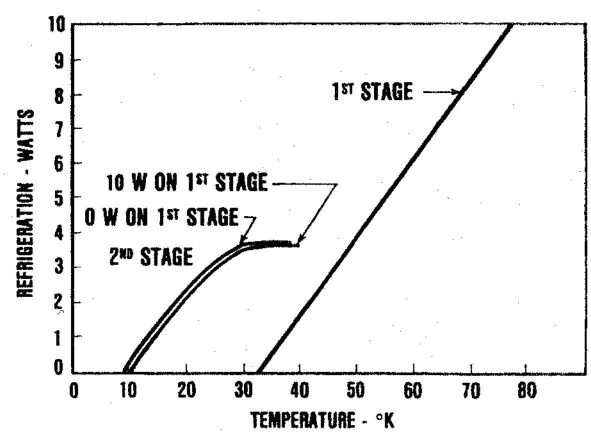

Fig. 2: Cooling capacity versus temperature of the 1st and 2nd cooling stage.

How does the cryogenic equipment work to establish such low temperatures as 10 K? The underlying method is the so-called **Gifford-McMahon principle** (Appendix A).

Before cooling the samples, however, a **vacuum** has to be established in the cryo-equipment. Use first the **coarse vacuum pump** (down to 10^{-1} bar) and then the **turbo-molecular pump** to reach a reasonable well vacuum (lower than 10^{-3} bar).

Information about how to run this instrumentation practically is given in Appendix B.

3. Experimental

The three different samples that ought to be studied are mounted on a copper plate (Fig. 3), which already resides inside the 2nd stage of the cooling head. The three samples are:

- Metal: Platinum
- Semiconductor: InSb
- Superconductor: $YBa_2Cu_3O_7$

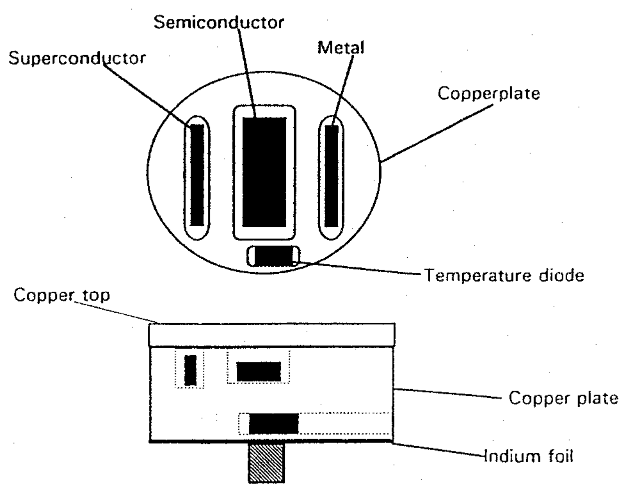

Fig. 3: Schematic drawing of the mounting of the samples on the copper plate.

To avoid temperature gradients between the samples and the copper plate, the samples are attached with a heat conducting paste, especially made for vacuum and low temperature applications. This paste contains a copper power, to increase heat conduction. The electrical conduction, however, must not be too high as that would short-circuit the electrodes of the samples. When the copper plate is screwed to the cooling head, indium foil is placed between them. Since indium is a very soft material at room temperature, it will smear out and thereby even out irregularities on the copper surface. That leads to a better surface contact between the copper plate and the cooling head and increases heat conduction.

Together with the samples, a **temperature sensor** (silicon diode DT-500 P/GR) is attached to the copper plate (**sensor 1**). Another temperature sensor of the same kind (**sensor 2**) is mounted under the upper plate of the 2nd stage of the cooling head (comp Fig. 1 and 3). With the computer program "Elledn" you can observe the temperatures measured with those two sensors. The **yellow crosses** represent sensor 1 whereas the **green crosses** show the values of sensor 2. Because of temperature gradients and inaccurate calibration, those two sensors will not always show the same temperature. For your measurements it is not that critical whether you refer to the exact temperature of the samples or a slightly different one since we are interested in the **general behavior** of the resistivity/conductivity with temperature (and not in absolute values). This behavior can readily be seen independently of which temperature sensor you use as a reference. If in doubt which one to take, choose sensor 2.

The resistance is measured with a "4-pole resistance measurement system" (Appendix C).

To **start** your experiment, follow the instructions of how to run the cryogenic equipment and the program "Elledn" (Appendices B and D).

Tasks in detail

- Make yourself acquainted to the **experimental setup**.
- **Cool down** the samples to approximately **10 K**. This may take a while (> 30 min).
- With the program **"Elledn"** raise the temperature stepwise and record the **electrical resistance** for the three materials for a number of temperatures.
- **Plot** the electrical resistance (related inversely proportional to the electrical conductivity) as a function of temperature. You can do that with Origin or directly with "Elledn" (option **R**).
- **Analyze** your measurement curves. Can you tell which curve corresponds to which sample?
- **Present the results to your supervisor!** Explain all features of the three curves in detail. If you need information about metals, semiconductors or superconductors refer to your course book or the compendium next to the experimental setup.

Discuss also the following questions and outline your answers in the presentation:

Additional questions

- For what purpose is vacuum established in the cryo-equipment?
- Why is the resistance measured with a "4-pole resistance measurement"?
- Why is the direction of the current through the samples altered for each measurement?
- Why does the cooling rate increase at low temperatures?

4. Appendix A: The Gifford-McMahon principle

The cryogenic equipment is working according to the Gifford-McMahon principle, with two isochores and two isobars, in a closed helium-gas cycle.

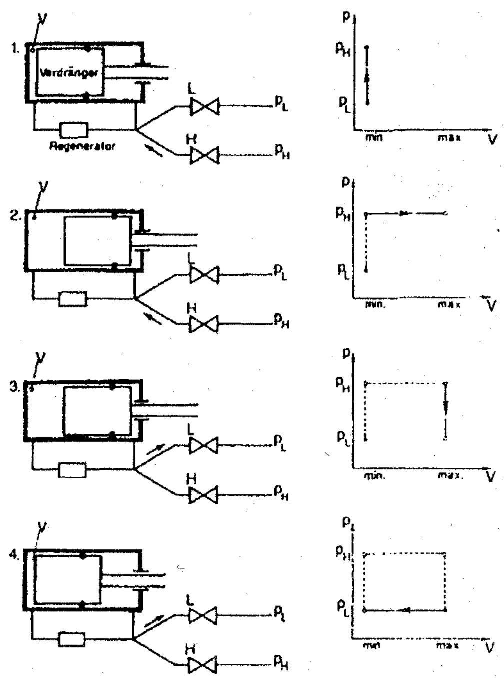

Fig. 4: The working cycle for the closed helium cryogenic system.

1st phase — The displacement piston is on the left side of the expansion volume V, which in this position corresponds to the dead volume. The valve of the low-pressure side is closed but the valve of the high-pressure side is opened. This causes the pressure to increase from a low pressure, p_L, to a high pressure, p_H, at a constant volume $V_{\min}$ (see the pV-diagram).

2nd phase — The displacement piston is withdrawn, while the high-pressure valve is still open. The volume increases to a maximum volume, $V_{\max}$, at constant pressure p_H.

3rd phase — The high-pressure valve, H, is now closed and the low-pressure valve, L, is opened. The pressure of the helium gas changes from p_H to p_L at constant volume V_{max}

4th phase — The displacement piston is brought to its original position at constant pressure p_L and the gas cycle is completed. The theoretical value of the heat absorbed during one cycle corresponds to the rectangular area in the pV-diagram, e.g.

$$Q_{ideal} = (V_{\max} - V_{\min}) \cdot (p_H - p_L)$$

5. Appendix B: How to operate the cryogenic equipment

Start:

1. Check if the water-cooling is connected to the cryogenic equipment. The green main tap should be open.
2. Check if the main switch is ON.
3. Turn on **ALL** measurement equipment, the voltage supply and the computer (otherwise "Elledn" does not work).
4. Press the button $\left[\frac{\text{RETURN}}{\text{HEATER}}\right]$ on the temperature control. The light on the temperature control should now be ON and the temperature can be regulated.
5. Start the coarse vacuum pump.
6. After <u>1 minute</u> open the read vacuum valve (between the turbo-molecular pump and the cryotank) Carefully turn counterclockwise until it stops. Do not break the valve!)
7. Pump until the pressure is smaller than 0.1 mbar.
8. Start the turbo-molecular pump. Press [START] on the control unit TURBOTRONIK NT10. You should hear a high frequency sound and the pressure soon reaches values $< 10^{-3}$.
9. Press the start-button on the compressor. A magnetic valve will open up the cooling-water pipe.
10. Start the program "Elledn" and observe how the temperature decreases.

Stop:

1. The temperature of the 2nd cooling stage should be around 300 K.
2. Turn OFF the compressor (the temperature control stays ON).
3. Close the read vacuum valve (turn clockwise carefully).
4. Turn OFF the turbo-molecular pump. Press [STOP] on the control unit and wait for <u>5 minutes.</u>
5. Turn OFF the coarse vacuum pump.
6. Close the (green) main tap for the cooling water.
7. Turn OFF the main switch for the cryo equipment.
8. Turn OFF all other measurement equipment.

6. Appendix C: The Measurement system

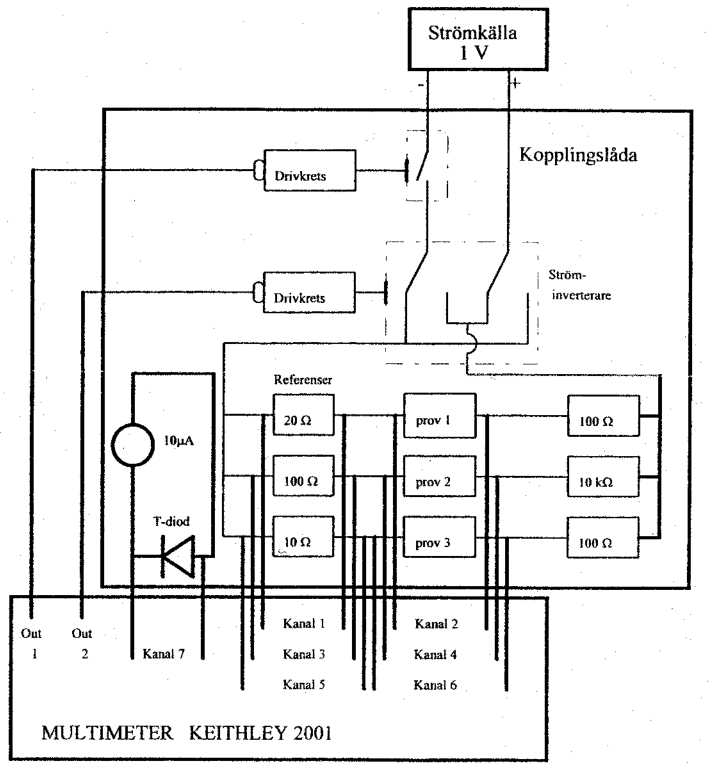

Fig. 5: Principle outline of the measurement system

7. Appendix D: The computer program "Elledn"

The temperature regulation and data acquisition are accomplished through a computer program called "Elledn" that is written in Turbo Pascal. Both the temperature of the cryogenic equipment and the measurements with the multimeter (Keithley 2001) are controlled via an IEEE 488 interface.

After starting the program, a menu opens providing different options:

Z: **New measurement series**

Warning !! All present data is erased !

Do this before you start a **new measurement** series in order to avoid that 'old' data interferes with your measurement.

B: **Set a new temperature value**

Choose the next temperature at which you want to measure. A temperature/time graph is automatically shown. Suitable measurement intervals are, for example:

10-80 K: one measurement every 5 K
80-100 K: one measurement every 2 K
100-300 K: one measurement every 10 K

T: **Temperature as a function of time**

Shows a graph temperature versus time from the present data.

M: **Perform a resistance measurement**

The resistances for all three samples are measured and **automatically** saved. Has to be executed for each data point **manually**!

R: **Resistance as a function of temperature**

Shows a graph resistance versus temperature from the present data.

F: **Continue temperature measurement**

Reads previous temp/time -data and continues temp/time-measurement.

S: **Save**

The measurement results are saved in three user-chosen files, one for each sample. You can use this function in the end if you want to export your files.

H: **Load**

Loads previously saved measurement files.

A: **Quit program**

The present results remain though, as long as you do not press "Z".