Department of Physics UZH

Manual for the experiment

Temperature-dependent measurement of the electrical resistance of a semiconductor

PHY220 Advanced Laboratory Course in Solid State Physics

October 21, 2022

1 Goal of the experiment

The goal is to measure the electrical resistance of a semiconducting sample of silicon as function of temperature. This will allow us to calculate the energy band gap of silicon.
You can find information about basic concepts for describing semiconductors in the following textbooks, for example:

- Ch. Kittel, *Introduction into Solid State Physics*, chapter 8 *Semiconductor Crystals*,
- P. Hofmann, *Solid State Physics - an Introduction*, chapter *Semiconductors*,
- (in German) K. Kopitzki (and P. Herzog), *Einführung in die Festkörperphysik*, Kapitel *Elektronen im Festkörper*, Sichworte (Halbleiter, Eigenleitung, Störstellenleitung)

Keywords include e.g. *intrinsic semiconductor*, *doping*, *resistivity*.
Beside the physics of electric transport in semi-conductors you will learn about several standard technologies like temperature control (so-called PID controllers) and temperature measurement, as well as some vacuum technology (but the vacuum system must be running all the time).

Some key questions which you may try to answer for yourself and may be used as guideline during the initial discussion:

1. What are energy bands and what is an energy gap? Do gaps only appear in semiconductors?
2. What is the meaning of the Fermi energy?
3. What is the difference between a metal, a semi-conductor, and an insulator? What is the role of the Fermi energy here?
4. How can a semiconductor be doped and what is the effect of doping?
5. What is n- and what is p-doping?
6. How can one calculate the density of carriers in an undoped (intrinsic) semiconductor at given temperature T if the total electron density n_V^0 and the size of the energy gap E_{gap} are known?
7. How can one calculate the density of carriers in an e.g. *n-doped* semiconductor at given temperature T if the density of doping atoms is n and the ionization energy of a doping atom is E_I? Is it larger or smaller than the intrinsic carrier density? Give some orders of magnitude.
8. What dependence on temperature do you expect for the resistivity of a semiconductor? Does it increase or decrease with temperature? What function describes the dependency?
9. What do the following words mean: conductivity, conductance, resistivity, resistance?

2 Experimental setup

A photograph of the setup is shown in Fig. 1.

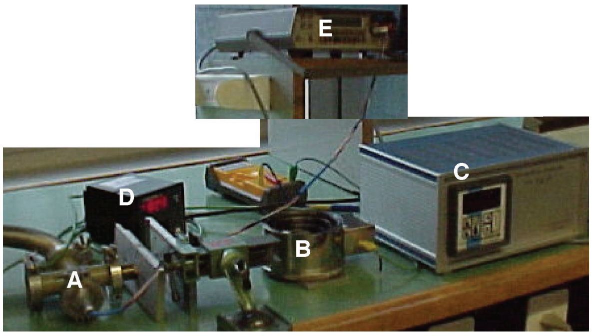

Figure 1: Setup of the experiment. A Cross-like vacuum chamber with connection to the vacuum pump, and the electrical feedthroughs for sample heating, temperature and resistance measurement. B Oven with thermal insulation. C Temperature control of the oven. D Display of the oven temperature. E Resistance measurement.

2.1 Design of oven and sample holder

Inside the oven a small silicon sample is mounted on a sample holder shown in Fig. 2. Four electrical contacts were spot-welded to the sample. These four contacts serve as current leads and voltage probes for the resistance 4-point-measurement described in section 2.3. The cylindrical sample holder is made of ceramic material which is insulating.

2.1.1 Temperature measurement

Beside the electrical contacts the sample (holder) is in thermal contact with a so-called **thermoelement** or **thermocouple** (because there are always two contacts), i.e. a point contact of two different metals with different thermoelectric coefficients. the temperature gradient between the hot sample and the second contact at room temperature produces an electrical potential difference across each wire. Since the material coefficients are different for both wires the end points at room temperature will be at different potential, and we measure a voltage between them. This thermovoltage is proportional to the temperature difference between the ends of each wire. You will find a short tutorial with the reference tables on the website of the laboratory course.

A second thermocouple is placed close to the heating of the oven. It is part of the feedback circuit for the temperature stabilization of the oven (see section 2.2).

2.1.2 Vacuum chamber

The oven is placed inside a vacuum chamber. The vacuum produced by a turbomolecular pump (TMP) is required for two reasons: Firstly it avoids oxidation and contamination of the parts and the sample at high temperature. Secondly, it thermally isolates the oven and the sample from the outer parts and the laboratory. The main principle is the same than for a thermos or a dewar, i.e. the suppression of thermal convection by air (or other gases) which is the main contribution to heat transport or thereby, heat loss.

The vacuum reached by means of the TMP and a second backing pump providing rough forevacuum is of the order of 10^{-5} mbar (note the unit milli-bar typically used in vacuum technology). The

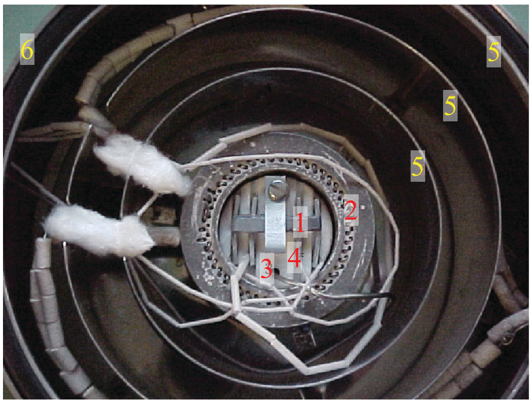

Figure 2: Top view of the oven with the sample mounted in the center. 1: silicon sample, 2: heating, 3: thermoelement for the sample temperature, 4: measurement contact (one out of four) 5: thermal shielding 6: outer vessel of the oven.

working principles of the TMP and the different ways to measure the pressure can be found in two tutorials (in German) on the webpage of this lab course.

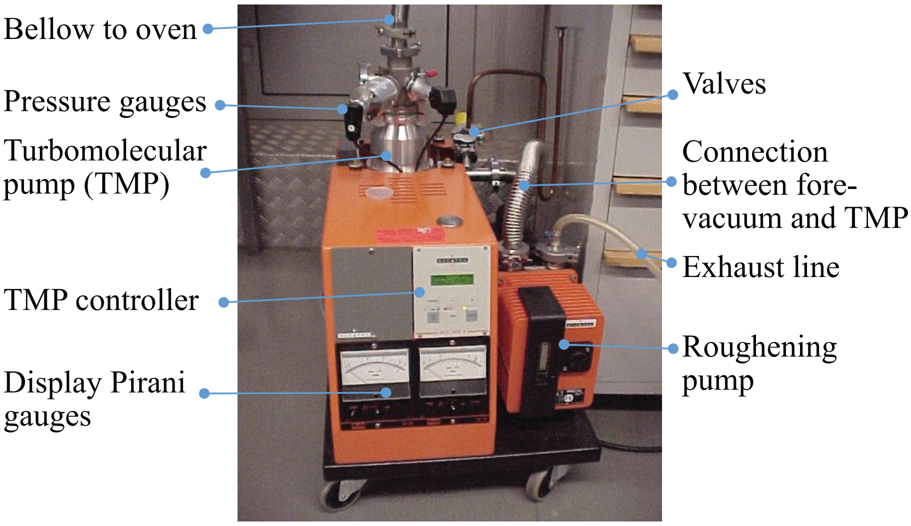

Figure 3: The vacuum system used in this experiment.

2.2 Control of the oven temperature

The control and stabilization of the oven temperature is done using a so-called **PID controller**: The acronym PID stands for Proportional–Integral–Derivative and means the feedback mechanism widely used for generating a control signal out of a measured quantity. Here, the controller regulates the heating by controlling the current through the heating filament. The temperature of the oven is constantly measured as the thermovoltage generated in the Ni-NiCr-thermoelement placed at the heater. This *process variable* is compared to a *setpoint* temperature given by the user and/or the computer program. The correction applied to the heating current is then calculated using the difference of process variable and setpoint as described in the next section.

Important: the sample temperature measured together with the resistance of the sample is always the reading of the thermovoltage produced by the second Ni-NiCr-thermoelement in direct contact with the sample! In this way, temperature differences between the heater and the sample do not falsify the results of the experiment.

2.2.1 The PID controller

In this section the working principle of a PID controller is briefly described taking as an example the stabilization of the oven temperature in our experiment. It is based on a closed feedback loop which is schematically drawn in Fig. 4. The temperature of the oven shall be stabilized at some desired value as defined by the user or some computer program running a temperature ramp, for instance. The true temperature of the oven may be different from this *set point* and be influenced by external parameters like the gas pressure in the vacuum vessel or some parasitic thermal contact. This temperature is called the *process variable*. Its measured value is compared to the desired value (setpoint). Out of the difference signal the controller generates an *error signal* which is applied as correction to the control variable (heating current): if the temperature difference is negative, i.e. the oven temperature lower than the setpoint, the error signal shall increase the heating current and vice versa.

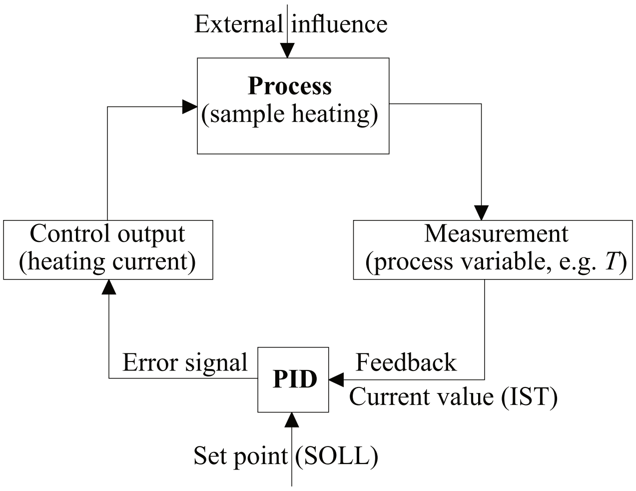

Figure 4: Generic scheme of a control unit.

PID refers to the way in which the error signal is calculated from the difference signal in the feedback loop:

1. **Proportional:** The error signal is proportional to the feedback signal, i.e. the correction of the heating current is proportional to the temperature difference signal at the input. The P–correction is almost instantaneous essentially limited by the response speed of the system, i.e. here the time between the increase of the heating current and the increase of the measured temperature. Moreover another problem is the fact that the temperature will only exponentially approach but never reach the desired value because the correction is always getting smaller at the same pace than the temperature difference.

2. **Integral:** This part averages the measured value over some time constant t_{int}. The error signal is then proportional to the difference between the averaged (integrated) measurement and the set point. Owing to the time constant this correction is slower than the bare P–signal and, as a positive side effect, averages over fast variations of the feedback signal as produced by electronic noise, for instance. Using the P– and the I–correction, one can show that the output indeed reaches the desired value.

3. **Derivative:** This part takes the instantaneous derivative of the temperature in to account for producing the error signal. Thereby it extrapolates the present process variable by multiplying the slope of the temperature with some time constant t_{der}. This part can substantially speed up the correction but makes the system unstable against perturbations of the process signal and tends to overdrive the system. This may be particularly harmful if the inertia or the time constant of the process (or response speed, c.f. P) is very slow.

2.2.2 Realization of the control circuit

For the controller of the oven temperature the PID is used in the following way:[1]
The P–part is limited to a certain *proportional band*, that means a temperature range in which the P–correction is applied. This is required by the limited power output provided by the controller. The maximum temperature range ΔT_{max}, in which the controller tries to apply the direct proportionality between feedback signal and error signal is given by (we still use the German terms IST for the measured signal and SOLL for the setpoint):

$$\Delta T = T_{\mathrm{IST}} - T_{\mathrm{SOLL}} \qquad \Rightarrow \qquad \Delta T_{\mathrm{max}} = \alpha \frac{P_H^{\mathrm{max}}}{G}$$

where α is some constant. P_H^{max} denotes the maximum heating power at the output of the controller and G the gain factor which can take values between 1 and 999. In Fig. 5 we show this proportional band schematically. Please note:

1. The larger the gain G is chosen, the smaller will be the proportional band.
2. The proportional band is *one-sided*, i.e. the controller will only heat if $T_{\mathrm{IST}} < T_{\mathrm{SOLL}}$.

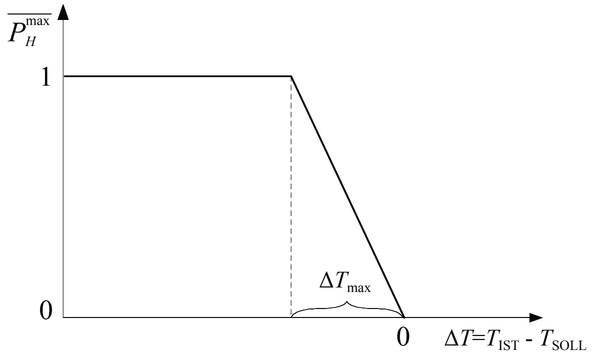

Figure 5: *Sketch of the proportionality band of the controller.*

The integral I–part will integrate the process signal over a time constant

$$\overline{T}_{\mathrm{IST}} = \frac{1}{t_{\mathrm{int}}} \int_0^{t_{\mathrm{int}}} d\tau \, T_{\mathrm{IST}}(\tau) \qquad \text{with} \quad t_{\mathrm{int}} = \frac{999\ \mathrm{s}}{R},$$

where the integration time interval t_{int} is determined by the *reset-rate* R with values between 1 and 999 (e.g. $R = 100 \Rightarrow t_{\mathrm{int}} \simeq 10$ s).

Finally the time constant t_{der} for the derivative D–part is given by $t_{\mathrm{der}} = (1/4)\,\beta\, t_{\mathrm{int}}$. β is a number in percent with values ranging from 0 to 200. In our experiment, we usually switch off the differential D–part due to the slow response time of the oven.

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[1] For details, please, refer to the controller manual.

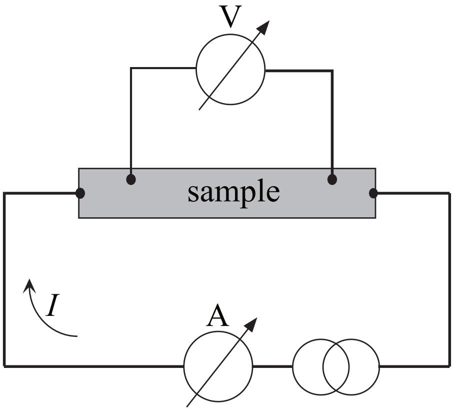

Figure 6: Schematic diagram of the 4-point-measurement. Note the separate contacts of current carrying wires and voltage measurement.

2.3 Measurement of the resistance

The resistance of the sample will be determined by the **four-point-method**: four contacts means that the current leads and the contacts for the voltage measurement are separated. At the points-of-contact between current leads and sample so-called *contact resistances* appear which depend critically on the quality of the bonding and on the materials in direct contact. In particular, at metal-semiconductor contacts a small barrier (Schottky barrier) may be formed which acts like a diode and whose voltage drop may depend exponentially on the current passing through the contact. Even if the contacts exhibit metallic behavior (so-called ohmic contacts) the finite resistance may take fairly large values and cause a significant voltage drop across the contact. Connecting the voltmeter to the same two contacts would then mean that the sum of the voltages at the contacts plus the voltage across the sample is measured. This is a systematic error.

In turn, if the voltage measurement is done using two separate wires and a voltmeter with very high internal resistance, the correspondingly small drain current used for the voltage measurement only causes a very small voltage drop at those contacts. In this way the systematic uncertainties due to the contact potentials and the wire resistances between sample and voltmeter can therefore be kept to a minimum.

3 Questions to answer in your report

1. In which way does the resistivity of a semiconductor depend on temperature?
2. Describe the dependence of the resistance on temperature quantitatively by determining the multiplier and the exponent from your data.
3. Calculate the energy gap of silicon from your data. Does this result depend on the geometry of the four-point measurement?
4. Discuss: how would doping change your measurements? Consider that for a doped semiconductor at typical doping concentration, the density of free electrons n and the density of free hole carriers p always fulfill the relation $np = n_i^2$ where $n_i = p_i$ denotes in *intrinsic* density of free carriers without doping.