

# Solid State Physics

## Resistance Measurements on Semiconductor (Si)

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### **Abstract**

Aim of the following experiment was to measure the temperature dependence of the resistance for the semiconductor silicon and determine the material specific energy gap. The energy gap is a concept in the band model of solids, it describes a forbidden energy area which can't be occupied by electron states. By using the band model and especially the characteristic energy gap of a material, metals, semimetals, semiconductors and isolators can be categorised.

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# 1 Physical background

For a semiconductor, the energy gap  $E_g$ , which describes the energy difference between the lowest energy in the conducting band and the highest energy in the valence band, is rather small ( $E_g \leq 2eV$ ). At a temperature of  $T = 0K$  all electron states are occupied in the valence band, in opposition to the conducting band, where states are unoccupied and therefore there is no electrical conductivity, which means that a semiconductor is an isolater at absolute zero. At higher temperature, electrons can be thermally excited and transit from the valence band to the conducting band, where they occupy free energy levels. The remaining orbitals in the valence band are called holes. Both carrier densities, the one of the electrons in the conduction band  $n$  and the one of the holes in the valence band  $p$  give a contribution to the electrical conductivity  $\sigma$  given by

$$\sigma = ne\mu_e + pe\mu_h, \quad (1)$$

where  $e$  is the elementary charge,  $\mu_n$  and  $\mu_p$  are the mobility of the electrons or holes, respectively. The mobilities are functions of the temperature in a low potential way. We will see that the conductivity will in general depend on the carrier density, which rises with increasing temperature, which explains the higher conductivity of semiconductors at high temperatures.

The occupation number is given by the Fermi-Dirac-Distribution:

$$f(E, T) = \frac{1}{\exp\left(\frac{\mu - E}{k_B T}\right) + 1} \quad (2)$$

where  $\mu$  describes the chemical potential which can be approximated by the fermi energy  $E_F$ . The fermi energy is the energy of the highest state that is occupied in the ground state. For a semiconductor the fermi energy is in between the valence and conduction band. In the case of energies over the fermi energy the distribution (2) goes to:

$$f(E, T) = \frac{1}{\exp\left(\frac{E - E_F}{k_B T}\right) + 1} \quad (3)$$

The carrier density in the conduction band is given by

$$n = \int_{E_C}^{\infty} D_e(E) f(E, T) dE, \quad (4)$$

where  $D_e(E)$  describes the electronic density of states and  $E_c$  the energy of the lower edge of the conducting band.

Using the fact, that the tempeprature dependence is restrained by the exponential term and in the case of charge conservation, where  $n = p$  holds, we get:

$$n = p \propto \exp\left(-\frac{E_G}{2k_B T}\right) \quad (5)$$

The mobilities in equation (1) are functions of low order and as mentioned the exponential term dominates, therefore it follows, that

$$\sigma \propto \exp\left(-\frac{E_G}{2k_B T}\right). \quad (6)$$

The relation between conductivity and resistance  $\sigma = \frac{1}{\rho} = \frac{AR}{l}$  where  $A$  is the cross section area and  $l$  the length of the solid, results in

$$R(T) = R_0 \cdot \exp\left(\frac{E_g}{2k_B T}\right). \quad (7)$$

Taking the logarithm leads to

$$\ln(R(T)) = \frac{E_g}{2k_B T} + \text{constant}. \quad (8)$$

By taking  $\ln(R(T))$  as a function of  $1/T$ , the slope of the straight line  $m$  gives directly the energy gap  $m = \frac{E_g}{2k_B}$  and therefore:

$$E_g = 2mk_B \quad (9)$$

## 2 Experimental setup

Figure 1 shows the oven with the silicon sample in the middle, prepared for the 4-point measurement. The cylindrical carrier of the sample consists of a ceramic material and is surrounded by the heater, which regulates the temperature. Also the four contacts for the measurement are fixed on the carrier which are connected with the data links. In the ideal case there is a thermal equilibrium of the carrier and the sample and therefore both should have the same temperature. To control that, two thermoelements were used, one to measure the temperature of the carrier and another one, integrated in the heater, which is connected to the PID-controller, which adjusts the heating temperature.

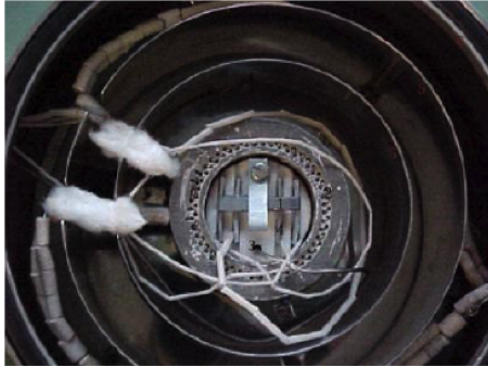


Figure 1: Sample in the oven.

The part inside the oven is isolated against the lab by a vacuum, produced by a turbomolecular pump. This results in a vacuum with a pressure better than  $10^{-5}$  mbar. The vacuum is important to prevent thermal convection and an oxidation of the sample, what both would disturb the system.

The record of the measuring datas and also the adjustment of the PID-controller has been controlled by a LabVIEW program.

Figure 3 shows the whole experimental setup, only without the computer where the LabVIEW program was installed.

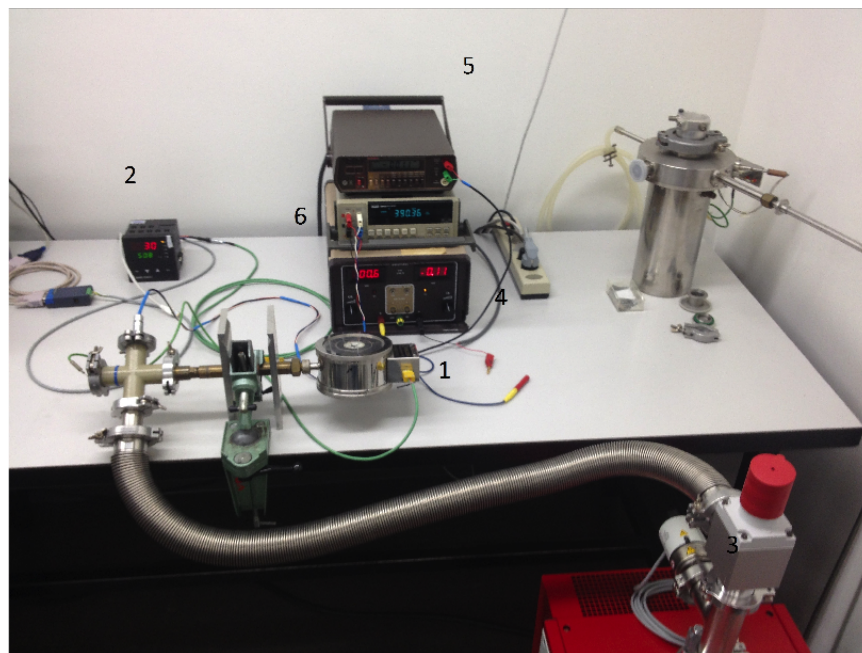


Figure 2: Experimental setup: 1) isolated tank with sample; 2) PID-controller; 3) vacuum pump; 4) heat- controller; 5) resistance meter; 6) voltage of thermoelement.

## 3 Equipment

### 3.1 4-point resistivity measurement

As seen in figure 3, a known current is applied to the two contacts outside and lead through the resistance. With the two contacts inside, the voltage difference can be measured. This is an advantage over the two point method, that voltage differences on the current supply doesn't distort the result of measurement. This fact gets very important to guarantee the resistance of the sample is in the region of the supply and contact resistances.

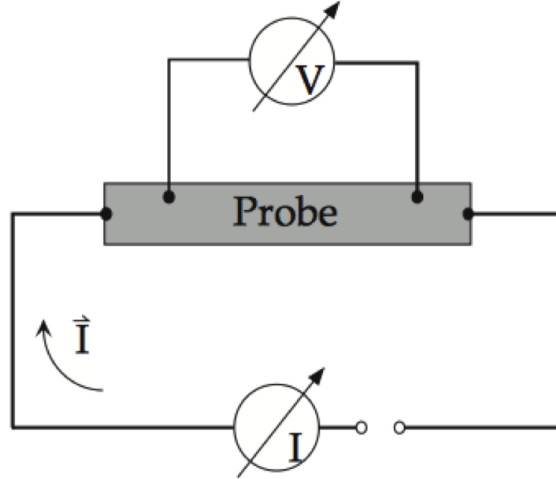


Figure 3: Scheme of a 4-point resistivity measurement.

### 3.2 Thermoelement

The temperature of the heating coil and silicon sample was measured by using a Ni-NiCr-thermoelement. The measurement with a thermoelement is based on the Seebeck-effect which explains the appearance of a voltage between two points with different temperatures in a conductor. The voltage has to be measured at two positions with the same temperature, therefore two conducting materials are needed, Ni and NiCr. The charge carriers distribute along the conductor, because they are responsible for heat transport. Then the thermal voltage can be measured between the two cold endings.

### 3.3 PID-controller

For the regulation of the temperature in the oven a PID-controller was used. Such a controller consists of three components: a proportional, integral and differential part. All these parts are based on the same principal of back coupling, where an IST-value, which is in our case the present temperature, is compared to a SOLL-value, the needed temperature. The PID-controller regulates the heating current as a function of the difference between the IST- and SOLL-value.

Proportional part:

That part is responsible for a fast reaction, because the heating current is proportional to the difference between the SOLL- and IST-value. It's possible to show, that for only a proportional regulation the SOLL-value will never be reached.

Integral part:

The integral part takes the average of the IST-value over a time interval  $t_{int}$ . The regulation of the heating current is then proportional to the difference between averaged IST-value and the SOLL-value. The integral part regulates slower than the proportional part, because it has to calculate the average over  $t_{int}$  first. It has the advantage that the SOLL-value will

be reached and all fluctuations of the IST-value vanish by taking the average.

Differential part:

For the differential part, the slope of the time dependent evolution of the IST-value will be used to extrapolate a future IST-value. The regulation is based on the difference of the extrapolated IST-value and the SOLL-value.

## 4 Measurements

### 4.1 Temperature Sequence

The resistance of the silicon sample has been measured in a heating process as well as in a cooling process. The temperature sequence of both processes is shown in figure 4.

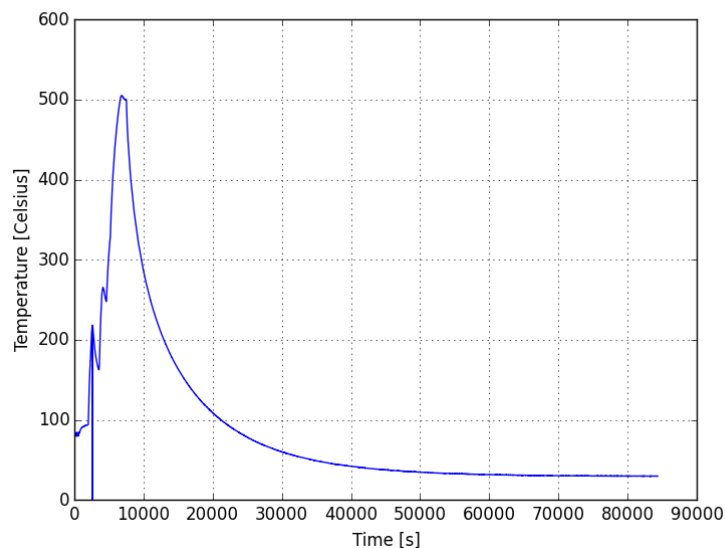


Figure 4: Temperature sequence of the silicon sample

### 4.2 Measurement of Resistance

#### 4.2.1 Heating process

First of all the temperature of the silicon sample was raised to 500°C, which can be achieved with the aid of the PID-controller. With this component, one can adjust the SOLL-value to 500°C. During this process the resistance has been measured by using the four-point method. We observed the resistance as a function of the temperature as shown in figure 5.

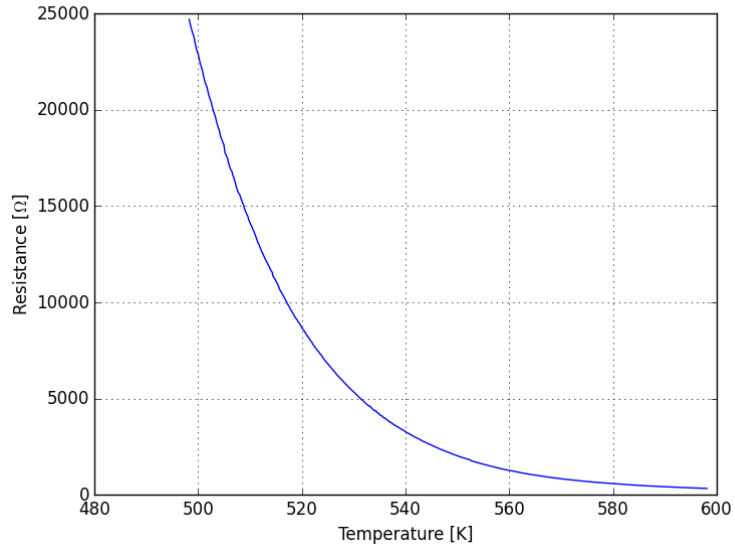


Figure 5: Measurement of resistance during heating-up process

The fluctuations at the lower end are due to the experimenters trials with the PID-controller to adjust the integrating part and getting to know the setup.

#### 4.2.2 Cooling-down

After the heating to 500°C the heater has been turned off in order to allow the sample to cool down. Again we used the four-point method to take the measurement of the resistance and it is shown as a function of the temperature in figure 6.

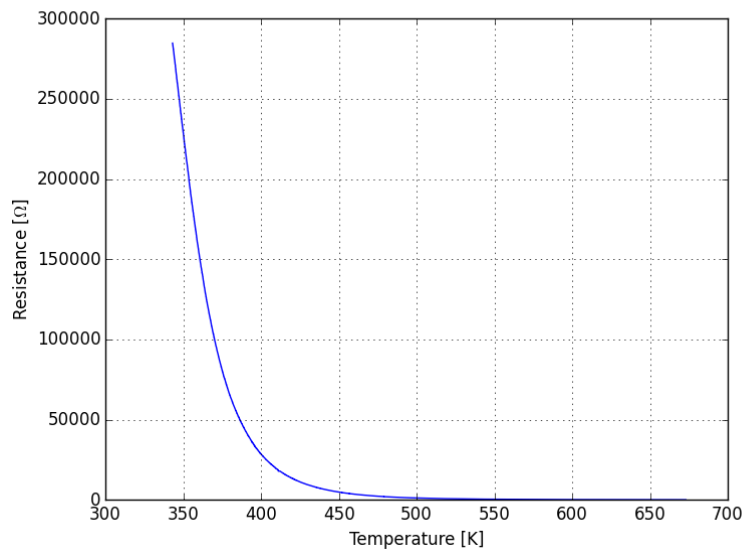


Figure 6: Measurement of resistance during the cooling process



Shown is exclusively the relevant part needed for the analysis, which shows a clear exponential behaviour of the relation between the resistance of the silicon and the temperature of the sample.

## 5 Examination

### 5.1 Logarithmization

In equation (8) the relation between the logarithm of the resistance and  $1/T$  is stated. When we plot the logarithm of the resistance against the reciprocal value of the temperature, one finds an area with a linear dependence as you can see in figure 7 and figure 8. That means a straight line can be fitted and by the determination of its slope one can compute the energy gap of silicon.

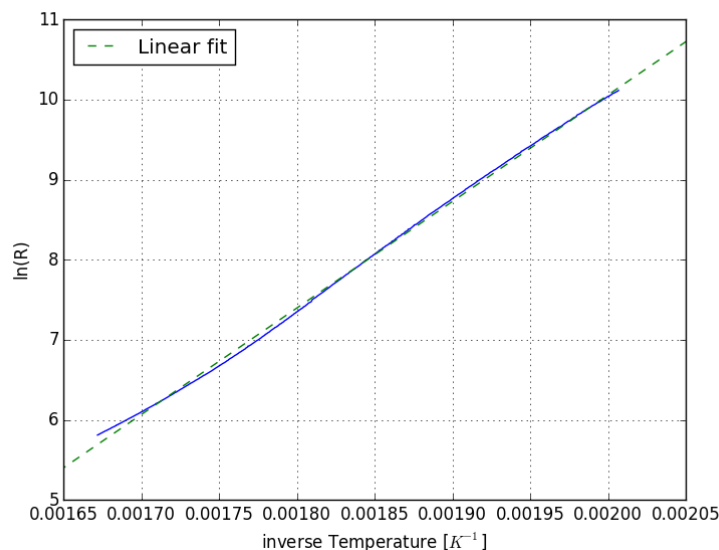


Figure 7: Logarithmized resistance against  $1/T$  during the heating process

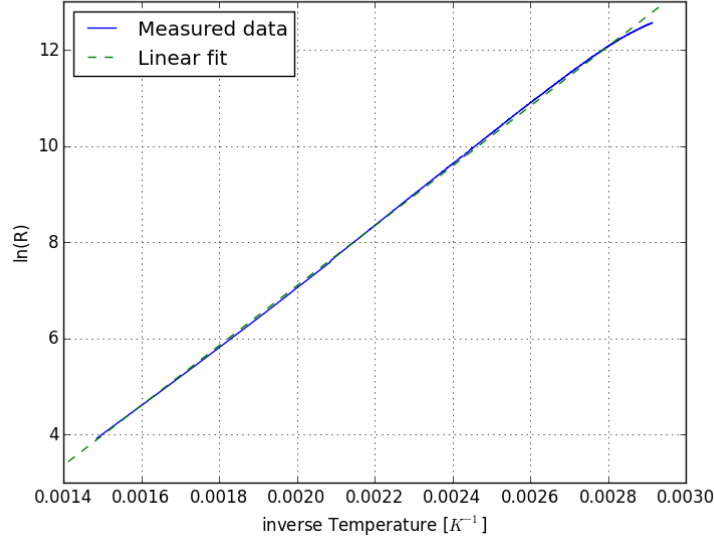


Figure 8: Logarithmized resistance against  $1/T$  during the cooling process

The slopes of the curves of the heating and cooling process are:

$$m_{he} = 13305.669K$$

$$m_{co} = 6219.915K$$

Therefore we get for the bandgap by using equation (9):

$$E_{G,he} = 2m_{he}k_B = 2.293eV$$

$$E_{G,co} = 2m_{co}k_B = 1.072eV$$

## 5.2 Estimation of Errors

### 5.2.1 Potential Error Sources

One can expect the following sources of error:

- The negligence of the temperature dependence of the charge carrier in equation (8)
- Damage or contamination of the sample
- Systematic errors of the equipment
- Absence of thermal equilibrium between sample and heater, especially during the heating process.
- Difference in temperature between sample and thermoelement during heating-up process

### 5.2.2 Method of least-square

At this juncture one can estimate the error for the energy gap by using the least-square method. Then we get:

$$\sigma_{E,he} = 0.118eV$$

$$\sigma_{E,co} = 0.040eV$$

## 6 Results

Below you can find a comparison of the result for the energy gap of silicium including the estimated error and the literature value of it.

$$E_G = (1.072 \pm 0.040)eV$$

$$E_{G,literature} = 1.11eV^1$$

## 7 Discussion

As one can presently see there is a large deviation between the two values for the energy gap even by taking into account the errors. Certainly we can consider as a source of trouble that the heating-up process takes place very rapidly. This means that we will barely find a thermal equilibrium and there will be a difference in temperature between sample and thermoelement during the process. On the contrary for the cooling-down process this is less the case. Therefore one assumes a higher precision for the value, which we got from the cooling-down process. Consequently the value for  $E_{G,he}$  has been neglected in the results. An additional experiment, which was concentrated specifically on the heating process, that means adjusting a thermal equilibrium right before the clearly exponential temperature dependence between 350 and 600 Kelvin, didn't result in a better outcome of the experiment.

By comparing the result with the literature value one can notice that the experimental value is too low. That can be originated very likely by contemplating the negligence of the temperature dependence of the charge carrier in equation (8). Nonetheless it is still inside the error bound, what signifies a satisfiable accordance with the literature value. Surely systematic errors of the equipment act a part in the exactness of the measurements.

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<sup>1</sup>Ch. Kittel, Einführung in die Festkörperphysik, 14. Auflage, 2006, Oldenbourg Wissenschaftsverlag GmbH