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1 Introduction

This experiment is constructed out of three experiments. The first one deals with the band gap of semiconductors. Aim is to compute the band gap energy of germanium and silicon with help of a transmission and absorption spectrum. To acquire the spectra different wave lengths will strike to semiconductor whereby absorption and transmission can be measured.

The second part is the Haynes & Shockley experiment. One frees electrons in a semiconductor with a laser beam. Because of an applied voltage the electrons move. This movement can be observed with an oscilloscope. With the measured data one determines the mobility $\mu_{\rm e}$ of electrons, the diffusion constant $D_{\rm n}$ and the half life $\tau_{\rm n}$ of an electron hole pair.

The third part is about semiconductor detectors. The considered detectors are a Sidetector and a CdTe-detector. With each detector the spectra of 57 Co and ${}^{241}_{Am}$ will be measured. The ratio of the absorption probabilities of Si and CdTe and the energy resolutions will be determined.

2 Physical background [2]

2.1 Ohm's law

A semiconductor is based on the change of the resistance, so it is unpreventable to engage with Ohm's law. It is given by

$$\rho = R \cdot \frac{A}{l},\tag{1}$$

while ρ is the specific resistance, R the resistance, A the cross-section area and l the length of the resistance . A conductor has a specific resistance $\rho \leq 10^{-3} \Omega$ cm, while for an isolator holds $\rho \geq 10^8 \Omega$ cm. Between them is the group of semiconductors.

2.2 Semiconductor

You distinguish between elemental semiconductors, e.g. silicon, germanium (both of main group IV), which consist of only one element, and compound semiconductors (e.g. gallium arsenide), which consist at least of two elements. Normally it is a combination of elements of main group III and main group V.

2.3 Band model

The energy band is the resolution of the interactions of many electrons. Because of quantum mechanics every electron has discrete energy level. If there are many electrons near to each other the wave functions overlap. As a consequence of the pauli principle the different energy level split up in several new energy level that are all a bit different. Because of the huge amount of atoms one can say that the energies are no longer discrete instead they are continuous energy bands. You can see a visualization of this phenomena in Figure 1. Near to the core there are smaller bands because electrons has a lower interaction among themselves if they are near to the nuclei. In case of semiconductors even the effect of fine-structure splitting is dominant.

Especially two bands are interesting for this experiment. On the one hand the valence band on on the other hand the conductor band.

The valence band is defined as the last band that is full up with electrons at a temperature of 0K. Full up bands are not of importance while talking about the current through a material. The reason is that the whole momentum of a full band is zero and so even the



Figure 1: Sketch of the emergence of energy bands ^[2]

current is zero.

The conductor band is the first band above the valence band. Electrons of the conductor band are responsible for the current. Therefore Materials with electrons inside the conductor band allows a current when a voltage is applied.

The definition of this bands allows another definition of isolators, semiconductors and conductors via the band gap between conductor and valence band. This is shown in Figure 2.



Figure 2: Definition of isolator, semiconductor and conductor via the band gap $^{[2]}$

2.4 Charge in semiconductors

At the ground state of a semiconductor there is a full valence band and the conductor band is empty. Now an electron can be excited and gets to the conductor band. This electron is effectively free and can move because of an applied voltage. Another reason for a possible current is that the electron leaves a hole inside the valence band. If there is a applied voltage the hole is a more favourable energetic state for another electron and so it gets to the old position of the electron which is in the conductor band now. So there is also a positive charge which takes part in the current intensity. One can refer a mass to both charges, m_n is the effective mass of the quasi-free electron and m_p the effective mass of the quasiparticle.



Figure 3: Excited electron in the conductor and the related hole in the valence band. Left: without applied voltage, Right: with applied voltage^[2]

2.5 Charge in an E-field and diffusion

An electron-hole pair has a half life. This becomes important when you applied a voltage. With knowledge about the half life τ and the electric field E one can compute the average velocity

$$\vec{v_{\rm n}} = -\frac{e\tau}{m_{\rm n}}\vec{E} = \mu_{\rm n}\vec{E} \qquad \vec{v_{\rm p}} = \frac{e\tau}{m_{\rm p}}\vec{E} = \mu_{\rm p}\vec{E}$$
(2)

where μ_n : mobility of the electrons

 $\mu_{\rm p}$: mobility of the holes

Also the diffusion can influence the charge transport. Without respecting the Coulomb interaction and with introducing an electron concentration $n(\vec{r})$ and a hole concentration $p(\vec{r})$ and a diffusion constant $D_{\rm n}$ and $D_{\rm p}$ one obtains for the flux of charge

$$\vec{j}_{\rm n,diff} = -D_{\rm n} \vec{\nabla} n \qquad \vec{j}_{\rm p,diff} = -D_{\rm p} \vec{\nabla} p.$$
(3)

So the electron current density $\vec{j_{n}}$ and the hole current density $\vec{j_{p}}$ are

$$\vec{j_{\rm n}} = -e\mu_{\rm n}\vec{E} - eD_{\rm n}\vec{\nabla}n \qquad \vec{j_{\rm p}} = -e\mu_{\rm p}\vec{E} - eD_{\rm p}\vec{\nabla}p.$$
(4)

So the whole current density is $\vec{j} = \vec{j_p} - \vec{j_n}$. The current density with negligence of the diffusion is

$$\vec{j} = e(\mu_{\rm p} + \mu_{\rm n}n)\vec{E} = \sigma\vec{E} = \frac{1}{\rho}\vec{E}.$$
 (5)

Where σ : specific conductivity

 ρ : specific resistance

Out of this the diffusion constants and the mobility are correlated by the Einstein equation

$$D_{\rm n} = \frac{kT}{e}\mu_{\rm n}$$
 and $D_{\rm p} = \frac{kT}{e}\mu_{\rm p}.$ (6)

2.6 Direct and indirect semiconductors

When you have a look at the band-sketch in the momentum space. Especially for semiconductors you can differentiate between two types. There are direct and indirect semiconductors.

2.6.1 Direct semiconductor

Direct semiconductors are defined by the characteristic that the maximum of the valence band is directly below the minimum of the conductor band.

It is clear that conservation of energy and of the momentum holds. So for a direct transition it is necessary to has an energy higher than the band gap energy E_{g}

$$E_{\rm photon} = \hbar \omega \ge E_{\rm g}.\tag{7}$$

In addition to that the whole momentum will transfer to the lattice

$$\vec{p}_{\text{photon}} = \hbar \vec{G} \qquad \vec{G} \in \text{reciprocal lattice.}$$
 (8)

However not every transition has to be a direct one in direct semiconductors. As it is shown in Figure 4 you need more energy and a transferred momentum.



Figure 4: Sketch of an indirect semiconductor(left) and a direct one (right)^[2]

2.6.2 Indirect semiconductors

Indirect semiconductors are those which have a momentum difference between the maximum of the valence band and the minimum of the conductor band.

Here, phonons play an important part for exciting electrons. They are lattice oscillations (quasi-particle) with a low energy comparable to its momentum. It holds energy conservation so the energy is equal or higher than E_g . That means that the momentum is set to

$$|\vec{p}| = \frac{E}{c}.\tag{9}$$

For conservation of momentum mostly a phonon is responsible. There are two possibilities, either the electron has a too low momentum and an additional momentum of a phonon is needed to realise the transition or the photon has too much momentum and so the a phonon has to be create because of momentum conservation.

2.7 Extrinsic semi-conductor and doping

A perfect semiconductor is called intrinsic. To create one is not possible so far because there are always defects inside the lattice which are responsible for additional energy levels and so on. A real semiconductor is extrinsic. That includes also that there are foreign atoms. For example in an intrinsic semiconductor an atom has a bound to four adjacent atoms. If there is a foreign atom with for example five valence electrons one can not be bounded in the lattice. This electron can move in case of an applied voltage.

In addition to that there can also be an atom with only three electrons. As a consequence there is a hole at one place. This hole can also move.

To be able to distinguish between this two types you are talking about donors (five electrons) and acceptors (three electrons).

As you can see, the foreign atoms can make a semiconductor more conductively. One can benefit of this effect because one foreign atom in a lattice of 10^6 atoms can increase the conductivity to several orders of magnitude. The process of putting foreign atoms to a lattice is called doping.

If you use donors you have a n-type semiconductor otherwise if you you use acceptors you have a p-type one. For the free charge it holds

n-type:
$$p \approx 0$$
, $N_{\rm A} \approx 0$, $n \approx N_{\rm D}$, $\sigma = \frac{1}{\rho} \approx e N_{\rm D} \mu_{\rm n}$
p-type: $n \approx 0$, $N_{\rm D} \approx 0$, $p \approx N_{\rm A}$, $\sigma = \frac{1}{\rho} \approx e N_{\rm A} \mu_{\rm p}$ (10)

While N_A the number of donated acceptors and N_D the number of donors and σ is the specific conductivity.

2.8 pn-diode

A pn-diode is a contact of p- and n doped semiconductors. Around the area of the contact some electrons of the n-doped side diffuse to the p-doped one and recombine there. In a row you can find positive ionised atoms at the n-doped side and negative ones on the p-doped side. Because the atoms itself are not able to move there is an electric field with a voltage $U_{\rm bi}$. The area where the ionised atoms are placed is called depletion region. Even if there is an excited electron, maybe because of thermal effects, it will be accelerate out of this region because of the electric field.

Semiconductor detector

Not only thermal effects can frees an electron even radiation is able to do this. That is the basic idea of an semiconductor detector. You can strike radiation to the detector and according to its energy a special amount of electrons becomes free. The number of electrons gives information about the energy of the incoming photon. With a pre amplifier this signal can be changed to voltage signal which can be transferred to a PC.

3 Measuring band gap

At this place the band gap energy of silicon and Germanium will be determined. Once with help of the transmission spectrum and once with the absorption spectrum.

3.1 Setup

The used setup for measuring the band gap is shown in Figure 5.



Figure 5: Setup for measuring the band gap. The lens between lamp and lattice is missing in the figure. ^[1]

The light of the lamp has a frequency of ca. 70 Hz because of an installed chopper which is placed in front of the lamp. After the chopper it follows a lens (not shown in 5) so the light of the lamp becomes parallel and strikes to a lattice. This one separates the different wavelengths of the light to a visible spectrum. A small part of the spectrum strikes now to a split and another lens which focuses the light to a semiconductor sample and a behind located pyrodetector. The semiconductor component is built in a way that it is possible to apply a voltage and to measure a current through the semiconductor sample. By rotating the lattice you are able to strike different parts of the spectrum to the split and the setup behind. So photons with different energies strike to the semiconductor and pyrodetektor. To be sure to strike only the first order of positive interference to the semiconductor there is built in a filter after the slit which filters out higher orders.

For analysing the data there is a PC which gets the information about the angle of the lattice via a control unit and the information of the semiconductor current and the pyrodetector signal via a Lock-in amplifier and the control unit. The program for analysing the data at the PC is called "LoggerPro". This program refers every angle to a wavelength by its own.

Important to know is that there are two different semiconductors (silicon and germanium) and also for each sample there are different lattices, and filter.

3.2 Implementation

At first one has to calibrate the angle setting at the PC. Therefore one illuminates the slit with the zero maximum and set the angle at the PC to zero. Third step is to check whether the signal arrives the saturation of the detectors. To check this it has to be measured without the semiconductor component. So there is only a signal of the pyrodetector.

Because of the given lattice the interesting angle is ca. 40° . So one acquires the spectrum from about -50° to 50° . When the signal exceeds 5V (exception: zero order) then one has to to close the slit a bit or change the amplifier to a lower level. Otherwise if the signal is to weak do the opposite setting changes.

In all further steps one measure the spectrum from -50° to 50° .

First really measurement is to acquire the background. For this purpose one covers the slit so no more light can go directly to the detectors. Now the semiconductor is on its place. Then you start the measurement. On this way one obtains the background of the sample- and pyrodetector signal.

Second measurement is with no covering of the slit. You measure the absorption and transmission of the given semiconductor sample with the full setup explained above.

To get knowledge about the uncertainties one does another measuring. So step four is to set an angle nearly the maximum and measure values for a ca. 10s. Later you need this to set the error bars.

One do this steps with silicon and germanium as semiconductor components. That also means that you have to change the lattice and filter.

3.3 Analyse

All errors in all parts are calculated with the Gaussian error propagation.

The angles are for different measurements different, because the lattice does not have a constant rotational velocity. So the angles of the three different measurement series (without the uncertainty measurement) have to be adapt and with it the related values. The left values are deleted.

The measured spectra are encumbered with an underground which has to be subtracted. This justified the formulas

$$Trans_{real} = \frac{Trans - Undergr_{trans}}{Lamp} \qquad Absorp_{real} = \frac{Absorp - Undergr_{real}}{Lamp}, \qquad (11)$$

which is executed for each triple of values. This values are plotted on the related energies, which are also given from the PC. So one gets two graphics (transmission, absorption) for each semiconductor (silicon (graphic 6,7), germanium (8,9)). In the graphics are only the relevant parts shown.

The expectation is that the transmission can be described with

$$\operatorname{Trans}(E) = A \cdot \exp(-\alpha(E) \cdot l). \tag{12}$$

For the absorption a correction is necessary, because some electron-hole couples recombine at defects near the surface. So here the expectation is

$$Absorp(E) = A \cdot \exp(-\alpha(E) \cdot d)(1 - \exp(-\alpha(E) \cdot l)), \tag{13}$$

while d is the thickness of the defect-layer. In both functions is A a constant, l the thickness of the semiconductor and $\alpha(E)$ the absorption coefficient in dependence of the energy, which is given by

$$\alpha(E) = AC \cdot \left(\frac{\Theta(E - E_{\rm g} + E_{\rm p})^2}{\exp(E_{\rm p}/kT) - 1} + \frac{\Theta(E - E_{\rm g} - E_{\rm p})^2}{1 - \exp(-E_{\rm p}/kT)}\right), \quad \text{with } \Theta(x) = \begin{cases} x \text{ for } x > 0, \\ 0 \text{ else.} \end{cases}$$
(14)

Here is AC : constant,

- E : energy of the irradiated photons,
- $E_{\rm g}$: band gap energy,
- $E_{\rm p}$: energy of the phonons,
- k : Boltzmann constant,
- T : temperature, which is estimated at T = 292 K.

The material constants are summed up in Table 1.

	$l [\mathrm{cm}]$	$AC \left[\frac{\text{eV}^2}{\text{cm}}\right]$	$E_{\rm p} \left[{\rm eV} \right]$
Silicon	0,06	6199	0,061
Germanium	$0,\!05$	8823	0,036

Table 1: Material constants of the Si and Ge semiconductors. The constants are taken from [1]

So these functions can be fitted on the related values. For the transmission part A and $E_{\rm g}$ are the free parameters, for the absorption part d is an additional free parameter. These fits can also be seen in the graphics 6-9.



Figure 6: Transmission of the silicon semiconductor. The fitted function is Trans(E). This are only the values in the important area.



Figure 7: Absorption of the silicon semiconductor. The fitted function is Absorp(E). This are only the values in the important area. The error bars are partial not visible, because otherwise the important part would not be good visible.



Figure 8: Transmission of the germanium semiconductor. The fitted function is Trans(E). This are only the values in the important area.



Figure 9: Absorption of the germanium semiconductor. The fitted function is Absorp(E). This are only the values in the important area. The error bars are partial not visible, because otherwise the important part would not be good visible.

From the fits the band gap energies $E_{\rm g}$ can be read out. The results are summed up in Table 2.

	$E_{\rm g,trans}$ [eV]	$E_{\rm g,absorp}$ [eV]
Silicon	$1,\!0941\pm\!0,\!0007$	$1,079 \pm 0,007$
Germanium	$0,\!661\pm 0,\!004$	$0,\!666\pm 0,\!008$

Table 2: Calculated band gap energies of Si and Ge

The thickness of the "damage layer" d could also be read out of the diagrams, but it is not very import.

4 Haynes & Shockley experiment

At this part one determine the diffusion coefficient $D_{\rm e}$, the mobility of free electrons and the average life time $\tau_{\rm e}$ of free electrons in p-germanium.

4.1 Setup

The setup for this experiment is shown in Figure 11.



Figure 10: Setup for measuring the diffusion coefficient $D_{\rm e}$, the mobility of free electrons μ and the average life time $\tau_{\rm e}$ of free electrons in p-germanium ^[1]

The important components are a pulsed Laser (30 Hz) which light is transfer to the surface of a germanium sample by fiber optics. This pulse frees electrons inside the semiconductor. Because of an applied voltage the electrons move through this potential. The voltage is also pulsed because otherwise the semiconductor becomes too hot and the values we want to measured depends on the temperature. The movement of the free electrons can be detected with an oscilloscope. Therefore one measures the voltage in a variable distances to the laser with a little peak on the surface of the semiconductor. Also the applied voltage that is responsible for the movement of the electrons is variable. This voltage can be measured with a voltage feeler. The informations are proceed with an unit component. At this one it is also possible to set the pulse width to a longer or shorter time and to set the laser intensity. Out of this there is also a delay option, so first the electric field is applied and then the laser frees electrons. Because of this a equilibrium is guaranteed. The oscillator just can record a data set if the measurement is "stopped". So the values are just a snap-shot and are consequently very error-prone. An averaging was because of a reason of time not possible.

4.2 Implementation

At first one has to annihilate the applied voltage by using level shift. Now for this experiment we acquire two different measurement series. You do following both steps.

- Measuring signal for different distances $(2-10\,\mathrm{mm})$ and with a applied voltage of ca. $50\,\mathrm{V}$
- Measuring signal for different applied voltages (15-50 V) with a consistent distance of ca. 4 mm

4.3 Analyse

The movement of the electrons is given by a differential equation. The solution of this equation is a Gaussian function

$$c(t,x) = C \exp\left(-\frac{t}{\tau_{\rm n}}\right) \cdot \frac{1}{\sqrt{4\pi D_{\rm n} t}} \cdot \exp\left(-\frac{(x-\mu_{\rm n} E t)^2}{4D_{\rm n} t}\right)$$
(15)

In measuring series 1 the distance d of the laser and the peak were variable. Now the electron mobility, the half life, the standard deviation and the diffusion constant will be determine with the acquired data.

One has a Gaussian peak for every distance. They can be fitted with the function

$$c(t) = A \cdot \frac{1}{\sqrt{2\pi\sigma^2}} \cdot \exp\left(-\frac{1}{2}\frac{(t-t_c)^2}{\sigma^2}\right).$$
(16)

Here only one graph is shown. The others can be found in the attachment (7).



Figure 11: Measured data for a distance $d = (2,90 \pm 0,14) \text{ mm}$

Now one has to read out the parameters A, s and x_c from every Gaussian fit. By comparing formula 15 with 16 one obtains

$$d(t) = \mu_{n} E t, \qquad A(t) = C \exp\left(-\frac{t}{\tau_{n}}\right) \quad \text{and} \quad \sigma(t) = \sqrt{2Dt}.$$
(17)

Now one can fit the three functions on the related pairs of values.

1. One wants to determine the **mobility** μ . The slope $b = (0.465 \pm 0.010) \frac{\text{mm}}{\mu\text{s}}$ of the first function Figure 12 can be read out as a fit parameter. Then it follows

$$b = \frac{d}{t} = \mu E$$
$$\Leftrightarrow \mu = \frac{b}{E}$$
$$= (2910 \pm 60) \frac{\text{cm}^2}{\text{Vs}}$$

2. The second fit (Figure 13) is for determining the half life of an electron-hole pair. The half life τ_n can be read out directly as a fit parameter. The fit reveals the value

$$\tau_{\rm n} = (6,81 \pm 0,08)\,\mu{\rm s.}$$
 (18)

3. With the third part one determines the **diffusion constant** $D_{\rm n}$. With the third function (Figure 15) it is possible to determine the parameter D. With a known mobility $\mu = (2910 \pm 60) \frac{\rm cm}{\rm Vs}$ one can compute the diffusion constant $D_{\rm n}$ with

$$D_n = D \cdot v^2 = D\mu^2 E^2 = D\mu^2 \frac{U^2}{l^2} \quad \text{with } l = 3.0 \,\text{cm}^{[1]}$$
$$= (101 \pm 4) \frac{\text{cm}^2}{\text{s}}$$

The last calculations are needed because it was easier to calculate with a σ which has the unit of a time and instead later transfer the parameter D to D_n .

The measurement point with the lowest distance $d = (2,30 \pm 0,14)$ mm is excluded from the measuring. The value seems to be very error-prone. For measuring this distance the fiber glass component and the voltage tester component are completely against each other. Maybe there is still a gap between the two plastic holders that was not measured.



Figure 12: Function $d(t) = \mu_n E t$ through the measured values (the left point is not part of the linear regression)



Figure 13: Function $A(t) = C \exp(-\frac{t}{\tau_n})$ through the measured values (left point is not part of the exponential fit)



Figure 14: Function $\sigma(t) = \sqrt{2Dt}$ through the measured values (left point is not part of the fit)

The second measuring series was taken with different voltages and a constant distance $d = (4,00 \pm 0,14)$ mm. The aim is again the determination of the three parameters μ_n , τ_n and $D_{\rm n}$. The procedure is very similar like above.

The applied voltage is is read out from the oscilloscope. Therefore the mean U_{low} of the first 200 values before the increase and the mean U_{high} of the last 200 values of the high voltage plateau were calculated. So the applied voltage is



$$U = U_{\rm high} - U_{\rm low}.$$
 (19)

Figure 15: Oscilloscope picture of the applied voltage

Here only one graphic and Gaussian fit will be shown the other graphics are in the attachment 7.



Variation of voltage, data 13

Figure 16: Measured data for a voltage $U = (48,66 \pm 0,03)$ V

1. The mobility μ_n can be compute with the data of the linear fit (Figure 18). It holds

$$d = \mu Et = \mu \frac{U}{l}$$
$$\Leftrightarrow \mu = d \cdot l \underbrace{\frac{1}{U \cdot t}}_{\text{slobe } b}$$

The slope $b = (3,28 \pm 0,05) \frac{1}{V_s}$ can be read out from the linear regression, l = 3 cm is given by the manual ^[1]. With the calculation above one obtains

$$\mu_{\rm n} = (2460 \pm 60) \frac{\rm cm^2}{\rm Vs}.$$

2. Now the half life τ_n will be determine. It is again the fit parameter which reveals

$$\tau_{\rm n} = (4,78\pm0,18)\,\mu{\rm s}$$

in this case.

3. The diffusion constant D_n is determined again with the parameter D from the square root fit which is shown in Figure 20. It is obviously that the fit doesn't fit very well, but to get a result the calculation is continued. With the parameter $D = (0.0479 \pm 0.0009) \,\mu\text{s}$ and the same calculation like above ones obtains

$$D_{\rm n} = (74 \pm 4) \, \frac{\rm cm^2}{\rm s}.$$

In all fits the most right value is not considered. As you can see in Figure 17 the measured signals are very weak and the Gaussian fit is very inexactly.



Variation of voltage, data 29

Figure 17: Measured data for a voltage $U = (14,67 \pm 0,03)$ V



Figure 18: Function $\frac{1}{U}(t) = \mu_n E t$ through the measured values (right point is not part of the linear fit)



Figure 19: Function $A(t) = C \exp\left(-\frac{t}{\tau_n}\right)$ through the measured values (right point is not part of the exponential fit)



Figure 20: Function $\sigma(t) = \sqrt{2Dt}$ through the measured values (right point is not part of the fit)

5 Semiconductor detectors

The setup for the third and last measurement is shown in Figure 21.



Figure 21: Setup for measuring the probability of absorption of silicon and CdTe and the relative energy resolution power ^[1]

The semiconductor detector experiment is composed of a semiconductor detector which signal is proceeded by an pre amplifier. The pre amplifier changes the measured current into a voltage signal which high depends on the energy of the incoming photon at the detector. Then there is a shaping amplifier and a multichannel analyser (MCA). The MCA refer each signal amplitude to a channel. The information about the channel is the output. So at least you have an information about the energy of the photon in form of channels. The number of channel is given to a PC and can be used to do a histogram with a program called "ADMCA". The given samples are ²⁴¹Am and ⁵⁷Co. Also there are two different detectors, one silicon detector and one CdTe detector.

5.1 Implementation

One measure for both detectors in each case the $^{241}{\rm Am}$ and $^{57}{\rm Co}$ sample. The duration for every measurement is 60 min.

5.2 Analysis

5.2.1 Energy calibration

To find out which channel of the MCA refers to which energy you have to do an energy calibration. The manual of the experiment ^[1] gives information about the possible decay energies. They are shown in Table 3.

sample	energy [keV]
Americium	59,5
Cohalt	122,06
Cobalt	136,47

Table 3: Possible energies for the decay of 241 Am and 57 Co

Now one has to compare the acquired spectra of 241 Am and 57 Co with the possible decay energies. Therefore the peaks of the spectra were fitted with a Gaussian function. One reads out the position of the maxima and refer it to a possible energy. Because of the fact that there are at most two peaks at the 57 Co spectrum and only one at the 241 Am spectrum the assignment is easy. The left peak is related to the lower decay energy and the right one to the higher energy.

The measured spectra and the Gaussian fits for the silicon detector are shown in Figure 22 and Figure 22.



Figure 22: Spectrum of americium measured with silicon-detector and a Gaussian fit at the 59,5keV-decay



Figure 23: Spectrum of cobalt measured with silicon-detector and a Gaussian fit at the 122,06 keV-decay

With help of the Gaussian fit one can read out the position of the maxima and obtain

the values listed up in Table 4. As you can see, there is no fit for the 136,47 keV-decay of cobalt. The peak is too weak for a meaningful and good fit. So the maximum is read out by hand and the error is appreciated bigger.

sample	energy [keV]	channel
Americium	59,5	$301,\!6\pm 0,\!5$
Cobalt	122,06	$622,0 \pm 0,6$
Cobalt	$136,\!47$	698 ± 5

Table 4: Decay energies with related channels for the silicon detector

Now one can plot the energies over the channel and obtain the energy calibration which is shown in Figure 24. So one gets for the energy E the channel

$$channel = a + b \cdot E, \tag{20}$$

with $a = -3,3 \pm 1,2$ and $b = (5,124 \pm 0,013) \frac{1}{eV}$.



Figure 24: Energy calibration of the Si-detector (From Si-detector measured channels over referred energies with a linear fit)

It follows the same procedure for the CdTe-detector. The spectra are shown in Figure 25-Figure 27.



Figure 25: Spectrum of americium measured with CdTe-detector and a Gaussian fit at the 59,5keV-decay



Figure 26: Zoomed spectrum of cobalt measured with CdTe-detector and a Gaussian fit at the $122,06\,\mathrm{keV}\text{-}\mathrm{decay}$



Figure 27: Zoomed spectrum of cobalt measured with CdTe-detector and a Gaussian fit at the 136,47 keV-decay

Both peaks of the cobalt spectrum and the peak of the americium spectrum are clearly visible and can be fitted with a Gaussian. The position of the maxima of the Gaussian fits are shown in Table 5.

sample	energy [keV]	channel
Americium	59,5	$315,\!25\pm0,\!15$
Cohalt	122,06	$651,0 \pm 0,2$
Cobalt	136,47	$726,2 \pm 0,7$

Table 5: Decay energies with related channels for the CdTe-detector

By plotting the data of the Table 5 and do a linear regression one obtain the energy calibration for the CdTe-detector. This is shown in Figure 28. So one gets for the energy E the channel

$$channel = a + b \cdot E, \tag{21}$$

with $a = -3.8 \pm 0.4$ and $b = (5.362 \pm 0.004) \frac{1}{\text{eV}}$.



Figure 28: Energy calibration of the CdTe-detector (From CdTe-detector measured channels over referred energies with a linear fit)

5.2.2 Absorption probability

To be able to compare the absorption probabilities one has to consider that the surface of the detectors is not equal. So you has to scale it by its size. Then the ratio is

$$dA = \frac{Abs_{\rm Si}}{Abs_{\rm CdTe}}(E) = \frac{A_{\rm Si}/a_{\rm Si}}{A_{\rm CdTe}/a_{\rm CdTe}}(E)$$
(22)

with $a_{\rm Si} = 100 \,\mathrm{mm}^2$ and $a_{\rm CdFe} 23 \,\mathrm{mm}^2$.

One compares the maxima of the spectra. Therefore you have to read out the parameter A of the Gaussian function for each maximum and then compute the ratios.

energy [eV]	$A_{\rm Si}$	$A_{ m CdTe}$	dA
$59,9~({\rm Am})$	940 ± 40	11890 ± 120	$0,\!0181 \pm 0,\!0007$
122,06 (Co)	1574 ± 28	$(1,\!64\pm\!0,\!03)\cdot10^4$	$0,\!0080\pm0,\!0004$
136,47 (Co)	$3,0\pm0,5$	$(1,\!55\pm0,\!07)\cdot10^3$	$0,\!00045\pm0,\!00008$

Table 6: Comparison of the absorption probabilities

5.2.3 Energy resolution

The last step is to determine the relative energy resolution (RER(E)) with help of radiation peaks. One uses the width σ and the position x_c of a radiation peak. The formula is

$$\operatorname{RER}(E) = \frac{\operatorname{FWHM}(E)}{E} = \frac{2\sqrt{2\ln 2\sigma(E)}}{E} \approx \frac{2,35\sigma(E)}{E}.$$
(23)

energy [eV]	σ	$\operatorname{RER}(E)$
59,9 (Am)	$12,2 \pm 0,6$	$0,\!48\pm\!0,\!02$
122,06 (Co)	12,16	$0,233 \pm 0,012$
136,47 (Co)	12,03	$0,\!21\pm0,\!05$

Table 7: Energy resolution of silicon

energy [eV]	σ	$\operatorname{RER}(E)$
59,9 (Am)	$11,\!14\pm\!0,\!11$	$0,\!437\pm 0,\!004$
122,06 (Co)	$12,\!98 \pm 0,\!02$	$0,\!250\pm 0,\!004$
136,47 (Co)	$15{,}2\pm0{,}9$	$0,261 \pm 0,016$

 Table 8: Energy resolution of CdTe-detector

6 Discussion

6.1 Band gap energy

In this part of the experiment the band gap energy of silicon and germanium was calculated. Therefore the transmission and the absorption spectrum was analysed. The obtained results and the related literature values are summed up in Table 9. The cal-

	$E_{\rm g,trans}$ [eV]	$E_{\rm g,absorp}$ [eV]	$E_{\rm g,literature}$ [eV]
Silicon	$1,\!0941\pm\!0,\!0007$	$1,\!079\pm\!0,\!007$	$1,12^{[2]}$
Germanium	$0,\!661\pm 0,\!004$	$0,\!666\pm 0,\!008$	$0,66^{[2]}$

Table 9: Comparison of the band gap energies of silicon and germanium with the literature values.

culated band gap energies of germanium are pretty good comparatively to the literature value, which is in both cases in the 1σ -area. The errors are also small, so results are acceptable. For the part with silicon as semiconductor the values are in the right order of magnitude, but they have, with the small error, a big deviation. An explanation could be that the reset of the angle was too bad or had an underrated error. It is also possible that the silicon is contaminated. It is to make a note that this experiment is useful to get the band gap energy.

6.2 Haynes & Shockley experiment

The determined values are shown in 45

	U=const, $d=$ variable	d = const, U = variable	literature ^[2]
$\mu_{\rm n}$	$(2910\pm60)\frac{\rm cm^2}{\rm Vs}$	$(2460\pm60)\frac{\rm cm^2}{\rm Vs}$	$3900 \frac{\mathrm{cm}^2}{\mathrm{Vs}}$
$\tau_{\rm n}$	$(6,81\pm0,08)\mu{ m s}$	$(4,78\pm0,18)\mu{ m s}$	$45,2\mu s$
$D_{\rm n}$	$(101 \pm 4) \frac{\text{cm}^2}{\text{s}}$	$(74 \pm 4) \frac{\text{cm}^2}{\text{s}}$	$101 \frac{\text{cm}^2}{\text{s}}$

Table 10: Sum up of all results of the second measurement part

When you compare the both measurement methods one can say, that the fist one is more exactly. So here it is better to change the distance instead of the voltage. Out of this the mobility μ_n is computed too low. Maybe the distance of the needle and the laser was determined not correctly. In this experiment the distance between the two plastic holders was measured and to this value the the distance between needle and laser was added (cf.7.2). So it is possible that this is the error source. Also the errors were estimated too small hence the complete error is too small, too.

The half life τ_n is too low in both cases. The reason could be that there are different effects on the surface and the charge is created 0,5 µm below the surface. So lattice effects shorten the half life extremely.

The diffusion constant D_n is also determined more precisely with the first method. Here the literature value is in an one error surrounding of the measured value. For the second measurement series the value is in a seven error surrounding. Here maybe the errors were estimated too small, too.

6.2.1 Semiconductor detector

The energy calibration of the MCA for both detectors gives the linear fits channel= $a + b \cdot E$

Silicon detector:
$$a = -3,3 \pm 1,2$$
 $b = (5,124 \pm 0,013) \frac{1}{\text{eV}}$
CdTe-detector: $a = -3,8 \pm 0,4$ $b = (5,362 \pm 0,004) \frac{1}{\text{eV}}$

The second step was to calculate the absorption probabilities. The results are shown in Table 11.

energy [eV]	dA	literature
59,9 (Am)	$0,\!0181\pm0,\!0007$	0,0140
122,06 (Co)	$0,\!0080\pm0,\!0004$	0,183
136,47 (Co)	$0,\!00045\pm0,\!00008$	0,0200

Table 11: Comparison of the absorption probabilities with literature values

In the context of the experiment only three energies were measured. Therefore the parameters of the fit have an uncertainty because of an insufficient number of measurements. Nevertheless the linear regression suits to the measurement points in a good way for both detectors. The absorption probability for the 59,9 keV-decay is near to the literature value. A deviation of six standard errors is given. So one can say, that the errors are estimated too small or were not included into the calculation.

The other values have big distances to the literature value. One reason can be that the 136 keV-decay detected with silicon was read out by hand because of a weak signal a Gaussian fit was not possible. It also seems to be realistic that some errors were not heeded. For example the thickness and the cross sectional area is not equal to the manufacturer information. In addition to this the SiO₂- and the epoxidelayer over the diodes is not heeded. These substances are not heeded whereas they have absorption and transmission effect, too.

Last step was to determine the energy resolutions of the detectors. The obtained values are shown in

energy [eV]	$\operatorname{RER}(E)_{\mathrm{Si}}$	$\operatorname{RER}(E)_{\operatorname{CdTe}}$
59,9 (Am)	$0,\!48 \pm 0,\!02$	$0,\!437\pm 0,\!004$
122,06 (Co)	$0,\!233\pm0,\!012$	$0,250 \pm 0,004$
136,47 (Co)	$0,\!21\pm0,\!05$	$0,\!261\pm 0,\!016$

Table 12: Energy resolution of the CdTe-detector

7 Attachment

- 7.1 Measuring 2: Haynes & Shockley experiment
- 7.1.1 Measuring series 1



Figure 29: Measured data for a distance $d = (4,00 \pm 0,14) \text{ mm}$



Figure 30: Measured data for a distance $d = (6,10 \pm 0,14) \text{ mm}$



Figure 31: Measured data for a distance $d = (7,00 \pm 0,14) \text{ mm}$



Figure 32: Measured data for a distance $d = 7,70 \,\mathrm{mm}$



Figure 33: Measured data for a distance $d = (8,60 \pm 0,14) \text{ mm}$



Figure 34: Measured data for a distance $d = (9,70 \pm 0,14) \,\mathrm{mm}$



Figure 35: Measured data for a distance $d = (2,30 \pm 0,14) \text{ mm}$



Figure 36: Measured data for a distance $d = (2,90 \pm 0,14) \text{ mm}$





Figure 37: Measured data for a voltage $U = (44,75 \pm 0,04)$ V



Figure 38: Measured data for a voltage $U = (40,274 \pm 0,003)$ V



Figure 39: Measured data for a voltage $U = (36,48 \pm 0,03)$ V



Figure 40: Measured data for a voltage $U = (32,69 \pm 0,03)$ V



Figure 41: Measured data for a voltage $U = (28, 26 \pm 0, 03)$ V



Figure 42: Measured data for a voltage $U = (23,40 \pm 0,03)$ V



Figure 43: Measured data for a voltage $U = (19,24 \pm 0,03)$ V

7.2 Measurement notes



Figure 44: Measurement notes (1)



Figure 45: Measurement notes (2)

References

- [1] Versuchsanleitung, Fortgeschrittenen Praktikum Teil 1- Halbleiter [http://hacol13.physik.uni-freiburg.de/fp/Versuche/FP1/FP1-13-Halbleiter/Anleitung.pdf] (called on: 24.09.17)
- [2] Halbleiter und Halbleiterdetektoren- Staatsexamensarbeit- Simon Amreim [http://hacol13.physik.uni-freiburg.de/fp/Versuche/FP1/FP1-13-Halbleiter/Staatsexamensarbeit.pdf] (called on: 24.09.17)