

V15

## **Characterization of silicon strip sensors**

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# 1 Objective

The objective of this experiment is to understand the workings of a silicone strip detector and its properties. Additionally, the use of readout electronics and resulting data is supposed to further introduce the participant into their usage in different detector systems.

## 2 Theory

In order to understand a silicone strip detector it is important to look at the theory of semiconductors.

### 2.1 Semiconductors

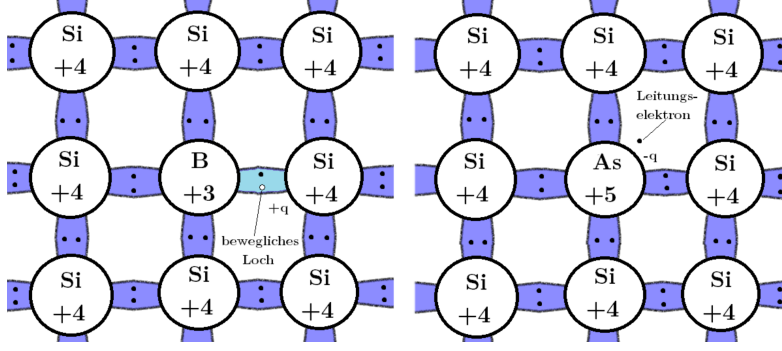
Semiconductors are defined by the energy gap of the valence and conduction band. If the bands overlap in a material it is referred to as *conductor* since the electrons can move freely in the material. If the energy gap is too great the electrons can't travel into the conduction band, therefore these materials are called *insulators*. If though the energy gap is in the range below 3 eV the material is a *semiconductor*. The semiconductor employed in this experiment is silicone with a band gap of 1,107 eV [1]. Silicone has four valence electrons and arranges itself in a diamond lattice structure. One of the properties of a semiconductor is, if the valence electrons are excited e.g. thermal effects or other external particles, it creates a hole in the valence band, which can be treated as a quasi particle with a negative charge. The electron and hole can form a bound state resembling an atom, if the material is placed into an electric field (e.g. by placing a cathode/anode to the material) the formation of such a state is prevented. The electrons and holes can now travel to the cathode/anode. This behavior can be modified by a process called *doping*, in which some of the silicone particles in the crystalline structure are replaced by elements that carry a higher/lower amount of valence electrons.

#### 2.1.1 n-type semiconductor

If the element used for doping has a valence charge higher than four (e.g. Arsenic: five valence electrons), one electron is not used for the binding in the crystalline structure so it can move almost freely in the material.

#### 2.1.2 p-type semiconductor

Analog to the n-type semiconductor the introduced material has fewer electrons in its valence band (Boron: three valence electrons). The boron would then leave one of the bonds to the it surrounding silicone atoms partially empty creating a hole, which then can move freely like the electron.



**Figure 1:** Graphical representation of boron and arsenic doping in silicone[1].

### 2.1.3 pn transition

If one connects a p and n doped material together so called a diode is created. Inside the diode the additional electrons from the n-side now want to recombine with the holes from the p-side. This results in a positive charge on the n-side and a negative on the p-side. The resulting difference of a few mV is called diffusion voltage  $U_D$  [1].

For the detection of ionizing particles a voltage is applied to either side of the diode, the electrons coming from the applied potential are then recombining with the holes on the p-side and the electron in the n-side flow into the anode, resulting in a zone in which no free charge carriers remain. This zone is called the *depletion zone* and its dimension can be determined to be

$$d(U) = \sqrt{\frac{2\epsilon(U_D + U)}{eN_{\text{eff}}}}, \quad (1)$$

where  $U$  is the voltage applied to the diode,  $\epsilon$  the dielectric constant of silicone,  $e$  the elementary charge and  $N_{\text{eff}}$  the effective charge carrier density.  $N_{\text{eff}}$  is determined by

$$N_{\text{eff}} = \frac{N_D N_A}{N_D + N_A},$$

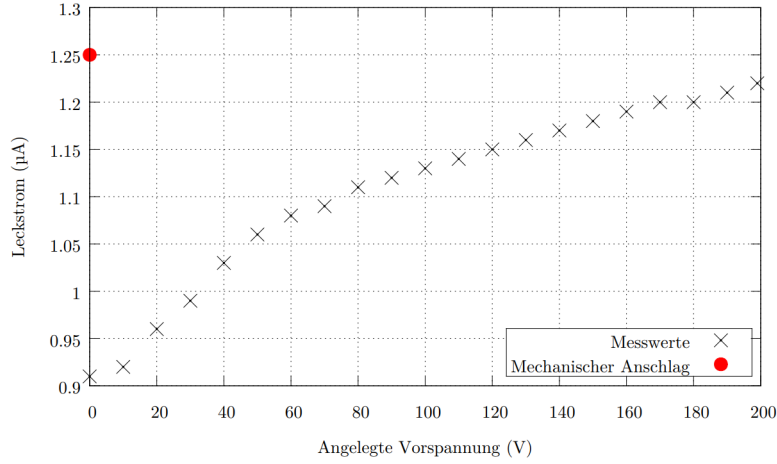
where  $N_D, N_A$  are the respective densities of the n and p doped materials. When the depletion zone is as large as the diode itself, one speaks of a full depletion at the depletion voltage  $U_{\text{dep}}$ . Using the fact that  $U \ll U_D$  it can be determined that  $U_{\text{dep}}$  is given by

$$U_{\text{dep}} \approx \frac{e}{2\epsilon} N_{\text{eff}} D^2$$

with the thickness of the diode  $D$ . If the applied voltage is below the depletion voltage then the distance  $d_c(U)$  can be approximated with

$$d_c(U) = D \sqrt{\frac{U}{U_{\text{depl}}}}.$$

Ideally, the diode is fully depleted so the signal generated by an ionizing particle can be detected. This is not the case since thermal effects an electron can enter the current band and create the so called *leakage current*. This effect increases with higher voltages. The relation between the current and voltage can be seen in Figure 2.



**Figure 2:** Current measured across the sensor in relation to the applied voltage [1].

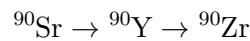
Using this plot the depletion voltage can be determined as the voltage at which the leakage current only increases linearly.

## 2.2 Ionizing radiation

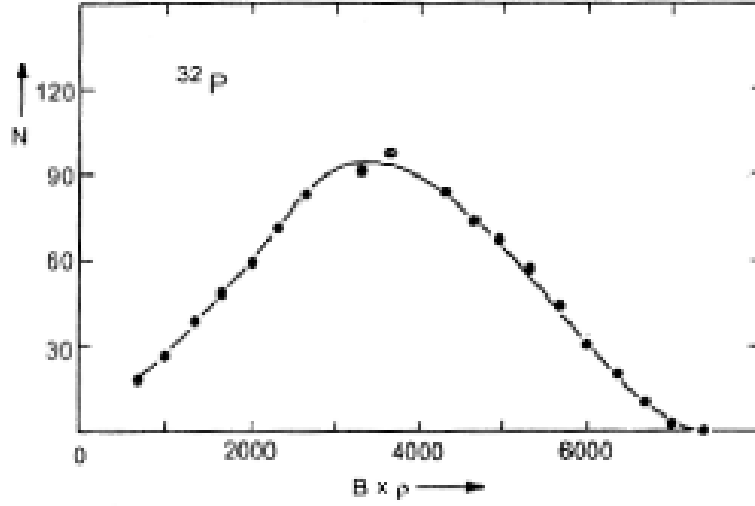
The silicone strip detector can be used to detect ionizing particles. During the experiment a source producing beta particles is employed.

### 2.2.1 Beta decay

The used source is the strontium isotope  $^{90}\text{Sr}$ , which decays via a  $\beta^-$  decay into yttrium (maximal energy 0,545 MeV), that intern decays into zirconium (maximal energy 2,28 MeV) [1].



During a  $\beta^-$  decay a neutron in the atomic nucleus decays into a proton, electron and an anti-electron-neutrino. Since this process is a three body decay the electron is not produced at a fixed energy. The energy of the emitted electron follows the distribution shown in Figure 3



**Figure 3:** Energy distribution of a electron originating from ab  $\beta^-$  decay [1].

The activity is defined as the rate of change of the number of nuclei  $A = -\dot{N}$ . From this it can be deduced that the activity can be written as

$$A = \lambda N_0 \exp(-\lambda t) = A_0 \exp(-\lambda t),$$

where  $A_0$  and  $N_0$  are the activity and number of nuclei at  $t = 0$ , and  $\lambda$  is the decay constant of the decaying material/particle.

### 2.2.2 Interaction in matter

Due to the energy of the electrons almost only their collisions with the nuclei in the matter it is traversing are contributing to the energy loss. The ionizing particles inside the detector are detected by these collision, as they excite the electrons in the crystalline structure of the detector material. These excited electron then create a measurable signature in the detector. The energy deposited by the electrons can be determined using the Bethe-Bloch equation with additional correction terms:

$$-\frac{dE}{dx} = 2\pi N_a m_e c \rho \frac{Z}{A} \frac{1}{\beta^2} \left[ \ln \left( \frac{\tau(\tau+2)}{2(I/m_e c^2)^2} \right) + F(\tau) - \delta - 2\frac{C}{Z} \right],$$

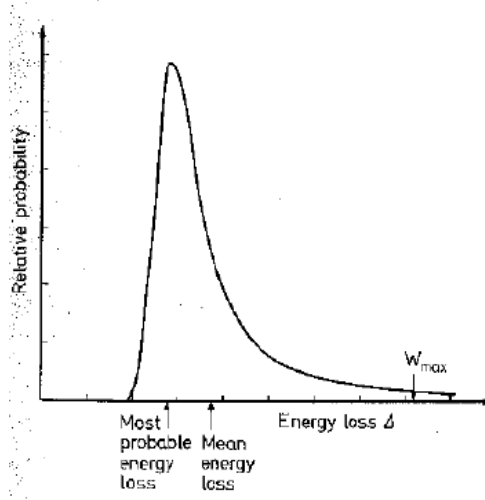
with

$$F(\tau) = 1 - \beta^2 + \frac{\frac{\tau}{8} + (2r_e + 1) \ln(2)}{(\tau + 1)^2}, \quad \text{where } \tau = \gamma - 1.$$

The meaning of the symbols and their values can be seen in [1]. From this formula it can be determined that the electron originating from the  $^{90}\text{Sr}$  source is depositing 3,88 MeV per cm [1].

Usually for particles traversing a silicone detector the deposited energy can be approximated by a Gaussian distribution. As for a thinner detector (e.g. like the 300  $\mu\text{m}$  of the

detector used in this experiment) the thickness is not sufficient enough for the energy loss to be described as Gaussian. The actual distribution is much better described by a Landau distribution. Another effect at play stems from the already described energy distribution of the emitted electron. This results in a convoluted Landau distribution shown in Figure 4.



**Figure 4:** Convoluted Landau distribution [1].

### 2.3 Noise and pedestals

As most electronics and detectors can't operate a hundred percent clean, there will always remain noise, signals that interfere with the intended measurement. So the recorded counts from the Analog-Digital-Converter (ADC) can be described by

$$\text{ADC}(i, k) = P(i) + D(k) + \text{Signal}(i, k),$$

ADC is the probability for a signal  $k$  at the  $i$ -th strip on the detector.  $P(i)$  is the so called *pedestal*. It is determined as the mean value of the  $\text{ADC}(i, k)$  without  $\text{Signal}(i, k)$ . So  $P(i)$  calculated for  $N$  measurements as

$$P(i) = \frac{1}{N} \sum_{k=1}^N \text{ADC}(i, k). \quad (2)$$

The  $D(k)$  contribution is the *common mode shift* and is calculated using

$$D(k) = \frac{1}{128} \sum_{i=1}^{128} (\text{ADC}(i, k) - P(i)) \quad (3)$$

From these distributions using the root mean square the noise is determined:

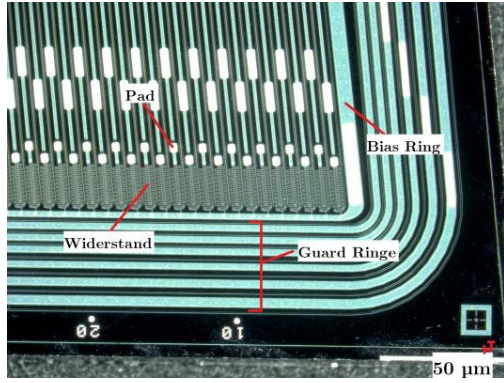
$$\text{Noise}(i) = \sqrt{\frac{1}{N-1} \sum_{k=1}^N (\text{ADC}(i, k) - P(i) - D(k))^2} \quad (4)$$

### 3 Experimental setup

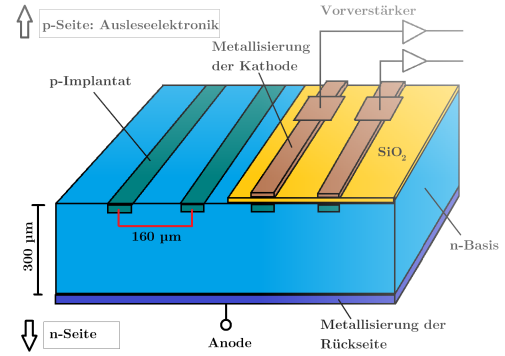
The experimental setup consists of a control unit, the detector unit and a computer with an application for the visualization and data taking. The control unit is connected to the detector unit using a ribbon cable and to the computer via a USB connection. Located on the control and detector unit is a glass fiber connection that is used to point a laser from the control unit onto the detector. Additionally, a strontium-90 source is provided and proper shielding for its application.

#### 3.1 Detector unit

The detector unit mainly consists of the silicon strip detector with 128 strips and a BEETLE readout chip. The silicon strip detector consists of a n doped silicone base with inlayed p doted silicone strips. The strips are then isolated by a  $\text{SiO}_2$  layer to which the readout electronics are connected. The thickness of the silicone strip sensor is 300  $\mu\text{m}$ . A schematic diagram of the sensor is shown in Figure 5b and a macroscopic picture is given in Figure 5a [1].



(a) Macroscopic picture of the silicone strip sensor [1].



(b) Schematic diagram of the silicone strip sensor[1].

In the case of a not fully depleted sensor some of the electrons and holes generated by the ionizing particles are recombined outside of the depletion zone. The charge collection efficiency (CCE) describing this process when applying a laser is given by

$$\text{CCE}(U) = \frac{1 - \exp\left(\frac{-d_c(U)}{a}\right)}{1 - \exp\left(\frac{-D}{a}\right)}, \quad (5)$$

where  $a$  is the penetration depth of the laser.

#### 3.2 Laser

The Laser employed in this experiment is fed into the detector unit using an optic fiber cable and it has a wavelength of 980 nm, a diameter of 20  $\mu\text{m}$ , a pulse length of 5 ns and



a peak power of 0,2 mW. The position and the focusing of the laser can be adjusted using two micrometer screws.

### 3.3 Control unit

The control unit houses the laser and is used to regulate the voltage applied to the silicone sensor. It can also measure the leakage current of the sensor. The data acquired by the control unit is transferred to the computer and can be collected there using the Alibava system.

## 4 Experimental procedures

Before starting the experiment it is advised to familiarize yourself with the experimental setup and the software. In the initial measurement, the current passing through the sensor is recorded at intervals of 10 V for the applied voltages. This is performed until a voltage 20 V above the expected depletion voltage is reached.

The first measurement using the software is performed in a *pedestal run* of 1 000 events, in order to determine the pedestal and noise.

Before using the laser or the radioactive source a set of calibration measurement is started. The first calibration is used to determine the optimal delay. It is started using the *Delay measurement* button in the Alibava software. After this run 5 different channels are used in a *Calibration run*, with the applied voltage above the depletion voltage. Another run is started afterwards with the applied voltage turned down to 0 V.

After the calibration measurement the laser is lead into the detector unit using the optic fiber cable. It is then focused and moved along the sensor until a maximally high peak is achieved in the Alibava software. Initially the optimal delay between the laser signal and the chip readout is determined using the *laser sync.* function. Then the structure of the sensor is probed by recording 1 000 events at 35 10  $\mu\text{m}$  intervals. During the next measurements the CCE is determined by recording 1 000 events from 0 to 200 V in 10 V steps.

A similar approach is used when measuring the radioactive source, with the difference of recording 10 000 events per scan.

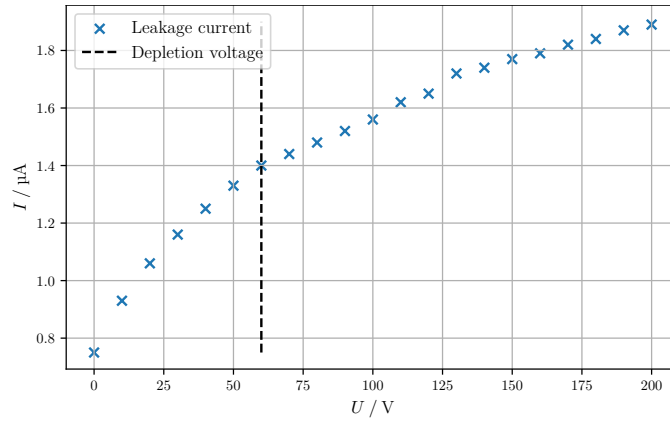
Finally a last scan using the radioactive source is performed and 1 000 000 events are recorded.

## 5 Analysis

As a first step all of the aquired *.h5* data is converted into *.txt* files with the help of the provided *execute.py* script.

### 5.1 Depletion voltage

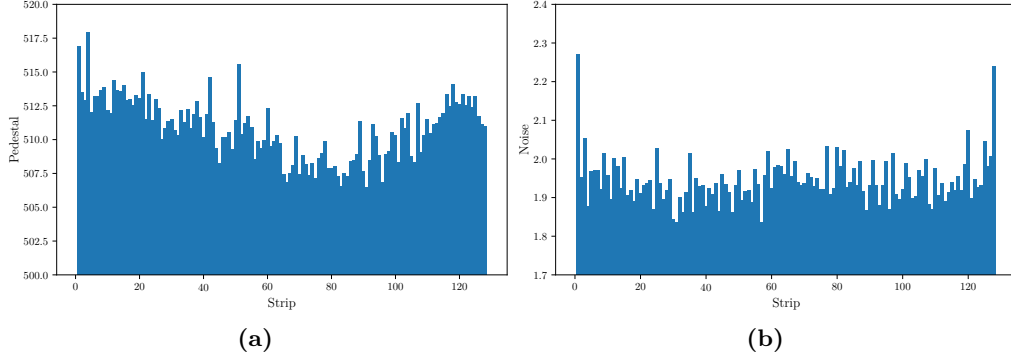
The first part of the analysis is the measurement of the current-voltage characteristic of the silicon strip sensor. In Figure 6, the measured leakage current is displayed with the corresponding applied bias voltage. A flattening of the curve at 60 V is clearly visible, this corresponds exactly to the depletion voltage  $U_{\text{dep}} = 60 \text{ V}$  of the chip stated by the manufacturer. For the following measurements, the bias voltage is set to 80 V to ensure the chip is always fully depleted.



**Figure 6:** Plot of the measured current-voltage characteristic.

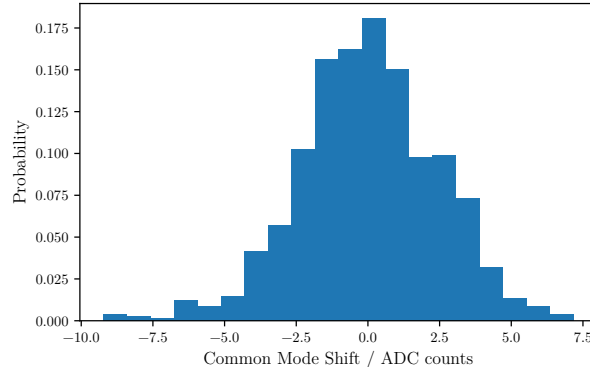
### 5.2 Pedestal run

Next, the pedestal run is evaluated to determine the noise of the strips. The pedestal for each strip is calculated by taking the mean value of the ADC counts of all events for each individual strip, as given by (2). The common mode shift for each event is then acquired by subtracting the pedestal from the ADC counts of each strip and again taking the mean value according to (3). At last, the noise is determined using the previous results by plugging them into (4). A bar diagram of the pedestals and noise is shown in Figure 7.



**Figure 7:** Bar diagrams of the pedestals (a) and noise (b) of the 128 individual strips.

The diagrams show a visible increase of the pedestals and noise towards the edges of the chip, this might have something to with the structure of the chip or the way the signal is read out. A histogram of the common mode shift is displayed in Figure 8.

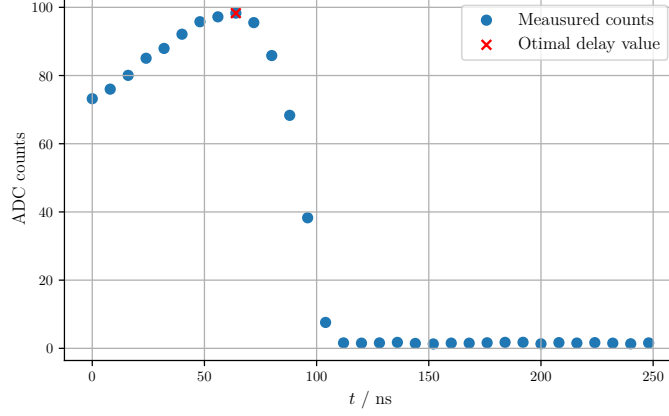


**Figure 8:** Common mode shift measured during the pedestal run.

As expected, the common mode shift also referred to as *common noise* follows a gaussian distribution around 0.

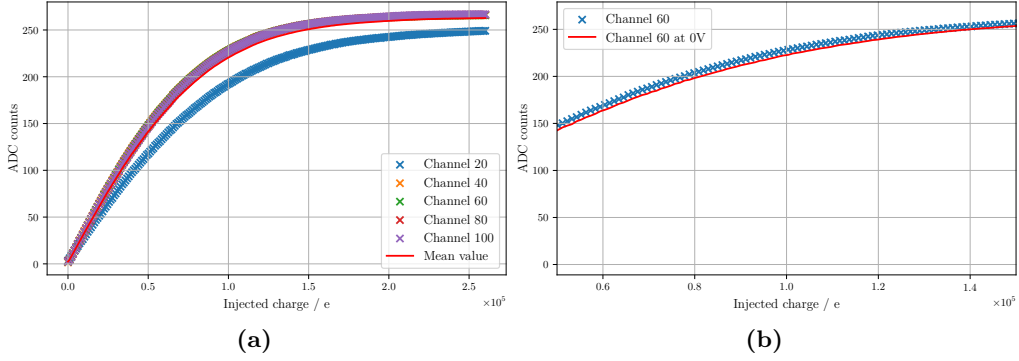
### 5.3 Calibration measurements

Next, the data acquired from the calibration run is analysed. The results from the delay measurement are shown in Figure 9.



**Figure 9:** Results from the delay measurement.

Figure 9 shows the ADC counts depending on the delay of the laser. The highest counts were achieved at 64 ns, which is why this value was set as the laser delay for the rest of the experiment. After this, a calibration curve is measured for five different channels. This curve gives the relation between the injected charge and the ADC counts. The five curves are given in Figure 10a. Additionally for channel 60, a curve at 0 V is recorded, it can be seen in Figure 10b, where it is compared to the regular curve of channel 60.

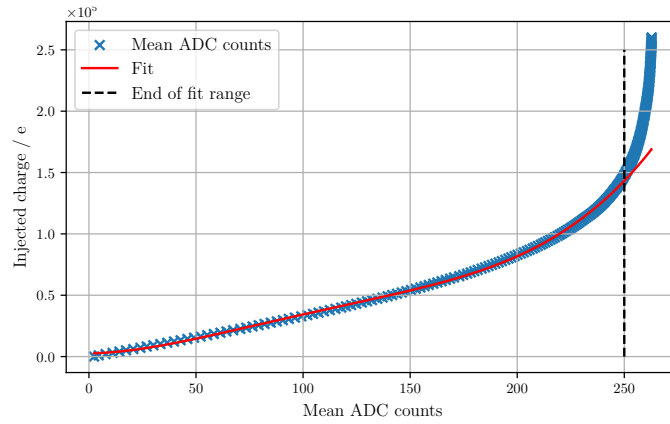


**Figure 10:** Calibration curve of five channels (a) and detailed view of channel 60 at 0 V (b).

As seen in Figure 10a, all channels show almost exactly the same calibration curve. For some unknown reason, channel 20 measured significantly less ADC counts. For the next step, the mean value of the five channels is taken. The calibration curve at 0 V is very similar to the one measured above the depletion voltage. This leads to the conclusion that the relation between the ADC counts and the injected charge does not depend on the applied bias voltage. To further quantify this dependency of the counts and the injected charge, a 4-th degree polynomial is fit to the mean counts of the five channels. The polynomial is of the form

$$Q(\text{ADC}) = a \cdot \text{ADC}^4 + b \cdot \text{ADC}^3 + c \cdot \text{ADC}^2 + d \cdot \text{ADC} + e. \quad (6)$$

The fit is performed using the *curvefit* method from the *scipy* [2] package. The result is shown in Figure 11, the fit range is restricted to the range below 250 ADC counts to get a good result.



**Figure 11:** Fit of 4-th degree polynomial to the mean ADC counts of the calibration run.

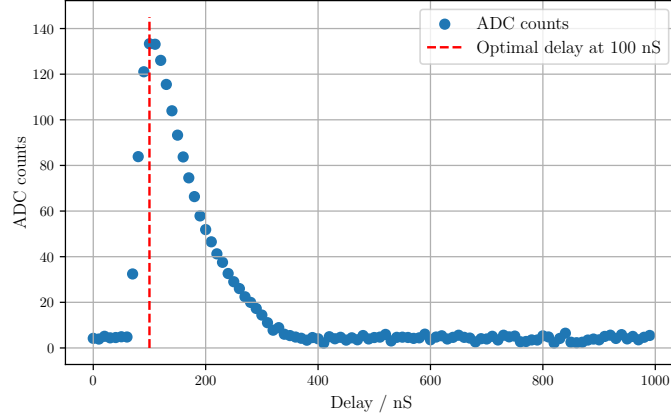
The fit yields the following coefficients for (6)

$$\begin{aligned}
 a &= (0,000\,111 \pm 0,000\,006) \text{ e} \\
 b &= (-0,0439 \pm 0,0032) \text{ e} \\
 c &= (6,2 \pm 0,6) \text{ e} \\
 d &= (30 \pm 40) \text{ e} \\
 e &= (2600 \pm 700) \text{ e} .
 \end{aligned}$$

These coefficients together with (6) now allow any ADC counts to be converted into an electric charge.

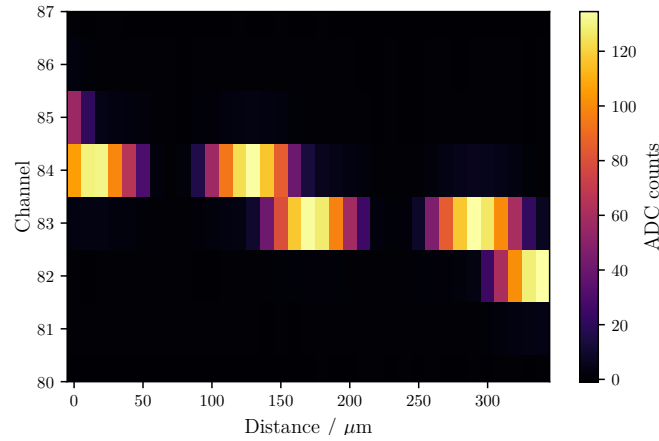
## 5.4 Measuring the strip sensor by using the laser

The physical structure of the sensor and its strips is determined by using the laser. Before the measurement can be started, the optimal delay between laser signal and chip readout is determined by plotting the data from the *Laser Sync* run. This is shown in Figure 12, where it is clearly visible that the maximum ADC counts are achieved at a delay of 100 ns.



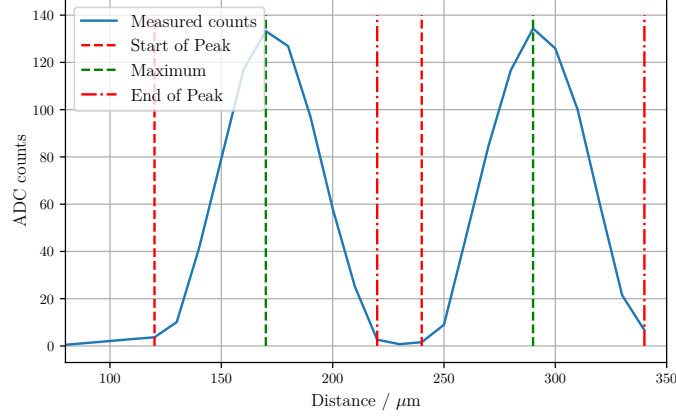
**Figure 12:** Results of the *Laser Sync* run.

After moving the laser across the  $35\mu\text{m}$  interval, a heatmap is produced showing the signal of the relevant channels that were hit by the laser. Figure 13 shows the affected channels 82-85 and their signal strength depending on the laser position.



**Figure 13:** Heatmap of the signal strength of the affected channels depending on the laser position.

In the following, the individual signal for channel 83 is analysed in Figure 14. The position of the beginning, peak and end of the signal is also shown.



**Figure 14:** Signal strength of channel 83 depending on the laser position.

The width of the strip is simply the distance between the two peaks, as this is the position where the laser is on the channel but reflected by the metal of the strip. The extension of the laser can be estimated by the distance between the start of a peak and its maximum. All relevant positions are marked in Figure 14 and the resulting values are:

$$\text{width of strips} = 290 \mu\text{m} - 170 \mu\text{m} = 120 \mu\text{m}$$

$$\text{laser extension} = 170 \mu\text{m} - 120 \mu\text{m} = 50 \mu\text{m} .$$

The distance of two strips can be determined by comparing the position of the maxima of two different channels in Figure 13:

$$\text{distance} = 40 \mu\text{m} .$$

The pitch is then calculated as the sum of the distance between the strips and their width:

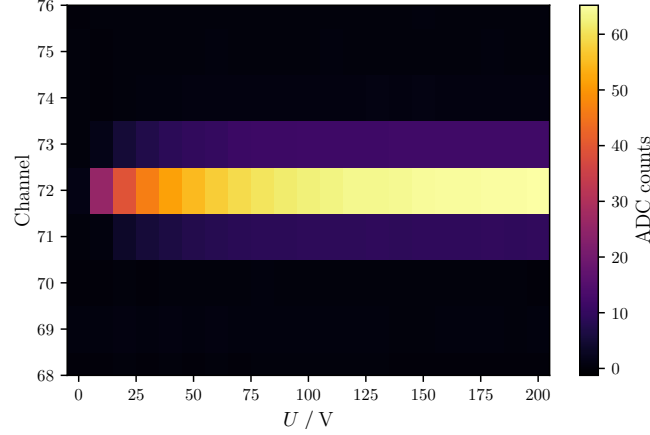
$$\text{pitch} = 120 \mu\text{m} + 40 \mu\text{m} = 160 \mu\text{m} .$$

## 5.5 Determination of the charge collection efficiency

The charge collection efficiency of the laser is determined by measuring the relation between the collected charge (ADC counts) and the applied bias voltage.

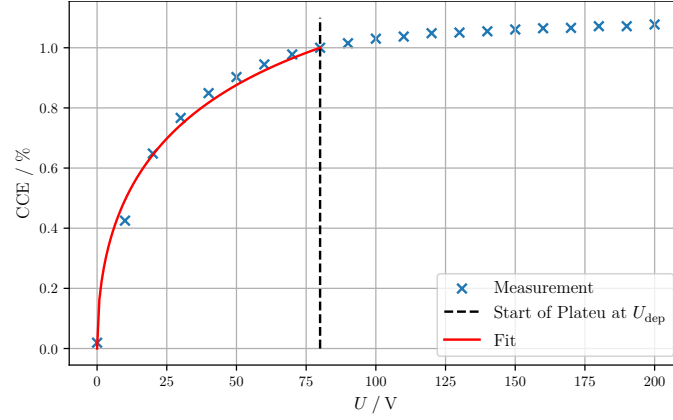
### 5.5.1 Using the laser

When using the laser, at first the channel on which the laser is focused during the measurement is to be determined. By plotting a heatmap of the ADC counts for each channel, Figure 15 clearly shows that the laser was focused on channel 73.



**Figure 15:** Heatmap showing the ADC counts of each channel and bias voltage.

Thus in the following, only the data from channel 73 is considered. In order to get the charge collection efficiency, the measured ADC counts have to be normalized in regard to the maximum ADC counts of the plateau. In theory, the plateau should show constant counts after the depletion voltage  $U_{\text{dep}}$  is reached, however the actual data shows a slight increase in this area. This is why the counts are normalized in regard to the first value of the plateau, so that a proper fit of (5) can be performed. The normalized counts in dependence of the bias voltage are shown in Figure 16.



**Figure 16:** Charge collection efficiency of channel 73.

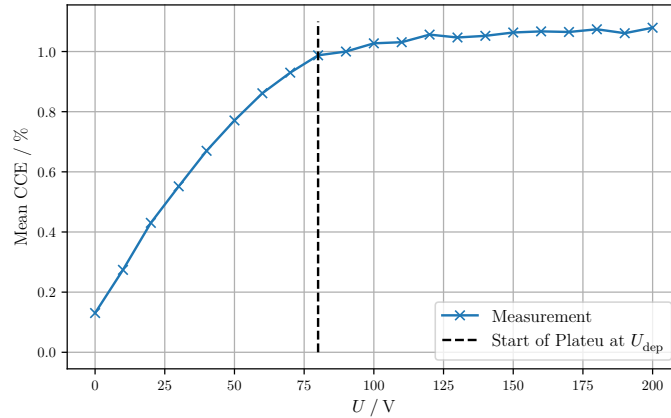
The fit was performed in the range  $0 \text{ V} < U < 80 \text{ V}$ . The depletion voltage of  $U_{\text{dep}} = 80 \text{ V}$  is a fixed parameter in (5), whereas the value of the penetration depth  $a$  of the laser is determined via the fit as

$$a = (253 \pm 6) \mu\text{m}.$$



### 5.5.2 Using the beta source

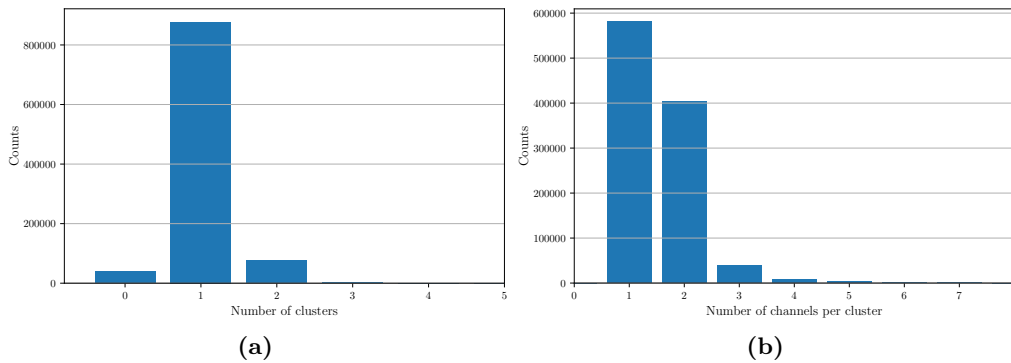
The same curve is now measured by replacing the laser as a source with a  $\beta^-$  source. The ADC counts are now determined in clusters. To get the charge collection efficiency, the entries in each cluster are summed, after this the mean value of all clusters is taken. A normalization is performed analogously to the one of laser measurement. The resulting curve is displayed in Figure 17.



**Figure 17:** Charge collection efficiency determined via the  $\beta^-$  source.

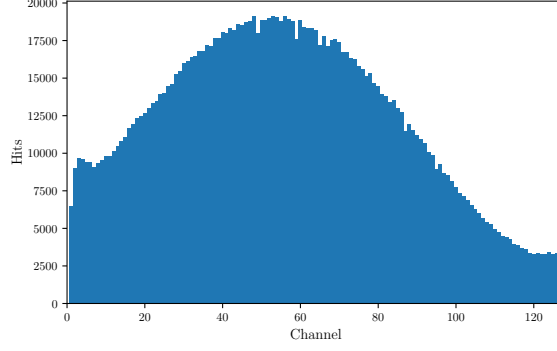
### 5.6 Large source scan

Finally, the large source scan containing roughly one million events is analysed. Figure 18 shows how the number of cluster per event is distributed as well as how many channels exist per cluster.



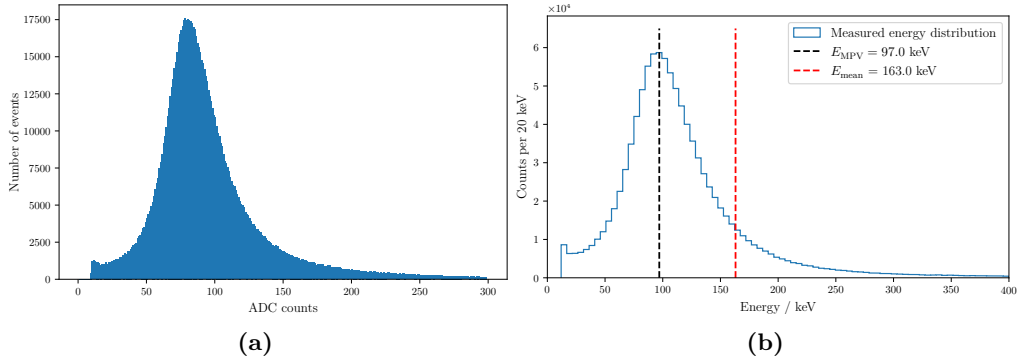
**Figure 18:** Number of clusters per event (a) and number of channels per cluster (b).

Next, a hitmap is produced for all channels. This is displayed in Figure 19 and shows how many events/hits were registered by each individual channel. An events mostly leads to the formation of one cluster, and each cluster usually contains the signal of one to three channels.



**Figure 19:** Hitmap displaying the events of each channel.

Most of the hits are registered in the middle of the chip, while the edges clearly show a lower amount of entries. Lastly, the distribution of the measured ADC counts as well as the energy spectrum is computed. To acquire the energy spectrum from the ADC counts, the counts are converted into an electric pulse with the conversion formula (6) determined during the calibration run. The pulse is then converted into an energy by using the fact that the energy needed to generate an electron-hole pair is approximately 3,6 eV [1]. Figure 20 shows both distributions.



**Figure 20:** Distribution of the ADC counts (a) and the energy (b).

The distribution of the energy spectrum allows to determine the most probable energy and mean energy of the  $\beta^-$  source as

$$E_{\text{MPV}} = 97 \text{ keV}$$

$$E_{\text{Mean}} = 163 \text{ keV}.$$

## 6 Discussion

### 6.1 Depletion voltage

In the first part, the depletion voltage is determined to be 60 V. Later, the depletion voltage is again measured by using the charge collection efficiency. In this case, a value

of 80 V is obtained. The manufacturer [1] states a depletion voltage in the range of 60 to 80 V, so both measurements are acceptable. Both values are only estimations, as they are obtained by roughly determining the point where a curve flattens into a plateau. Therefore it is not unexpected that they don't fully agree.

## 6.2 Measuring the strip sensors

The pitch of the strip sensors has been calculated from their measured width and distance to be 160  $\mu\text{m}$ . This is the exact value given by the manufacturer [1], the high precision could be achieved through the 10  $\mu\text{m}$  resolution chosen for the scan. The laser's extension was measured at 50  $\mu\text{m}$  and is thus significantly larger than the stated [1] 20  $\mu\text{m}$ . This indicates that the laser probably was not fully focused during the measurement, which is to be expected as it proved difficult to find an absolute maxima when adjusting the horizontal micrometer screw.

The charge collection efficiency curve shows a behaviour close to the theoretical one, with the exception that the plateau slightly increases for voltages above the depletion voltage. This might be a consequence of noise that increases with the bias voltage and is not fully removed from the data.

The value for the penetration depth  $a = (253 \pm 6) \mu\text{m}$  seems consistent with the sensor thickness of  $D = 300 \mu\text{m}$  and the given penetration depths of lasers with slightly different wavelengths in [1].

## 6.3 Energy spectrum

During the large source scan, the calculated energy spectrum resembles the expected convolution of a Landau and Gauss distribution [1], where the most probable energy is lower than the mean energy. Using the modified Bethe-Bloch equation, it can be calculated that the average energy disposition of an ionising electron of the maximum energy of the primary decay of  $^{90}\text{Sr}$  in pure silicon is 3,88 MeV/cm. Multiplying this by the sensor thickness  $D$ , the theoretically expected mean energy loss becomes  $\bar{E}_{\text{theo}} = 116,4 \text{ keV}$ . This can be compared this to the measured mean energy loss

$$\begin{aligned}\bar{E}_{\text{theo}} &= 116,4 \text{ keV} \\ \bar{E}_{\text{exp}} &= 163 \text{ keV} .\end{aligned}$$

A deviation of 28,6 % is observed, which is quite large. A possible reason might be an underestimation of the noise in the sensor, also the modified Bethe-Bloch equation is only an approximation with limited precision.

## References

- [1] *V15-Characterization of silicon strip sensors*. TU Dortmund, Department of physics.
- [2] Pauli Virtanen et al. "SciPy 1.0: Fundamental Algorithms for Scientific Computing in Python". In: *Nature Methods* 17 (2020), pp. 261–272. DOI: 10.1038/s41592-019-0686-2.