Chapter 7

Results with prototype sensors for the upgrade

As part of the VELO upgrade a testbeam programme has been carried out to compare the performance of the sensors before and after irradiation. A number of prototype sensors from Hamamatsu and Micron have been examined as DuTs (Devices under Test) in the Timepix3 telescope. Different measurements, depending on the DuT configuration with respect to the beam, were performed on the irradiated and non-irradiated sensors. With the sensors being placed perpendicular with respect to the beam, measurements on the charge collection efficiency and diffusion were performed. In addition, measurements of the collected charge versus depletion depth profile, time to threshold versus depletion depth profile and of various radiation induced effects (like charge trapping and the effective doping concentration) were performed with the sensors rotated by large (grazing) angles with respect to the beam.

7.1 Assemblies tested

Each assembly consists of a Timepix3 ASIC bump-bonded to either a Hamamatsu or a Micron sensor. The sensors from Hamamatsu are produced from one single wafer, are 200 µm thick n-on-p type and feature 35 or 39 µm implant widths that are isolated using the p-stop technique described in Section 4.4.2. The sensors from Micron come from two different wafers. The sensors from the 200 µm thick wafer are n-on-p type while the ones from the 150 µm thick wafer are n-on-n type. All Micron sensors feature 36 µm wide implants isolated using the p-spray technique. The non-irradiated assemblies tested are presented in Table 7.1.

A subset of the assemblies were irradiated with neutrons at the JSI institute in Ljubljana [87] up to fluences of $8 \times 10^{15}$ 1 MeV $n_{eq}$/cm$^2$. This fluence corresponds to the expected NIEL$^1$ fluence that the sensors will have been

---

$^1$The NIEL is defined in Section 4.1.3.
CHAPTER 7 RESULTS WITH PROTOTYPE SENSORS FOR THE UPGRADE

Table 7.1: Non-irradiated sensors tested.

<table>
<thead>
<tr>
<th>Assembly ID</th>
<th>Thickness [µm]</th>
<th>Sensor Type</th>
<th>Vendor</th>
<th>Implant width [µm]</th>
<th>Full depletion [Volts]</th>
<th>Doping level [cm⁻³]</th>
</tr>
</thead>
<tbody>
<tr>
<td>S6</td>
<td>200</td>
<td>n-on-p</td>
<td>Hamamatsu</td>
<td>39</td>
<td>140</td>
<td>4.5×10¹²</td>
</tr>
<tr>
<td>S20</td>
<td>200</td>
<td>n-on-p</td>
<td>Hamamatsu</td>
<td>35</td>
<td>140</td>
<td>4.5×10¹²</td>
</tr>
<tr>
<td>S23</td>
<td>200</td>
<td>n-on-p</td>
<td>Micron</td>
<td>36</td>
<td>&lt;40</td>
<td>&lt;1.2×10¹²</td>
</tr>
<tr>
<td>S33</td>
<td>150</td>
<td>n-on-n</td>
<td>Micron</td>
<td>36</td>
<td>&lt;25</td>
<td>&lt;1.4×10¹²</td>
</tr>
</tbody>
</table>

Table 7.2: Irradiated sensors tested.

<table>
<thead>
<tr>
<th>Assembly ID</th>
<th>Thickness [µm]</th>
<th>Sensor Type</th>
<th>Vendor</th>
<th>Implant width [µm]</th>
<th>Fluence 1 MeV nₑq/cm²</th>
</tr>
</thead>
<tbody>
<tr>
<td>S15</td>
<td>200</td>
<td>n-on-p</td>
<td>Hamamatsu</td>
<td>35</td>
<td>4×10¹⁵</td>
</tr>
<tr>
<td>S17</td>
<td>200</td>
<td>n-on-p</td>
<td>Hamamatsu</td>
<td>39</td>
<td>8×10¹⁵</td>
</tr>
<tr>
<td>S22</td>
<td>200</td>
<td>n-on-p</td>
<td>Hamamatsu</td>
<td>35</td>
<td>8×10¹⁵</td>
</tr>
<tr>
<td>S27</td>
<td>150</td>
<td>n-on-n</td>
<td>Micron</td>
<td>36</td>
<td>8×10¹⁵</td>
</tr>
</tbody>
</table>

exposed to at the end of LHC Run 3. The irradiated sensors that were tested are presented in Table 7.2.

7.2 Equalisation & Calibration

The threshold settings for all pixels of an assembly need to be adjusted in order to achieve an equal threshold. This process is known as equalisation. If the threshold level of a pixel cannot be adjusted to the same level as the rest of the pixels then that pixel is deactivated. The number of deactivated pixels for the devices in Tables 7.1 and 7.2 are in the range of 300–500 corresponding to < 1 % of the total number of pixels.

The amount of charge collected by a pixel is measured in ToT counts. To convert the ToT counts to charge, a calibration function is used that is obtained from test pulses as described in Section 4.3.4. Subsequently the measured charge is converted to electron units thus the detectors are calibrated. The most probable electron/hole pair generation in a 200 µm thick sensor is about 15,000 e⁻, which (for a Timepix3 ASIC) corresponds to about 200 ToT counts².

²The number of ToT counts depends on the time the preamplifier needs to fully discharge the integrated signal, which is adjusted by the Ikrum setting.
The charge distribution of the collected charge is fitted with a Langaus
and the most probable value (MPV) errors from the fit are $<10$ e$^-$. In a
perfectly calibrated, non-irradiated detector and assuming a uniform thickness
and depletion width throughout the sensor, the Landau MPVs of all pixels
should be equal. In reality the MPVs of all pixels differ. Assuming that the
thickness is uniform, the calibration error is defined as the standard deviation
of the MPVs per pixel. The calibration error, which is about 100 e$^-$, is the
main contributor to the error on the amount of charge collected. The individual
error bars are not shown in figures showing charge distributions.

7.3 Leakage current

The leakage current as a function of bias voltage was measured for each as-
sembly of Tables 7.1 and 7.2. Operating a sensor at bias voltages beyond the
the breakdown voltage leads to high currents as shown in Figure 4.5. These
currents are a signature of the avalanche breakdown that may destroy the sen-
so. The leakage current as a function of the bias voltage for a 200 µm thick
sensor from Hamamatsu (S22) before and after irradiation is plotted in Fig-
ure 7.1(a). The measurements before irradiation were taken with the sensor
kept at a temperature of 15°C while after irradiation the sensor was at -24°C.
Before irradiation the breakdown voltage of the sensor is about 800 V while
after irradiation the sensor reaches breakdown at voltages in excess of 900 V.

According to Eq. (4.12) the leakage current depends on temperature. Op-
erating the sensor at low temperatures is required in order to avoid thermal
runaway. The leakage current of the irradiated sensor was measured with
the sensor cooled with a Peltier cooling module at -24°C and with dry air
at +17°C (Figure 7.1(b)). If the sensor is operated at +17°C breakdown oc-
curs at about 800 V while when the sensor is kept at -24°C the breakdown
shifts to a higher bias voltage.

7.4 Testbeam data

The data presented in the rest of the chapter are acquired by placing the pro-
tototype assemblies as DuTs in the Timepix3 telescope described in Chapter 5.
The telescope was placed in a beam of 180 GeV protons and pions at SPS.
The duration of a typical Run is one or two SPS spills corresponding to about
10$^6$ particles per spill.

A number of selection criteria are applied to the data (see Section 5.2.2). The
cluster on the DuT closest in time to a track, but within a time window of
50 ns, is associated to the track. Tracks traversing the detector at the edges of
CHAPTER 7 RESULTS WITH PROTOTYPE SENSORS FOR THE UPGRADE

(a) Leakage current before and after irradiation.

(b) Leakage current after irradiation at two different temperatures.

Figure 7.1: Leakage current plot of a Hamamatsu sensor (S22): (a) before and after being irradiated to $8 \times 10^{15}$ 1 MeV $n_{eq}/\text{cm}^2$ and (b) operated at two different temperatures after irradiation.
the sensor (3 first and last rows and columns) and tracks close to deactivated or dead pixels are excluded from the measurements since part of the charge liberated may not have been collected. In general, around 600,000 tracks per Run qualify for further study.

All sensors were operated at negative bias voltages. However, the voltage values in all plots are positive to ease the interpretation of the magnitude of the bias voltages applied.

In Sections 7.5 and 7.6 measurements of the charge collection efficiency and charge diffusion of the non-irradiated and irradiated assemblies are presented, respectively. In both measurements the DuTs are placed perpendicular to the beam.

### 7.5 Charge collection efficiency

If the sensor is partially or fully depleted and assuming there are no inactive areas close to the electrodes, the energy deposited in each pixel’s volume follows a Langaus distribution. The charge collection efficiency is shown by plotting the Landau MPV component as a function of the bias voltage. The charge collection efficiency for the non-irradiated devices is illustrated in Figure 7.2.

![Charge collection efficiency](image)

**Figure 7.2:** Charge collection efficiency for the non-irradiated devices.

The charge collected from the depleted region of the Hamamatsu sensors (blue and black lines with triangles) increases with bias voltage until a plateau is reached at about 140 V. The beginning of the plateau region marks the full depletion voltage. In case of the Micron sensors (red and green lines with squares and circles) the charge collection efficiency has a different pattern. The amount of charge collected is constant as a function of the applied bias voltage...
indicating that the full depletion voltage is already reached below a few tens of Volts.

The difference in charge collection efficiency between two assemblies irradiated to different fluences can be seen in Figure 7.3. Two Hamamatsu sensors, S15 and S22, were irradiated to 4 and $8 \times 10^{15}$ $1$ MeV $n_{eq}/cm^2$, respectively. The amount of charge collected increases linearly as a function of the applied bias voltage. At the maximum voltage, the amount of charge collected is less than half of the charge collected when the sensor is non-irradiated, as can be seen in comparison to Figure 7.2. The assembly irradiated to the lower fluence (S15) was not protected against sparking and therefore could not be operated up to 1000 V.

![Figure 7.3: Charge collection efficiency for Hamamatsu sensors irradiated at different fluences. The lines are drawn to guide the eye.](image)

Comparing the amount of charge collected from each sensor at a certain bias voltage, the assembly exposed to the lower fluence (S15) collects more charge. The value of the effective doping concentration $N_{eff}$ for S15 is lower than that of S22, implying that for the same bias voltage the depleted region extends deeper into the bulk resulting in more charge being collected. Another factor contributing to the higher charge collection efficiency of S15 is the smaller charge trapping rate. According to Eq. (4.25), the trapping rate of the charge carriers increases with fluence. The width of the depleted region as well as the effect of charge trapping are studied and evaluated in Section 7.7.

In total three of the prototype sensors from Table 7.2 (sensors S17 and S22 from Hamamatsu and the Micron sensor S27) were exposed to a fluence of $8 \times 10^{15}$ $1$ MeV $n_{eq}/cm^2$. The charge collection efficiency for these sensors is plotted in Figure 7.4. The amount of collected charge for the irradiated Micron sensor is almost equal to that of the 50 µm thicker irradiated Hamamatsu sensors. The amount of charge collected grows almost linearly as a function of
7.6 Diffusion measurement

Assuming that charge carriers drifting towards the electrodes form a *cloud*, charge diffusion in the sensor can be studied by measuring the width of this charge cloud. The DuTs for this study are placed perpendicular to the beam. The telescope information is used to predict the point at which a track traverses the DuT.

The number of one-pixel clusters is compared with the prediction of the impact point. The telescope prediction of the intercept point of a track on the DuT is scaled to the pixel pitch as shown in Figure 7.5. Since the DuTs are placed perpendicular to the beam, tracks forming one-pixel clusters follow a flat distribution in the center of the pixel. The distribution decreases towards the edges of the pixel. This is due to the fact that the charge liberated along the
track intercepting the sensor close to a pixel boundary has a high probability to be shared between several pixels, as shown in Figure 5.8.

![Graphs showing normalized number of events vs track intercept for non-irradiated and irradiated sensors](image)

(a) Non-irradiated. (b) Irradiated.

**Figure 7.5:** Formation of one-pixel clusters normalised in the pixel pitch for a non-irradiated (a) and an irradiated (b) sensor. Both sensors are 200 µm thick. In the case of the irradiated sensor, one-pixel clusters are formed in a larger fraction of the pixel. The solid (red) curves represent the fits from 7.1.

The widths of the flat regions are now used to compare the amount of charge diffusion between the non-irradiated and irradiated sensor. Each edge of the distribution is fitted with the cumulative distribution function of the normal distribution:

\[
f(x) = c + s \cdot \frac{1}{2} \left(1 + \text{Erf}\left(\frac{x - \mu}{\sigma \sqrt{2}}\right)\right)
\]

where \(c\) is an offset, \(s\) is a scaling factor, \(\text{Erf}()\) the error function with \(\mu\) the mean and \(\sigma\) the standard deviation of the normal distribution. The mean \(\mu\) is used as a measure for the width of the flat region. For the non-irradiated sensor (Figure 7.5(a)) the width of the flat region is 44 µm while for the irradiated sensor (Figure 7.5(b)), the width of the flat region is 50.5 µm. The larger width of the flat region in the distribution indicates that the width of the charge cloud is smaller for the irradiated sensor.

The difference in the formation of one-pixel clusters between the irradiated and non-irradiated sensor is mainly due to the amount of charge collected with respect to the threshold value, which is depicted qualitatively in Figure 7.6. According to Figure 7.2, the measured Landau MPV of the non-irradiated 200 µm thick sensors is about 15,000 e⁻. Assuming that at a certain position \(x_s\), the majority of that charge is collected by pixel B (Figure 7.6(a)), then only 7 % of the total amount of charge needs to be collected by the neighbouring pixel A.
in order to cross the threshold of 1000 $e^-$ and form a two-pixel cluster. For an irradiated sensor operated at 1000 V, the Landau MPV is 7500 $e^-$ according to Figure 7.4. Since at the same position $x_s$ charge sharing is the same for the two sensors, for a charge deposition of 7500 $e^-$ the amount of charge collected by pixel B will not be larger than the threshold (7 % of 7500 $e^- < 1000 e^-$).

As a result only pixel B will register a hit therefore an one-pixel cluster is formed. The low signal yield and the effect of the threshold need to be taken into account when studying the cluster size distribution and cluster formation in an irradiated sensor.

An additional factor that contributes to the formation of one-pixel clusters is the effect of the drift time. According to [37], the profile of the diffusion follows a gaussian distribution where its variance $\sigma_d$ grows with the square root of the drift time $t_{\text{drift}}$ of a single electron. In the depleted region of the sensor, $t_{\text{drift}}$ is influenced by the electric field. The non-irradiated and irradiated DuT sensors have average electric fields of 8,000 V/cm and 50,000 V/cm, respectively. For a non-irradiated fully depleted 200 µm thick sensor operated at 160 V, the time needed for a single electron to drift from the backplane to the pixel electrode is about 3.2 ns. For an irradiated sensor operated at 1000 V, the drift time of a single electron is about 2 ns. Since $\sigma_d \propto \sqrt{t_{\text{drift}}}$, in the non-irradiated sensor diffusion is larger than in the irradiated sensor by a factor of 1.3. The combined effects of lower signal yield and shorter drift time lead to the formation of one-pixel clusters in a larger fraction of the pixel for an irradiated sensor.

### 7.7 Grazing angle measurements

Studying the depletion depth profile of irradiated sensors helps to understand the details of the charge collection process. This profile can be studied by
generating a known amount of charge at a certain depth in the sensor while measuring the detector response. A commonly used technique makes use of infra-red light with the sensor illuminated from the side [70]. The drawback of this technique is that one cannot probe the center pixels of a large pixel matrix (like for the sensors on the Timepix3 chips) due to the small mean free path of the infra-red light\(^3\). In addition, the point where the photons interact and liberate the charge carriers is not precisely known. The method used in this manuscript instead makes use of minimum ionizing particles and is known as the grazing angle technique [71].

### 7.7.1 Grazing angle setup

In this technique the sensor is rotated with respect to the beam as depicted in Figure 7.7. The incoming particle traverses multiple adjacent pixels and forms long tracks. The path length in each pixel is the same except for the first and last pixel on the track. Knowing the angle of incidence (\(\theta\)), the pixel pitch (\(p\)) and the number of hit pixels (\(N\)), the information from a pixel \(N(i)\) is assigned to a certain depth \(d(i)\) using the formula:

\[
d(i) = \frac{p \times N(i)}{\tan(\theta)}.
\]

A particle traversing a sensor with a thickness \(t = 200 \, \mu\text{m}\) and a pixel pitch of \(p = 55 \, \mu\text{m}\) at \(\theta = 85^\circ\) with respect to the beam yields a value of \(N \approx 42\). According to Eq. (7.2) the depth of the interaction can be determined with a step size of 4.8 \(\mu\text{m}\). In reality, the number of pixels hit varies due to a number of factors as will be discussed in Section 7.7.3.

![Figure 7.7: Illustration of the grazing angle technique in the XZ plane (top view of the sensor).](image)

\(^3\)Although different wave lengths can be used to probe deeper in the sensor bulk, focusing the laser in a pixel is difficult.
7.7 GRAZING ANGLE MEASUREMENTS

7.7.2 Thickness calculation

The accuracy of the grazing angle technique can be extracted by calculating the sensor thickness\(^4\) defined as \(t\). Solving Eq. (7.2) for \(N\) gives:

\[
N(\theta) = \frac{\tan(\theta) \times t}{p}.
\]  \hspace{1cm} (7.3)

The most probable cluster length is measured at different grazing angles and plotted in Figure 7.8 for one of the 200 \(\mu\)m thick Hamamatsu sensors, S6. The systematic offset from the rotation is 0.2\(^5\) and the cluster size error is 1 pixel\(^5\). The nominal thickness of the sensor and the angle offset can be extracted from a fit to the data using Eq. (7.3). The calculated thickness (193 ± 14 \(\mu\)m) is in good agreement with the nominal thickness of the sensor.

![Figure 7.8](image-url)

**Figure 7.8**: Calculating the sensor thickness and the angle offset using the grazing angle technique in the case of a 200 \(\mu\)m thick sensor from Hamamatsu.

For all non-irradiated sensors, the thickness calculation using the grazing angle technique showed no deviation from the nominal thickness as presented in Table 7.3 illustrating that the sensors are indeed fully depleted. Taking into account the fit errors, the largest error (15 \(\mu\)m) is chosen as the thickness error.

\(^4\)A precise measurement of the sensor thickness with metrology was not performed.

\(^5\)In the measurement of the number of hit pixels \(N\) in Eq. (7.3), 1 pixel was subtracted.
CHAPTER 7 RESULTS WITH PROTOTYPE SENSORS FOR THE UPGRADE

Table 7.3: Calculated thickness of non-irradiated sensors tested.

<table>
<thead>
<tr>
<th>Assembly</th>
<th>S6</th>
<th>S20</th>
<th>S23</th>
<th>S33</th>
</tr>
</thead>
<tbody>
<tr>
<td>nominal thickness [µm]</td>
<td>200</td>
<td>200</td>
<td>200</td>
<td>150</td>
</tr>
<tr>
<td>thickness from fit [µm]</td>
<td>193±14</td>
<td>197±15</td>
<td>209±15</td>
<td>157±10</td>
</tr>
</tbody>
</table>

7.7.3 Data selection

For all grazing angle data, the sensors were rotated at a large angle around the y-axis (see Figure 7.7) and at a small angle around the x-axis estimated to be 1.36°. The path length of a track in the sensor is expressed in units of adjacent columns. Similarly, the width of the track is expressed in units of adjacent rows. For the grazing angle set up, the projected cross section of the sensor is smaller compared to the perpendicular set up. The time duration of each Run was adjusted to ensure that the number of tracks in the DuT is of the same order of magnitude as in the charge collection and diffusion studies.

![Figure 7.9: Charge distribution in a 200 µm thick sensor (S6) set at 85°. The peak positions and width of the simulated charge distribution from Geant4 (red solid line) are in fair agreement with the peak positions and width of the data (black circles).](image)

Before looking at the different types of tracks in the sensor, the charge collected in a non-irradiated sensor at the grazing angle configuration is examined. The charge distribution of all clusters formed in a 200 µm thick sensor set at 85° is plotted in Figure 7.9. For comparison the same configuration is simulated in Geant v4.9.5 and superimposed to the data. The peak positions and the widths of the two distributions are in fair agreement. Any difference is
(a) Track types at grazing angles, viewed from the YZ plane (side view of the sensor). The pixels hit by the beam (blue) or a δ-ray (red) are marked as grey.

(b) Tracks extending to two rows with the row crossing occurring: (i) close to the backplane, (ii) in the middle of the sensor, (iii) close to the pixel electrode and (iv) in the middle of the track. The most common tracks are these of type (ii).

**Figure 7.10:** Different tracks types at grazing angles.
due to the fact that various chip and sensor mechanisms, like the effect of the threshold and charge sharing, were not taken into account in the simulation.

A couple of effects influence the track length. One of these effects is charge sharing which is more likely to occur at the boundaries of a pixel or when electrons\textsuperscript{6} drift from deeper in the bulk. Another frequent phenomenon that will increase the number of pixels hit is the creation of $\delta$-rays. The most common types of tracks formed by taking into account the previous effects are depicted in Figure 7.10(a). These are tracks:

- confined in one row (particle A)
- extending to two rows (particle B)
- releasing a $\delta$-ray in the same row (particle C)
- releasing a $\delta$-ray that extends to two rows (particle D)
- releasing a $\delta$-ray that extends to more than two rows (particle E)
- formed from scattered particles intercepting the sensor at an angle smaller than the grazing angle (particle F)

The distribution of length versus width for tracks formed in a non-irradiated sensor operated at 160 V and set at a grazing angle of 85° is shown in Figure 7.11(a). The majority of tracks have a length equal to 42 and a width $\leq$2. These tracks are of type A, B, C and D. Tracks of type A and C have a width equal to 1 while tracks of type B and D have a width equal to 2. Tracks of type E have a length about 42 but extend to more rows. Tracks of type F appear as a separate smaller distribution having a smaller length and width than tracks of the other types. An indication of a $\delta$-ray is a larger energy deposition per track segment compared to the theoretical MPV in that track segment. A cut in the energy deposition per track segment to distinguish between tracks containing $\delta$-rays and tracks with no $\delta$-rays (track type A from C and track type B from D) was not applied to avoid biasing the energy loss distribution of the tracks.

Tracks with a width of 2 (types B and D) can be further categorised. The most common tracks extending to two rows are depicted in Figure 7.10(b). If the double row group of pixels is within 3 columns from the first (last) pixel then the row crossing occurs close to the pixel electrode (backplane) that is defined as type $i$ (type $iii$). If the double row group of pixels is more than 3 columns away from the first and the last pixel, the row crossing occurs in the middle of the sensor and the track is defined as type $ii$. A last category includes tracks in which the double row group of pixels is more than 3 columns away from the first and the last pixel but the majority of the pixels are in one

\textsuperscript{6}For all assemblies tested, electrons give the major contribution to the induced currents in the pixel electrodes. This is not true for depths close to the pixel electrodes where electrons cannot induce large currents due to their short drift distance.
Figure 7.11: Distribution of the number of columns versus the numbers of rows for tracks in non-irradiated S6 operated at 160 V (a) and irradiated S22 operated at 1000 V (b) set at a grazing angle of $85^\circ$. The areas in the dashed lines correspond to the track types defined in Figure 7.10.
row. This track is defined as type iv and it is an evident case of a δ-ray. More than 85% of the tracks with a width of 2 are of type (ii).

The distribution of length versus width for tracks formed in an irradiated sensor at the same grazing angle is shown in Figure 7.11(b). The most probable length is about 10 columns smaller than the length of tracks in the non-irradiated sensor indicating that not all of the charge liberated deeper in the bulk of the irradiated sensor is collected. The irradiated sensor in this case is operated at a bias voltage of 1000 V. Due to the high electric field in the sensor (> 60 kV/cm), the velocity of the charge carriers is higher compared to the velocity of the charge carriers in the non-irradiated sensor. The higher velocity corresponds to a shorter collection time. Hence, charge carriers diffuse less and as a result the majority of tracks are contained in a single row (track type A or C). The fraction of track type F is larger for the irradiated sensor. These additional tracks are formed from particles produced from the decay of radioactive elements in the irradiated assembly.

Opposed to the charge sharing and δ-ray creation that increase the number of pixels hit, \( N \) becomes smaller if the amount of charge deposited in a pixel is below threshold. The feature of the clustering algorithm described in Section 5.2 that searches for hits beyond adjacent pixels is used to bind segmented tracks and include them in the data selection.

All tracks except tracks of type F are considered for the analyses. The track selection is based on a lower cut in length. For the non-irradiated sensors tracks with length >30 are considered while for the irradiated sensors tracks with length >11 are selected. An additional selection is applied in case of tracks extending to two rows (track types B and D). For these tracks, only the ones for which the row crossing occurs in the middle (type ii) are considered.

### 7.7.4 Collected charge profile of the sensor

Since the Timepix3 ASIC measures the ToT and ToA, a simultaneous measurement of the charge deposition and the charge drift time on each pixel is made. Using this feature of Timepix3, the collected charge and time to threshold as function of depth of the sensor can be measured.

To measure the collected charge profile, each pixel hit from a track formed in the sensor is assigned to a certain depth using Eq. (7.2). The distribution of the charge collected at a certain depth bin is fitted with a Langaus. Only distributions with >1000 entries are taken into account in order to make a reliable fit.
7.7 Grazing Angle Measurements

Figure 7.12: Charge distribution fitted with a Langaus at (a) 20 μm, (b) 100 μm and (c) 180 μm depth of the non-irradiated 200 μm thick sensor (S6) operated at 160 V.
CHAPTER 7 RESULTS WITH PROTOTYPE SENSORS FOR THE UPGRADE

Non-irradiated sensors

The charge distributions close to the pixel electrode, at the middle of the sensor and close to the backplane are presented in Figure 7.12. The most probable value as a function of depth for the 200 µm thick Hamamatsu and Micron sensors at different bias voltages is plotted in Figure 7.13. The pixel electrode is at 0 and the backplane at 200 µm. The depletion in an n-on-p sensor starts from the pixel electrode as described in Section 4.4.1. When a non-irradiated sensor is operated at voltages above the full depletion voltage, all the deposited charge will be collected. This explains the constant amount of charge collected when the sensors are fully depleted (V_{bias} > 40 V for S23 and V_{bias} > 140 V for S6) in Figure 7.13. The path traversed by the particle in each pixel when the sensor is tilted at 85° with respect to the beam is 55.2 µm, which is almost equal to the pixel pitch. A minimum ionizing particle is expected to create about 72 e⁻/h pairs per µm [37], therefore the most probable charge deposited in each pixel is 3960 e⁻. The amount of liberated charge is measured to be 3850±100 e⁻ where the error is from the calibration as explained in Section 7.2. The amount of charge collected from the first and the last pixel is lower because the path traversed by the particle in those edge pixels is on average smaller than in a center pixel.

In case of the Micron sensor (Figure 7.13(a)) the amount of charge collected at 20 V bias is constant up to about 120 µm. Beyond that depth the amount of charge collected drops almost linearly. The same behaviour occurs for the Hamamatsu sensor (Figure 7.13(b)), but at a higher voltage. The depth region in which the amount of charge collected is lower corresponds to the non-
7.7 GRAZING ANGLE MEASUREMENTS

depleted region of the sensor. The amount of charge collected from this region decreases up to a point where it is equal to about 1500 e\(^{-}\) and the detector no longer registers a hit. Although the threshold is set at 1000 e\(^{-}\), the collected charge does not go down to that value. The reason that no charge is collected between 1000 e\(^{-}\) and 1500 e\(^{-}\) is due to the time limit in the integration of the signal. If the time required to integrate a signal is too long, then it will not be registered as a hit. The time needed for charge liberated deep in the non-depleted region to diffuse and then drift towards the pixel electrodes is larger than that of charge liberated in the depleted region.

For bias voltages below the full depletion voltage (\(V_{bias} < 40\) V for S23 and \(V_{bias} < 140\) V for S6) the minimum amount of charge collected flattens for about 10 \(\mu m\). As can be seen in the number of hits per depth bin plot of S6 at 20 V in Figure 7.14, for depths beyond 100 \(\mu m\) (where the saturation occurs) the number of entries is less than half compared to the maximum number of entries. This will result in enhancing the tails of the Landau distributions influencing the MPV. Because of these low number of entries the fits are biased and reach an equilibrium value around 1500 e\(^{-}\).

![Figure 7.14: Number of entries in the profile histogram of S6 at 20 V.](image)

![Figure 7.15: Simulation of charge collected in the non-depleted region of a 200 \(\mu m\) thick sensor for values of the mean free path of electrons \(\lambda_e\) in Si equal to 1, 2 and 4 nm.](image)

In principle, charge liberated in the non-depleted region will not drift towards the electrodes due to the absence of the electric field and will hence not be collected. However, charge carriers diffuse independently of the drift field presence. According to [72] electrons and holes liberated in the non-depleted region close to the boundaries of the depleted region, may diffuse towards the depleted region and subsequently drift to the electrodes. This effect is
known as charge migration. The collection of the charge carriers liberated in the non-depleted region is simulated in a dedicated Monte-Carlo. A charge cloud (consisting of the most probable number of charge carriers liberated in 55 $\mu$m of Si) is liberated at different distances from the edge of the depleted region. In Figure 7.15, the collected charge is plotted as a function of the distance from the depleted edge assuming a maximum charge collection time of 100 ns. The amount of collected charge drops linearly as a function of the distance from the edge of the depletion region. Different values of the mean free path of electrons $\lambda_e$ in silicon, corresponding to the electron energy range of 50-2000 eV [88], are plotted in order to study which value describes the data best. For a value of $\lambda_e = 2$ nm the slope, which represents the amount of charge collected per distance, agrees well with the slope of S23 and S6 in Figure 7.13.

**Irradiated sensors**

The effects that reduce the amount of charge collected in an irradiated sensor are charge trapping and the fact that the sensor is only partially depleted. The grazing angle measurements provide us additional information about how these effects contribute to the collected charge.

The charge distributions at three different depths in the irradiated Hamamatsu sensor (S22), operated at 1000 V, are presented in Figure 7.16. The charge distribution at 150 $\mu$m has an order of magnitude less hits therefore a larger statistical uncertainty compared to the other two histograms. Looking at the number of entries per depth bin of S22 at 1000 V in Figure 7.17(a), the number of entries decreases significantly beyond 100 $\mu$m. This is due to the fact that charge drifting from deep in the sensor has a high probability to be trapped as will be discussed later in this section. For depths $>130$ $\mu$m the number of entries is less than half of the maximum entries therefore the corresponding charge distributions are biased.

The collected charge profile for S22 is plotted in Figure 7.17(b) for different bias voltages. For the irradiated S22 the depleted region does not reach the backplane even when the sensor is operated at 1000 V. The shape of the collected charge is similar at each applied bias voltage. The amount of charge collected slightly increases as a function of depth until it reaches a maximum. Beyond this point, the amount of charge collected decreases. At 1000 V and for depths $>130$ $\mu$m the amount of charge collected flattens. As explained using Figure 7.17(a), this flattening is related to the low number of entries per depth bin similar to the case of the non-irradiated sensor.

To understand the charge profile in the irradiated sensor the effect of charge trapping needs to be taken into account. As discussed in Section 4.5.1 the trapping rate of electrons and holes is not the same. Holes drifting to the
7.7 GRAZING ANGLE MEASUREMENTS

Figure 7.16: Charge distribution fitted with a Langaus at (a) 35 µm, (b) 90 µm and (c) 150 µm depth of an irradiated 200 µm thick sensor (S22) operated at 1000 V.
backplane have a higher probability to be captured than electrons drifting towards the pixel electrode. According to [73], the effective trapping rate can be described by the formula:

\[ q(d) = q(0)e^{-d/(v_{\text{sat}} \cdot \tau_{\text{eff}})} \]  

(7.4)

where \( q(d) \) the amount of charge drifting at depth \( d \), \( q(0) \) the amount of charge initially deposited, \( v_{\text{sat}} \) the saturated velocity\(^7\) and \( 1/\tau_{\text{eff}} \) the effective trapping rate in ns\(^{-1}\) defined in Eq. (4.25). At the depleted region close to the backplane (between 70 and 155 \( \mu \)m) electrons contribute more to the collected charge since holes drift for a short distance. Fitting Eq. (7.4) to the collected charge profile of the irradiated S22 operated at 1000 V (Figure 7.18) and excluding the depth range with the low number of entries, the calculated effective trapping rate for electrons is found to be \( 1/\tau_{\text{eff,e}} = 0.65 \pm 0.12 \) ns\(^{-1}\).

The same procedure is repeated for the other irradiated Hamamatsu sensors, S15 and S17 and the results are summarised in Table 7.4. The results of the S15 sensor are compatible with reports at similar fluences [74]. Measurements of the effective trapping rate in neutron irradiated sensors at fluences beyond \( 4 \times 10^{15} \) 1 MeV n\(_{\text{eq}}\)/cm\(^2\) have not been reported in literature. Extrapolating the effective trapping rate from lower fluences as reported in [73] does not agree well with the data giving a trapping rate larger than the measured rate. A more elaborate model than that of Eq. (7.4), which takes also the hole

---

\(^7\)As a consequence of the high electric field in the sensor the charge drift velocity is constant (velocity saturation).
contribution into account, needs to be implemented to describe the collected charge profile of the irradiated sensor.

Table 7.4: Effective trapping rates of the irradiated Hamamatsu sensors.

<table>
<thead>
<tr>
<th>Assembly</th>
<th>S15</th>
<th>S17</th>
<th>S22</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluence $[10^{15} \text{ 1 MeV n}_{\text{eq}}/\text{cm}^2]$</td>
<td>4</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Measured $1/\tau_{\text{eff}} \text{[ns}^{-1}]$</td>
<td>0.51±0.14</td>
<td>0.61±0.12</td>
<td>0.65±0.12</td>
</tr>
</tbody>
</table>

For the 150 µm thick irradiated Micron sensor, the grazing angle measurements were taken with the preamplifier discharging faster (high Ikrum value). As a result the entire ToT distributions\(^8\) have <5 counts. The resulting small dynamic range of the measured ToT values provides only a very coarse measurement of the collected charge therefore the charge profile of the irradiated Micron sensor is not studied in detail.

Track type dependence

As described in the end of Section 7.7.3, the selection criteria for the non-irradiated sensors include tracks with length >30 and for the irradiated sensors tracks with length >11. However, according to the distributions in Figure 7.11 the width of the selected tracks varies. In a track with a width >1, the charge liberated at the boundaries of two rows is shared between the pixels in these adjacent rows. In order to study how charge sharing influences the collected charge profile, these profiles are measured separately for tracks extending to

\(^8\)A typical calibration curve was presented in Section 4.3.4.
CHAPTER 7 RESULTS WITH PROTOTYPE SENSORS FOR THE UPGRADE

Figure 7.19: Collected charge profile for different track types for a non-irradiated (a) and an irradiated (b) sensor.

For the non-irradiated sensor (Figure 7.19(a)), the difference from the expected most probable charge deposition is not significant in the order of a 100 e\textsuperscript{−}. The error bars represent the uncertainty from the fits. For tracks extending to two rows the difference is less than 100 e\textsuperscript{−} in the depth range of 50–140 µm. This depth range corresponds to the region where the charge liberated from the track registers hits in adjacent rows. The 100 e\textsuperscript{−} difference is within the measurement error calculated by adding the calibration errors of the two pixels in quadrature.

For the 200 µm thick irradiated sensor (S22), the collected charge profiles for the three categories are almost identical except for the depth range of 20–100 µm (Figure 7.19(b)). The average charge collected in the case of tracks extending to two rows is about 150 e\textsuperscript{−} smaller than the average charge collected in the case of tracks confined in one row.

Studying tracks that extend to two rows in more detail provides additional information. The majority of these (>85 %) consist of tracks where the row crossing occurs roughly in the middle of the track\textsuperscript{9}. The charge distribution of individual, which will be referred to as single, pixels from these tracks is plotted in Figure 7.20. The distribution has a minimum of about 1300 e\textsuperscript{−} that indicates an offset compared to the expected threshold value of 1000 e\textsuperscript{−}. Additional information on this threshold offset can be found in Appendix A.

\textsuperscript{9}These tracks are defined as type (ii) in Figure 7.10(b).
7.7 GRAZING ANGLE MEASUREMENTS

Figure 7.20: Charge distribution of single pixels in track type (ii) in case of the irradiated sensor (S22) set at 85°. The charge distribution has a threshold of 1300 e⁻.

The effect of the higher threshold on the pattern of the collected charge profile can be understood by looking at the charge distribution of single row and double row pixels. For every track extending to two rows, pixels in the same row are studied separately from pixels in double rows (Figure 7.21). Most of the hits confined in a single row collect <2600 e⁻ as shown in Figure 7.22(a). Adjacent pixels extending to two rows (Figure 7.22(b)) have two characteristics. Firstly, they are located in the depth range of 20–100 μm due to the cuts imposed in Section 7.7.3. Secondly, the total amount of charge collected is >2600 e⁻.

Figure 7.21: Example of a track (type ii) extending to two rows in the 200 μm thick irradiated sensor (S22) set at 85°. The intermediate missing pixels are added from the clustering algorithm.

The fact that the amount of charge collected in adjacent pixels extending to two rows is larger than the charge collected in pixels confined in a single row is due to the threshold. Pixels collecting charge <1,300 e⁻ will not be
activated due to the higher threshold. Hence, the amount of charge collected by adjacent pixels extending to two rows will be at least two times larger than the threshold.

The effect of the threshold is reproduced using a dedicated Monte Carlo. Random charge values are generated from Landau distributions with MPVs in the range of 1600–2800 e\textsuperscript{−} and widths of 100–300 e\textsuperscript{−} based on the distributions of Figure 7.16. According to the number of entries of each profile in Figure 7.22, this charge is assigned to one-pixel clusters with a probability of

Figure 7.23: Normalised charge distributions of hits in adjacent rows for the irradiated sensor (S22) simulated in a dedicated Monte Carlo (a) and plotted from data (b). The majority of the charge collected is > 2600 e\textsuperscript{−} (dashed vertical line).
0.85 and to two-pixel clusters with a probability of 0.15. Next, the charge assigned to two-pixel clusters is shared between the two pixels assuming a probability drawn from a uniform distribution. If the charge of each pixel is larger than the threshold value of 1300 e\(^-\), the summed charge is plotted in the distribution of Figure 7.23(a). For comparison, the same distribution from the data (projected from Figure 7.22(b)) is plotted in Figure 7.23(b). Both distributions of Figure 7.23, where each is normalised to the integral of the histogram, peak at about 4000 e\(^-\). The difference in the widths of the distributions is probably due to the assumption that the charge assigned to two-pixel clusters is shared between the two pixels following a uniformly distributed probability. This distribution was used since a theory that describes the charge sharing ratio is not reported in literature. A more detailed model of how charge is shared in a two-pixel cluster is not studied.

### 7.7.5 Time to threshold profile of the sensor

Besides the charge distribution, the charge collection time has also been investigated. Each pixel hit on the DuT gets a timestamp \(t_{\text{hit}}\) as described in Section 5.2.1. This timestamp indicates the time the hit is registered with respect to the beginning of a Run. A track intercepting the telescope will liberate charge almost instantaneously in both the telescope and the DuT sensors. Since the DuT shares the same clock with the telescope planes, the time needed from the moment the charge is liberated to drift and cross the threshold in the DuT can be calculated by subtracting the time the track intercepted the telescope from \(t_{\text{hit}}\). The time difference \(t_{\text{hit}} - t_{\text{track}}\) will be referred to as time to threshold.

The time to threshold of a pixel hit \(t_{\text{hit}}\) is a combination of two factors: the drift time due to the presence of the electric field \(t_{\text{drift}}\) and the time needed for the integrated charge to cross the threshold \(t_{\text{int}}\). In addition, a number of small factors may contribute to \(t_{\text{hit}}\). If the charge is liberated in the non-depleted region of the sensor, the extra time needed for the charge to diffuse to the depleted region will add to \(t_{\text{drift}}\). If the amount of charge is small, additional time will be introduced due to timewalk \(t_{\text{walk}}\) as described in Section 4.3.5. In this section the effect on time to threshold from \(t_{\text{drift}}, t_{\text{int}}\) and \(t_{\text{walk}}\) is studied for the non-irradiated and irradiated sensors.

The timewalk effect can be visualised by plotting \(t_{\text{hit}} - t_{\text{track}}\) as a function of the charge collected per pixel hit. This is shown in Figure 7.24 for the non-irradiated Micron S23, Hamamatsu S6 sensors and the irradiated Hamamatsu S22 sensor\(^{11}\). The time to threshold is different for the three sensors beyond 2500 e\(^-\) due to the different electric fields in the sensors. Although

\(^{10}\) The calculation of \(t_{\text{track}}\) is described in Section 5.3.2.

\(^{11}\) The data is from the grazing angle measurements in contrast to Figure 4.11 in which the data is taken with the DuT perpendicular to the beam.
CHAPTER 7 RESULTS WITH PROTOTYPE SENSORS FOR THE UPGRADE

Figure 7.24: Time to threshold for irradiated and non-irradiated sensors set at grazing angles. For charges >3000 e\textsuperscript{−} the average timewalk of all assemblies is <5 ns.

the two non-irradiated sensors are operated at the same bias voltage, the different doping level (as shown in Table 7.1) influences the shape of the electric field according to Eq. (4.5). For the irradiated sensor the time to threshold is shorter compared to the non-irradiated sensors due to the higher electric field. For charges >3000 e\textsuperscript{−} the average timewalk of all assemblies is <5 ns. Therefore, for these amounts of charge collected timewalk will not contribute significantly to the time to threshold.

Non-irradiated sensors

Similar to Section 7.7.4 where the depth dependence of the collected charge was studied, the time to threshold is studied as a function of depth. In Figure 7.25 the time to threshold profiles of the non-irradiated 200 µm Micron S23 and Hamamatsu S6 sensors are plotted. When the sensors are fully depleted the time to threshold is <10 ns along the whole sensor depth. The average time to threshold in the depleted region is about 5 ns.

The depth regions with the strong increase of the charge collection time (>20 ns for S23 at 20 V and S6 at 20 V) correspond to the non-depleted regions of the sensors. The increase of the time to threshold is due to the fact that charge liberated beyond this depths needs additional time to diffuse towards the depleted region (before it drifts towards the electrodes and induces a signal high enough to cross the threshold).

In a fully depleted non-irradiated sensor, \( t_{\text{hit}} - t_{\text{track}} \) is influenced by both the collection time \( t_{\text{int}} \) and timewalk \( t_{\text{walk}} \). At depths close to the pixel electrodes,
electrons will drift for a short distance until being collected and therefore barely contribute to the induced charge. Hence the induced current is mainly due to the motion of the slower holes. In a similar way, at depths close to the backplane holes will drift for a short distance so the induced current is largely due to the drift of electrons. This information is crucial to understand the shape of the measured profile.

The time to threshold profile is simulated for the sensors of the same geometry, type and doping as S23 and S6 operated at 120 V and 160 V respectively. The electric and weighting fields are simulated numerically using WEIGHTFIELD [89]. The fields are then used to simulate the current induced by the drift of electrons and holes liberated at a certain depth. Subsequently, the time needed for the integrated current to cross the threshold of 1000 e\(^{-}\) at each depth is calculated and superimposed to the data as shown in Figure 7.26. The error in the calculated time, which is due to the assumed uncertainty on the full depletion voltage, is marked by the grey area. A constant offset, which is related to the response time of the discriminator, of 1.6 ns for S23 and 2.3 ns for S6 has been added to the simulations. Overall, the simulation agrees well with the data. Beyond about 100 µm the measured time to threshold becomes larger than the simulated time. This can be due to the fact that the behaviour of the discriminator is not well described by simply adding a constant offset in the simulation curves.
CHAPTER 7 RESULTS WITH PROTOTYPE SENSORS FOR THE UPGRADE

![Graphs showing the time-to-threshold profile of non-irradiated and irradiated sensors](image)

**Figure 7.26:** Simulation and measured time-to-threshold profile of the non-irradiated 200 µm thick n-on-p sensors: (a) Micron S23 operated at 120 V, (b) Hamamatsu S6 operated at 160 V. The grey area represents the error in the calculated time due to the assumed uncertainty on the full depletion voltage. A constant offset, which is related to the response time of the discriminator, has been added to each simulation curve.

**Irradiated sensors**

For the operational voltage of the sensor used in the grazing angle measurements, the drift time $t_{\text{drift}}$ of the irradiated sensors is shorter than the non-irradiated ones. The depletion width of S22 at 1000 V is about 160 µm (as seen in Figure 7.17(b)) and the depletion width at 250 V is about 55 µm resulting in average electric fields of 66,000 V/cm and 45,000 V/cm, respectively. At these high fields, the $t_{\text{drift}}$ of a single electron from the edge of the depleted region is <0.5 ns assuming that the velocity is saturated and no charge trapping takes place.

The time to threshold profile of the irradiated Hamamatsu sensor S22 is presented in Figure 7.27(a). The time to cross the threshold is <20 ns independent of the applied bias voltage. Due to the effect of charge trapping, no charge is collected from the non-depleted region of the irradiated sensor (in contrast to the non-irradiated sensor where charge is collected also from the non-depleted region). The smaller time to threshold range compared to the non-irradiated sensors is a result of the shorter charge collection time in the irradiated sensor and the fact that charge is not collected from the non-depleted region.

To understand the pattern of the time to threshold profile, the time to threshold is simulated and superimposed on the data of the irradiated S22 op-
7.7 GRAZING ANGLE MEASUREMENTS

![Graphs showing time to threshold profile](image)

(a) Time to threshold profile for the 200 µm thick irradiated Hamamatsu sensor S22. (b) Simulation of the time to threshold profile for a 200 µm thick n-on-p sensor operated at 1000 V superimposed on data from Hamamatsu S22 operated at the same bias voltage. The grey area represents the error in the calculated time due to the assumed uncertainty on the full depletion voltage.

Figure 7.27: Time to threshold profile of a 200 µm thick n-on-p sensor.

erated at 1000 V (Figure 7.27(b)). The error in the calculated time (due to the assumed uncertainty on the full depletion voltage) is marked by the grey area. A simulation of the time to threshold based on Ramo’s theorem (red line) [42], as done in the case of the non-irradiated sensor, fails to describe the data. According to the collected charge profile of S22 in Figure 7.17(b) the charge collected at each depth is <2800 e⁻. For these amounts of charge timewalk should not be neglected according to Figure 7.24. The time to threshold is well described by the simulation including the average timewalk as function of charge as shown in Figure 7.27(b).

7.7.6 Effective doping concentration

Based on the width of the depleted region as a function of the bias voltage, a simple model is used to extract the effective doping concentration $N_{\text{eff}}$ for an irradiated sensor. More elaborate models, e.g. involving the formation of a double junction in the sensor [75], are not studied in this manuscript.

The data for S22 is plotted in Figure 7.28. The errors represent the uncertainty in depth for the non-irradiated sensors calculated in Section 7.7.2. Fitting Eq. (4.23) to the data, the $N_{\text{eff}}$ for the irradiated sensors of Table 7.2 can be calculated. Since measurements of the effective doping concentration in neutron irradiated sensors at these fluences have not been reported,
CHAPTER 7 RESULTS WITH PROTOTYPE SENSORS FOR THE UPGRADE

Figure 7.28: Depth as a function of depletion voltage of the irradiated Hamamatsu sensor S22. Data fitted with Eq. (4.23) and with a straight line for comparison.

the expected $N_{\text{eff}}$ is predicted by extrapolating the curve in Figure 4.17 for oxygenated float zone silicon (DOFZ). The measured and expected values of $N_{\text{eff}}$ for the irradiated sensors are summarised in Table 7.5. Although the poor ToT resolution of the irradiated Micron sensor (S29) did not allow a detailed study of the charge profile of the sensor, it is not an obstacle in calculating its $N_{\text{eff}}$. This is due to the fact that the depth at each bias voltage is based on measuring the track length and not the amount of charge collected.

Table 7.5: Effective doping concentration of the irradiated sensors.

<table>
<thead>
<tr>
<th>Assembly</th>
<th>S15</th>
<th>S17</th>
<th>S22</th>
<th>S29</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fluence [$10^{15}$ 1 MeV n$_{\text{eq}}$/cm$^2$]</td>
<td>4</td>
<td>8</td>
<td>8</td>
<td>8</td>
</tr>
<tr>
<td>Measured $N_{\text{eff}}$ [$10^{13}$ cm$^{-3}$]</td>
<td>3.2±0.3</td>
<td>6.9±1.0</td>
<td>6.8±0.9</td>
<td>6.7±0.9</td>
</tr>
<tr>
<td>Expected $N_{\text{eff}}$ [$10^{13}$ cm$^{-3}$]</td>
<td>3.1</td>
<td>6.3</td>
<td>6.3</td>
<td>6.3</td>
</tr>
</tbody>
</table>

The measured $N_{\text{eff}}$ for all sensors is in fair agreement with the expected value. However, the square root model of Eq. (4.23) fails to describe the data accurately. The depletion depth appears to depend linearly on the bias voltage suggesting that the sensor has a resistor-like behaviour.

7.8 Conclusions

Prototype sensors from Hamamatsu and Micron irradiated to the maximum required fluence of $8 \times 10^{15}$ 1 MeV n$_{\text{eq}}$/cm$^2$ have been studied. The maxi-
7.9 RECOMMENDED R&D SENSOR STUDIES

The irradiated sensors can deliver 7000 e\(^-\) when operated at 1000 V, as shown in Figure 7.4, hence satisfying the minimum amount of charge collected that is required for the VELO upgrade. The 150 \(\mu\text{m}\) thick sensor from Micron collects the same amount of charge as the 50 \(\mu\text{m}\) thicker Hamamatsu sensors. This shows that by using a thinner sensor the material budget can be minimised without a loss in the signal yield.

The collected charge and time to threshold profile of the sensors are obtained by performing measurements at grazing angles. Using the grazing angle technique, the maximum thickness error is found to be 15 \(\mu\text{m}\). In addition, the depth in the sensor can be measured in bins of 5 \(\mu\text{m}\).

The collected charge profile in a fully depleted non-irradiated sensor is uniform (Figure 7.13) in contrast to the collected charge profile in an irradiated sensor (Figure 7.17(b)). In an irradiated sensor, charge collection is influenced by charge trapping and the fact that the sensor is not fully depleted even at the maximum operational bias voltage (1000 V). The measured effective trapping rates \(1/\tau_{\text{eff}}\) for electrons, the charge carriers that give the major contribution to the signal of the tested irradiated sensors, agree with other results reported in literature [74].

The time to threshold profile in a depleted non-irradiated sensor can be described by using Ramo’s theorem of induced currents (Figure 7.26). However, for an irradiated sensor set at grazing angles the measured time to threshold contains a contribution from timewalk. After a long wait, the time to threshold profile of an irradiated sensor can be described by taking into account the timewalk effect as shown in Figure 7.27(b).

The effective doping concentration \(N_{\text{eff}}\) is calculated using a simple model based on the information of the depleted depth. Although the model does not describe the data accurately, the measured values of \(N_{\text{eff}}\) (Table 7.5) are in fair agreement with the expected values.

The measurements performed in this chapter show that the tested prototype irradiated sensors from Micron and Hamamatsu qualify for the VELO upgrade in terms of charge collection and time of arrival.

7.9 Recommended R&D sensor studies

Based on the testbeam results, a number of effects presented in this work can be further studied. Although these studies strictly speaking are not required for the VELO upgrade, they are interesting from an R&D perspective.
CHAPTER 7 RESULTS WITH PROTOTYPE SENSORS FOR THE UPGRADE

Bias voltage & threshold

Two parameters that influence the charge collection and charge drift time are the bias voltage and the threshold. Measurements of the collected charge and time to threshold profiles should be performed with the sensors operated at different bias voltages to investigate the effect of the electric field on the ToT and ToA of the charge. Additional studies with the assemblies operated at lower threshold values will provide a higher signal yield. The minimum threshold value at which the noise becomes significant and the maximum threshold value at which the hit efficiency is about 100 % can be used as input for the future operation of the silicon sensors.

Diffusion

Another effect that can be studied in further detail is diffusion. Diffusion has been discussed briefly in Section 7.6 where the sensor was placed perpendicularly to the beam. Placing the sensor at grazing angles allows to measure the effect of charge sharing between adjacent pixels in different rows in more detail. As a result, the magnitude of the charge cloud can be described as a function of depth. Similar measurements have been reported with Timepix [76] [45]. However, performing these measurements with the Timepix3 assemblies gives the possibility to study the time to threshold profile of the charge cloud. This is particularly interesting for irradiated sensors where, compared to the non-irradiated ones, the lower amount of charge collected influences cluster formation.

Radiation induced effects

The effects of radiation in the silicon sensor studied in this manuscript, i.e. effective trapping rate and effective doping concentration, can be studied in more detail. The effective trapping rate of electrons has been calculated in Section 7.7.4. However, the effective trapping rate of holes needs to be determined to provide a better understanding of how trapping between the different charge carriers behaves. Regarding the effective doping concentration $N_{\text{eff}}$ of the irradiated sensors a more elaborate model, compared to the simple model presented in Section 7.7.6, such as the Hamburg model needs to be studied in order to acquire a more accurate value of $N_{\text{eff}}$. Another effect that needs to be taken into account is the formation of a doubly peaked electric field in a $n$-on-$x$ type heavily irradiated sensor. The trapping of the mobile charge carriers will produce a net positive (negative) space charge near the $p^+$ back-plane ($n^+$ implant). As a result, $pn$-junctions will be formed in both sides of the sensor (Figure 7.29). This effect, which is described by the so-called double junction model [75], can be studied using the grazing angle measurements.
7.9 RECOMMENDED R&D SENSOR STUDIES

The model, similar to one proposed in [10], is based on the Shockley-Read-Hall statistics and produces an effective space charge density from the trapping of free carriers in the leakage current. The effective charge density is related to the occupancies and densities of traps as follows,

\[ \rho_{\text{eff}} = N_D f_D + N_A f_A + \rho_{\text{dopants}} \]  

where: \( N_D \) and \( N_A \) are the densities of donor and acceptor trapping states, respectively; \( f_D \) and \( f_A \) are the occupied fractions of the donor and acceptor states, respectively, and \( \rho_{\text{dopants}} \) is the charge density due to ionized dopants.

Each defect level is characterized by an electron and hole trapping cross section, \( D_{\text{e/h}} \) for the donor or acceptor trap, respectively, and by an activation energy, \( E_D \) and \( E_A \) for the donor and acceptor trap, respectively.

An illustrative sketch of the double trap model for a reverse biased device is shown in Fig. 1. Trapping of the mobile carriers from the generation-recombination current produces an effective positive space charge density near the p+ backplane and a net negative space charge density near the n+ implant as shown in Fig. 1(a). Since positive space charge density corresponds to n-type doping and negative space charge corresponds to p-type doping, there are p-n junctions at both sides of the detector. The electric field in the sensor follows from a simultaneous solution of Poisson’s equation and the continuity equations. The resulting \( z \)-component of the electric field is shown in Fig. 1(b). It varies with an approximately quadratic dependence upon \( z \) having a minimum at the zero of the space charge density and maxima at both implants. A more detailed description of the double junction model and its implementation can be found in [2].

4D DATA ANALYSIS

Charge collection across the sensor bulk was measured using the "grazing angle technique" [11]. As is shown in Fig. 2, the surface of the tests sensor is oriented by a small angle (15°) with respect to the proton beam. A large sample...

Figure 7.29: Illustration of the double peak of the electric field [75].

The results from this thesis support the decision to start procurement of the sensors for the upgrade. To arrive at an even more detailed understanding of the future behaviour of the sensors, a number of additional tests should be performed.