On the cutting edge of semiconductor sensors: towards intelligent X-ray detectors

Bosma, M.J.

Citation for published version (APA):
Bosma, M. J. (2012). On the cutting edge of semiconductor sensors: towards intelligent X-ray detectors
Active-edge sensors: electrical characterisation

In Chapter 2, two types of planar edgeless sensors were introduced: slim-edge and active-edge sensors. This chapter will focus on characterisation of the latter.

Although active-edge sensors were already proposed in 1997 [107], interest in these sensors only grew in recent years. The greatest challenge in manufacturing edgeless sensors is to minimise the inactive peripheral area without affecting the detection characteristics of the active region. To accomplish that, edge effects giving rise to leakage currents in the active region have to be minimised. It is therefore required to use dicing methods that cause minimal damage to the edge and to passivate possibly active surface states.

To evaluate the electrical integrity of a sensor, which indirectly provides feedback on the quality of the manufacturing process, its electrical properties are commonly characterised. Two conventional characterisation methods are capacitance-voltage (C-V) and current-voltage (I-V) profiling.

In this chapter, both techniques are used to characterise active-edge sensors. The leakage current of these devices is compared to that of conventional sensors in order to evaluate their viability. In particular, the dependence of the leakage current on the electrode topology at the edge is studied to determine the minimum edge distance for which the leakage current in the active region is still acceptable.

4.1 Sample specifications

In the framework of the Relaxd project, a batch of active-edge sensors was fabricated by Canberra in order to test their potential for large-area detector applications. Sensors with different edge topologies were manufactured for the purpose of comparing their performance with that of existing conventional devices, rather than performing a systematical study on the minimum acceptable edge distance. As a result, a variety of sensors with...
Table 4.1: Sample overview

Four different types of sensors were fabricated, each with various electrode topologies at the edge (see Figure 4.1). The design of the TOTEM strip sensors and Medipix sensors can be found in [108] and [94], respectively.

<table>
<thead>
<tr>
<th>Samples</th>
<th>Electrode configuration</th>
<th>Active area (cm²)</th>
<th>Stop ring width (µm)</th>
<th>Edge distance (µm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>6 TOTEM sensors</td>
<td>128 strips</td>
<td>0.64</td>
<td>15</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>30</td>
<td>50</td>
</tr>
<tr>
<td>13 Medipix sensors</td>
<td>256 × 256 pixels</td>
<td>1.98</td>
<td>5</td>
<td>10</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>10</td>
<td>20</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>15</td>
<td>30</td>
</tr>
<tr>
<td>11 Circular diodes</td>
<td>single diode</td>
<td>0.1943</td>
<td>5</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.1924</td>
<td>10</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.1885</td>
<td>15</td>
<td>50</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.1810</td>
<td>25</td>
<td>100</td>
</tr>
<tr>
<td>10 Rectangular diodes</td>
<td>single diode</td>
<td>0.2375</td>
<td>5</td>
<td>13</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.2350</td>
<td>10</td>
<td>25</td>
</tr>
<tr>
<td></td>
<td></td>
<td>0.2301 – 0.1836</td>
<td>25</td>
<td>50, 150, 300</td>
</tr>
</tbody>
</table>

Different edge designs were produced. Table 4.1 lists the samples that were available. All are p-in-n silicon sensors fabricated on 300 µm thick ν-type substrate material. Each type was manufactured with various edge topologies characterised by:

1. the distance between the active-area electrode and the physical edge of the structure, referred to as the edge distance.
2. the width and doping type of the ring electrode at the edge, which is referred to as the stop ring.

For each topology, two samples were fabricated. One with a p-type stop ring and one with an n-type stop ring. The doping type determines whether the stop ring functions as an extension of the active edge or as a drain for currents generated at the edge. This will be discussed in more detail in Section 4.4.

Figure 4.1 shows the main processing steps together with a close-up view of the edge. First, trenches of approximately 250 µm deep were made from the back side using deep reactive ion etching (see Section 2.3.3). This gave access to the side-walls, which were subsequently doped with phosphorus atoms using a spin-on diffusion process. After doping, the sensor structures were separated by a second etch from the active-area side of the
sensor. The process required very careful handling of the sensor wafer, since no support wafer was used. Once the first deep trench is made, the sensor dies were held together by 50 µm of silicon only. Despite the fact that the wafer did not break during handling, there were difficulties with the sensor die separation. The sensors were processed on 150 mm wafers, while the patterning equipment was suited for 200 mm diameters only. Therefore,

![Diagram of edge processing](image)

**Figure 4.1: Edge processing**

The edges were processed in three steps. First, a deep trench was etched from the back side. This provided access to the side-wall, which was subsequently implanted with phosphorus atoms. Finally, the structures were separated by etching from the front. The bottom part shows a schematic close-up view of the edge. Its topology is determined by the edge distance as well as the width of the n⁺ or p⁺ stop ring.
the sensor wafer had to be mounted on a 200 mm adaptor wafer. Non-uniformity of the bonding process, however, caused an irregularity in the separation process. As a result, not all dies were etched through completely and some of them had to be separated mechanically. This caused damage to the edge. Moreover, no passivation layer was deposited between the stop ring and active area. Hence, the active area was not protected against possible surface currents induced by the edge. How this affects the leakage-current behaviour of these devices will be discussed in more detail in Section 4.3.2.

In Figure 4.2 the edge of a conventionally processed TOTEM sensor is compared to that of one with active edges. Whereas for conventional sensors the active area typically starts several hundreds of micrometers from the edge, this active-edge sensor has an edge distance of only 50 µm. In addition, the plasma etched sensor shows much less damage at the edge and seems to be spared from chip-outs.

Figure 4.2: Conventional edge versus active edge

Top-view photographs of a conventional TOTEM strip sensor (a) and one with an active edge (b). The edge distance of the active-edge sensor is ten times smaller than that of the conventional one. Moreover, the plasma-etched edge shows much less damage. The strip pitch is 50 µm.
4.2 Experimental set-ups

The prototypes of Table 4.1 are characterised by measuring the capacitance and leakage current at various bias voltages, which results in a characteristic C-V or I-V curve. Detailed descriptions of the set-ups for both C-V and I-V profiling are given in Appendix A. Contact with the samples is made using probe needles. An example of this can be seen in Figure 4.3. It shows a needle that makes contact with the stop ring of one of the circular diodes via a dedicated pad at the edge.

Probing is done in a probe station. It uses a chuck that supports the sensor, allows for biasing and at the same time provides precise positioning of the sensor with respect to the needles with a resolution of 0.5 μm. In addition, its housing provides electrical shielding and light tightness. Both are important requirements for this type of measurement, as will be discussed in Section 4.2.1.

![Figure 4.3: Probing](image)

A top-view snapshot of one of the probe needles touching a dedicated probe pad at the edge of one of the circular diodes, which allows for contacting the stop ring.

4.2.1 Sources of error

Due to the small dimensions of the samples (see Table 4.1) as well as the high purity of the silicon substrate material, both capacitance and leakage current take on low values, typically of the order of pF and pA, respectively. Therefore, the instruments must be highly sensitive. This makes the measurements very susceptible to possible sources of error that affect or even obscure the actual measurement. Before a reliable measurement
can be made, proper precautions must be made to avoid the most erroneous influences. In addition, remaining extraneous currents need to be subtracted from the measurement, which requires a precise calibration of the set-up. Potential sources of error are discussed below. They can be related to either the measurement set-up, referred to as circuit offsets, or to environmental influences.

**Circuit offsets**

Circuit offsets can be categorised into internal and external offsets. Internal offsets are related to the measurement device itself, i.e. to the source-measure units and the LCR meter\(^2\) (see Appendix A). These can be caused by bias currents of active devices and leakage currents through insulators within the instrument. External circuit offsets are related to any circuit component but the measurement device itself. Possible sources and ways to minimise their influence are discussed below.

Cables of incompatible type as well as faulty connections can affect the measurement. Capacitance measurements require coaxial cables of a very precisely known length. As the cable itself has a non-negligible capacitance, the length of the cable must be very precisely known in order to correctly calibrate the LCR meter before measurement.

Low-level current measurements require triaxial cables. These cables are similar to coaxial cables, except that they have a second tubular conductor. This conductor is in between the wire and the shielding conductor and is referred to as the guard. It is driven at the same potential as the wire, which results in a zero potential difference between them and therefore eliminates possible leakage paths through the insulator. The outermost conductor is grounded, which makes that the guard is shielded from unwanted electromagnetic interference.

Tribo-electric currents are caused by friction between a conductor and an insulator. This friction can liberate electrons, which generate a charge inequality that causes current flow. This can happen when cables are bent, vibrate or when being subject to a temperature change. It is therefore required to stabilise the cable environment.

Mechanical stress on the sensor’s surface can cause deformation. This can also result in a charge unbalance and hence current flow, known as the piezo-electric effect. A possible cause is the probe needle pressing on the sensor’s surface. Low contact pressure is therefore desirable.

As both the probe station and the measurement device are connected to different power outlets, their ground potentials may differ. If a circuit has more than one physical ground connection, this could cause interference and may generate an unwanted current path, known as ground loop. Ground loops can be avoided by ensuring that the system is physically grounded to one common point.

---

\(^2\) An LCR meter is an electronic instrument used to measure the inductance (L), capacitance (C) and resistance (R) of a device.
Environmental influences

In addition to circuit offsets, the environment may also affect the measurement. Various sources are addressed below.

Most semiconductor sensors are sensitive to light. Ambient light can cause generation currents as high as several $\mu$A/cm$^2$. Measurements should therefore be made in a dark environment. Settling times after exposure can be as long as minutes.

As discussed in Chapter 2, water can form chemical bonds with contamination on the surface of the sensor or at the edge. This can cause leakage paths along the edges and through the top layers of the surface. High ambient humidity can severely affect the leakage-current behaviour of the sensor. Sensors are therefore commonly stored in nitrogen-purged (i.e. dry) environments.

The temperature determines the thermal velocity of charge carriers. Both generation in the depletion region and diffusion in the bulk regions outside the depletion region are therefore a function of temperature. The proportionality between the generation current and the temperature is given by:

$$I_{\text{gen}} \propto n_i \propto T^{3/2} e^{-\frac{E_g}{2k_B T}}.$$  \hspace{1cm} (4.1)

At two temperatures $T_1$ and $T_2$ the ratio of generation currents is then given by:

$$\frac{I_{\text{gen}}(T_2)}{I_{\text{gen}}(T_1)} = \left(\frac{T_2}{T_1}\right)^{3/2} \exp \left[ -\frac{E_g}{2k_B \left(\frac{T_1 - T_2}{T_1 T_2}\right)} \right].$$  \hspace{1cm} (4.2)

From this, it follows that the thermal generation current reduces by a factor of approximately two when the temperature drops with eight degrees. The diffusion current is also temperature dependent. Its proportionality is given by:

$$I_{\text{diff}} \propto n_i^2 \propto T^3 e^{-\frac{E_g}{k_B T}}.$$  \hspace{1cm} (4.3)

At normal operating temperatures, the generation current dominates, whereas at higher temperatures diffusion prevails.

4.3 Characterisation

A fundamental requirement for the suitability of sensors in particle and imaging detectors is electrical integrity. Before a sensor is mounted on a read-out chip, it is therefore first characterised with respect to its electrical properties. Two common methods are capacitance-voltage and current-voltage profiling.
4. Active-edge sensors: electrical characterisation

4.3.1 Capacitance-voltage profiling

As the name of the method implies, C-V profiling provides information on a sensor’s capacitance as a function of bias voltage. Hence, it gives insight into the growth of the depletion region and therefore parameters such as the full-depletion voltage as well as the average doping concentration of the bulk can be derived from the C-V curves.

As discussed in Section 2.2.1, the free-carrier depleted space-charge region forms a capacitor together with the p and n regions as electrodes. The width of this region (W_{dep}) and thus the sensor’s capacitance depend on the applied reverse bias voltage. For a one-sided abrupt p-n junction, the capacitance can be approximated as:

\[ C = \frac{\varepsilon_r \varepsilon_0 A}{W_{\text{dep}}} = A \sqrt{\frac{q \varepsilon_r \varepsilon_0 N}{2(V_{\text{bi}} - V_{\text{bias}})}} \approx A \sqrt{\frac{q \varepsilon_r \varepsilon_0 N}{2V_{\text{bias}}}}, \tag{4.4} \]

where \( A \) is the average area of the electrodes. A plot of the sensor’s capacitance as a function of the applied bias voltage (a C-V curve) therefore provides information on the growth of the depletion region. At the full-depletion voltage the region stops growing, which translates into a minimum of the C-V curve.

Another parameter that can be derived from C-V curves is the doping concentration of the substrate. Differentiating Equation 4.4 with respect to the bias voltage leads to the following expression:

\[ \frac{d(1/C^2)}{dV} = \frac{2}{q \varepsilon_r \varepsilon_0 A^2 N(W)}. \tag{4.5} \]

Because of the linear dependence of the doping concentration on \( d(1/C^2)/dV \), the capacitance of C-V profiles is often represented as \( 1/C^2 \). Figure 4.4 shows an example C-V curve together with its \( 1/C^2 \)-representation. The full-depletion voltage can be derived from the intersection of two linear fits to the \( 1/C^2 \)-curve, one in the depletion domain (i.e. below full depletion), the other in the domain beyond full depletion. The bulk donor concentration \( N_d \) can be derived from the slope of the depletion-domain fit, using the relation of Equation 4.5. This equation shows that for a correct determination of the donor concentration, the electrode area \( A \) must be accurately known (because of its quadratic dependence on \( d(1/C^2)/dV \)).

4.3.2 Current-voltage profiling

Current-voltage profiling gives information on the sensor’s leakage current as a function of bias voltage. It is a common first measurement to test the quality of the sensor and thus the reliability of the fabrication process. As will be discussed below, the leakage current is a superposition of different contributing components.

As described in Section 4.1, all sensor samples are p-n junction diodes. An ideal diode permits current flow under forward bias conditions, while at reverse bias current cannot pass through. However, electrons and holes can be thermally generated at temperatures...
above absolute zero (see Section 2.1). As a result, a small current can flow under reverse bias. This current is known as the reverse leakage current or dark current.

The I-V characteristic of an ideal diode is given by the Shockley equation:

\[ I = I_{\text{sat}} \left( e^{\frac{qV_{\text{bias}}}{k_B T}} - 1 \right). \]  

(4.6)

Under forward bias, this equation can be approximated by:

\[ I = I_{\text{sat}} e^{\frac{qV_{\text{bias}}}{k_B T}}. \]  

(4.7)

For reverse bias voltages, the equation reduces to \( I = -I_{\text{sat}} \), where \( I_{\text{sat}} \) is the reverse saturation current. In reality, however, the reverse current as a function of voltage is not constant. Impurities in the silicon bulk as well as damage and contamination at the edges cause an unwanted increase of current flow under reverse bias. Hence, in addition to the total leakage current at a given voltage, a current-voltage curve can provide information on the device’s electrical integrity. The leakage current is a superposition of three individual currents:

1. a generation current in the depletion region
2. a diffusion current in the bulk regions outside the depletion region
3. a surface current due to the surface states at the edges and faces
4. Active-edge sensors: electrical characterisation

**Generation current** Under reverse bias, free charge carriers are swept from the depletion region. As a consequence, there are no charges available for capture and thus recombination is not likely to occur. Emission processes dominate, which results in a generation current. This current depends on the carrier emission rate $dN_e/dt$ and is determined by the intrinsic carrier concentration $n_i$ and the generation lifetime $\tau_g$ (see Section 2.1.3). The generation current therefore reflects the concentration of emission states within the band gap and thus provides information on the purity of the crystal. Assuming a uniform distribution of emission centres throughout the depletion region, the generation current $I_{gen}$ can be expressed as a function of the depletion-layer width:

$$I_{gen} \approx qA \frac{dN_e}{dt} W_{dep} \approx qA \frac{n_i}{\tau_g} \sqrt{\frac{2\epsilon_r \epsilon_0 (V_{bias})}{qN}}.$$  (4.8)

**Diffusion current** In addition, charge carriers from the non-depleted regions of the sensor may diffuse into the depletion region. Once they enter this region they are subject to the externally applied electric field and drift towards one of the electrodes. This causes an additional current flow, which is called the diffusion current. This current component is proportional to $n_i^2$ and is usually insignificant.

**Surface current** The abrupt ending of the crystal at the edge and surfaces of the sensor cause dangling bonds, which give rise to intermediate states in the forbidden gap. These states increase the conductivity of those regions, as a result of which a surface current flows along the edges and through layers on the surface. Damage and contamination, which may be caused by dicing and improper passivation, promote this current flow at the edges and hence can cause undesirably high leakage currents.

An I-V profile can reveal which of the above currents is dominant and can therefore provide feedback on the manufacturing process. Neglecting diffusion currents, the leakage current $I_{leak}$ in the active area can be represented by:

$$I_{leak} = I_{gen} + I_{surf} = J_{gen} A + J_{surf} P,$$  (4.9)

where $J_{gen}$ is the generation-current density in the bulk (in A/cm$^2$) and $J_{surf}$ the surface-current density (in A/cm). $A$ and $P$ are the area and perimeter of the active area, respectively. The generation current scales with the depletion volume and thus with the square root of the voltage, while the surface current behaves Ohmically.

Therefore, the I-V curves can be fitted by the following function [109]:

$$I(V) = A \sqrt{V} + BV + C \quad \text{if } V \leq V_{fd}$$

$$I(V) = A \sqrt{V_{fd}} + BV + C \quad \text{if } V > V_{fd},$$  (4.10)

where $V_{fd}$ is the full depletion voltage and $C$ is a constant to absorb for measurement offsets.
Characterisation

An example fit together with the separate contributions of the generation current and the surface current is shown in Figure 4.5. The data are from one of the conventional TOTEM strip sensors. It shows the $\sqrt{V}$-dependence in the depletion domain and an Ohmic (i.e. linear) part beyond full depletion. In the fitting procedure, the full-depletion voltage was set as a free fit parameter. The fit-parameter values and calculated current components are listed in Table 4.2. The offset value is relatively large in this case. The current components are therefore not the true values, but they do show the ratio between the surface and volume contribution.

**Table 4.2:** Fit-parameter values and calculated current contributions from the fit of Figure 4.5

<table>
<thead>
<tr>
<th>A</th>
<th>B</th>
<th>C</th>
<th>$V_{fd}$</th>
<th>$I_{gen}$ (50 V)</th>
<th>$I_{surf}$ (50 V)</th>
<th>$\frac{I_{surf}}{I_{gen}}$ (50V)</th>
</tr>
</thead>
<tbody>
<tr>
<td>(pA/$\sqrt{V}$)</td>
<td>(pA/V)</td>
<td>(pA)</td>
<td>(V)</td>
<td>(pA)</td>
<td>(pA)</td>
<td></td>
</tr>
<tr>
<td>4.7</td>
<td>0.16</td>
<td>-8.8</td>
<td>27</td>
<td>24</td>
<td>8.1</td>
<td>0.33</td>
</tr>
</tbody>
</table>

**Figure 4.5:** Current-voltage curve fitting

The I-V curve of one of the conventional TOTEM sensors fitted by function 4.10. The separate contributions are plotted as well, which demonstrate the $\sqrt{V}$-dependence in the depletion domain and an Ohmic part above full depletion.
4. Active-edge sensors: electrical characterisation

4.4 Simulations

Before characterisation, the electric field distribution of both a sensor with n-type stop ring and one with a p-type stop ring was studied using TCAD\textsuperscript{3} software for semiconductor device simulation [110]. Some details about simulating field distributions in semiconductor sensors using this software are described in Appendix B. Figure 4.6 shows simulations of the potential distribution at full depletion of an n-type stop-ring structure and one with a p-type stop ring. The n-type stop ring is left floating, whereas the p-type stop ring is biased at the same potential as the active area. This has consequences for the electrical characteristics of the edge area, which will be discussed below. Both sensors are 300 µm thick.

![Simulations of the potential distribution at the edge at 40 V reverse bias. Part (a) represents the distribution for a sensor with an n-type stop ring, whereas part (b) shows that of a p-type stop-ring sensor. At the p-type stop ring edge, three high-field regions can be distinguished (indicated by the boxes). The n-type configuration results in only one such region.](image)

The edge distance is 100 µm and the stop ring is 25 µm wide. The simulation’s input parameters for the doping were based on the specifications given by the manufacturer. A value of $5 \times 10^{11}$ cm\(^{-3}\) was chosen for the doping concentration of $\nu$-type bulk. The diode junction was formed by a 0.4 µm deep boron implant with an acceptor concentration of $5 \times 10^{19}$ cm\(^{-3}\). The back and edge were simulated as phosphorus implants of 0.4 µm thick with a donor concentration of $5 \times 10^{19}$ cm\(^{-3}\). Using Equation 2.32, it can be calculated that at this concentration the approximate voltage at which the sensor is fully depleted

\textsuperscript{3}TCAD stands for Technology Computer-Aided Design
is:

\[ V_{\text{ld}} = \frac{qNW_{\text{ld}}^2}{2\varepsilon_r\varepsilon_0} \approx 34\text{V} \]  

(4.11)

The bias voltage used for the simulation was 40 V.

There are a number of important differences between the functionality of an n-type and a p-type stop ring. The p-type stop ring is kept at the same potential as the active area. This results in zero potential difference between the stop ring and the active region and therefore ensures there is no current flow through possibly active surface states between the stop ring and the active area. Moreover, any surface current along the edge is drained through the stop ring. In addition, a p-type stop ring straightens the equipotential lines at the edge. This has two consequences. First, the depletion region may reach the edge, as a result of which edge-defect induced generation currents may flow into the active region. Secondly, the high-field region at the edge of the active region is reduced, which has a favourable effect on the break-down voltage (see Section 4.5.2). Nevertheless, multiple high-field regions arise due to the use of a p-type stop ring, which is indicated in Figure 4.6(b).

For n-type stop rings, the field configuration is different, as shown in Figure 4.6(a). Here, the stop ring is electrically in contact with the edge electrode. As a result, surface currents can flow more easily from the edge to the active area. On the one hand, because there is a potential difference between the active area and the stop ring. On the other hand, because it does not function as a drain. Nevertheless, due to the indirect contact with the edge, n-type stop rings terminate the electric field and hence confine the depletion region more effectively than p-type stop rings at the edge.

4.5 Results

The C-V measurements were done to get a better understanding of the sensors’ internal characteristics. The results presented in this chapter, however, focus on the leakage-current characteristics of each device.

For all measurements the active area and stop ring were probed, while the back side was in contact with the electrically conductive chuck of the probe station.

For the C-V measurements the bias voltage was applied to the back electrode, while the active area and the stop ring (in case of p-type stop rings) were kept at ground. This configuration is required by the auto-balancing bridge, as leakage may occur when the low terminal is connected to the chuck.

For the I-V measurements, the biasing configuration was the other way around. Due to the availability of only two source-measure units, the active area and the p-type stop ring were biased individually, whereas the back electrode was connected to ground.
4. Active-edge sensors: electrical characterisation

4.5.1 Capacitance-voltage measurements

Figure 4.7 shows the C-V curve of one of the rectangular diodes (150 µm edge distance and 25 µm wide stop ring) together with its $1/C^2$-representation. A full-depletion voltage of approximately 22 V is derived from the intersection of two linear fits to the $1/C^2$-curve. Subsequently, the bulk donor concentration $N_d$ is derived from the slope of the depletion-domain fit, using the relation of Equation 4.5. To estimate the effective active area, the C-V response was simulated for sensors with various edge distances and a constant electrode area. Figure 4.8 shows the simulated capacitance as a function of edge distance for various bias voltages. It demonstrates that the capacitance is a function of the cross-sectional area of the depletion region rather than the electrode area. As a result of lateral growth of the depletion region, the C-V curve is smoother for large edge distances than for smaller ones.

In addition to a precise determination of the active area, the $1/C^2$-V curve should show good linearity in the depletion domain in order to accurately derive its slope. However, a discontinuity was observed in the depletion domain of some of the C-V curves. Figures 4.9(a) and (b) show the measured C-V curves for both active area and stop ring of two p-type stop-ring sensors with different edge distance (175 µm and 8 µm, respectively). The discontinuity effect is most pronounced for sensors with a large gap between the active area and the stop ring and especially shows up when the neighbouring electrode is floating. A possible explanation for this effect is shown in Figure 4.9(e). It depicts the presence of an accumulation layer of electrons directly below the thermal oxide between the active area and the stop ring. This layer is caused by positive oxide charges. At low

![Figure 4.7: Capacitance-voltage diagram](image-url)
Figure 4.8: Lateral depletion

Simulated capacitance as a function of edge distance for various bias voltages. As a result of lateral growth of the depletion region, the C-V curve is smoother for large edge distances than for smaller ones. The values are of the order of fF, because the simulated capacitance is derived from a one-dimensional representation of the sensor.

Bias voltages, these electrons may contribute to an increase of the capacitance. When the voltage is sufficiently high, the area below the oxide gets depleted from electrons, as a consequence of which the capacitance will drop. This translates into the observed discontinuity in the C-V curves. The effect is confirmed by simulations on structures with similar edge topologies. Figures 4.9(c) and 4.9(d) show simulated C-V curves with and without charges in the 180 nm thick thermal oxide. Figure 4.9(c) represents a sensor with a 175 µm gap, whereas Figure 4.9(d) shows the curves of a sensor with a 8 µm gap. Clearly, the discontinuity is not observed when there are no oxide charges present or when the gap is small, i.e. only little amount of oxide charges present.

Keeping these two effects in mind, the donor concentration of some of the rectangular diodes was determined. Table 4.3 lists these values. The average of the active area and the total area of the sensor was used for the calculation. For the error calculation, both the error on the slope of the fit and the estimated error on the active area were taken into account.

Also, the implantation process may cause variations in the doping concentration. The literature reports resistivity variations of up to 15 % [11].
4. Active-edge sensors: electrical characterisation

(a) Rect. diode; gap = 175 µm

(b) Rect. diode; gap = 8 µm

(c) Simulation; gap = 175 µm

(d) Simulation; gap = 8 µm

(e) Figure 4.9: A drop in capacitance is observed for sensors with a large gap between the active area and stop ring, especially when the neighbouring electrode is not grounded. The effect is most pronounced in the C-V characteristic of the stop ring. The same effect shows up when simulating the presence of positive charges in the thermal oxide. This may be explained by an accumulation layer of electrons directly below the thermal oxide between the active area and the stop ring, which is induced by positive oxide charges.

82
Table 4.3: The bulk donor concentration extracted from the slope of the depletion domain of the $1/C^2$-V curve.

<table>
<thead>
<tr>
<th>Rectangular diode</th>
<th>$\frac{d(1/C^2)}{dV}$ ($\cdot 10^{20} \text{ V}/\text{C}^2$)</th>
<th>Area ($\text{cm}^2$)</th>
<th>$N_d$ ($\cdot 10^{11} \text{ cm}^{-3}$)</th>
</tr>
</thead>
<tbody>
<tr>
<td>A</td>
<td>5.03 ± 0.12</td>
<td>0.21 ± 0.005</td>
<td>5.3 ± 0.3</td>
</tr>
<tr>
<td>B</td>
<td>4.68 ± 0.05</td>
<td>0.23 ± 0.005</td>
<td>5.0 ± 0.2</td>
</tr>
<tr>
<td>C</td>
<td>4.07 ± 0.05</td>
<td>0.24 ± 0.005</td>
<td>5.1 ± 0.2</td>
</tr>
</tbody>
</table>

4.5.2 Current-voltage measurements

Current-voltage measurements were made on all sensor samples with two main objectives: (i) to determine the total leakage current beyond full depletion in order to evaluate their viability and (ii) to determine a minimum edge distance for which the total leakage current is still acceptable. First, measurements were carried out to determine the overall functionality of the sensor as well as the its dependence on environmental influences.

Sensor functionality and dependencies

Before the measurements, the set-up was calibrated. The internal current offset was corrected by subtracting the open-circuit current of each source-measure unit from the measurement. By connecting the set-up components one-by-one and measuring the open circuit current for each configuration, the contributions of the individual components were determined. These are known as the external offsets of the system. A total offset of approximately 10 pA was determined, which was subtracted from the measurement results. The measurement accuracy of both source-measure units is $\pm (0.050 \% \text{ of reading} + 30 \text{ pA})$ for current values below 100 nA.

Stop-ring functionality As explained in Section 4.4, n-type stop rings are left floating, while p-type stop rings are kept at the same potential as the active area. This allows to measure the current drained at the stop ring independently and to study the functionality of the stop ring. Figure 4.10(a) shows measurements of the stop-ring and active-area current as a function of voltage. The leakage current in the active region is plotted under both biased and unbiased stop ring conditions. It demonstrates that the active-area leakage current is significantly reduced, when the p-type stop ring is biased.

Break-down voltage  Biasing the p-type stop ring straightens the isopotentials and therefore reduces the field at the edges of the active area. Figure 4.10(b) shows I-V curves up to the break-down voltage of both n-type and p-type stop-ring structures. The n-type
Figure 4.10: Stop-ring functionality and break-down voltage

(a) Current-voltage curves of the active area with and without biasing the p-type stop ring. A biased stop ring significantly reduces the leakage current. [b] Breakdown occurs above 160 V in the case of n-type stop-ring structures and above 190 V for p-type stop-ring structures.

stop ring sensors show breakdown between 160 V and 180 V reverse bias. Slightly higher breakdown voltages, not lower than 190V, were observed for p-type stop-ring sensors.

**Temperature** Generation and diffusion processes in the bulk are dependent on the temperature. Both can be modelled by the Arrhenius equation [112]:

$$I = Ae^{-\frac{E_a}{k_B T}},$$  \hspace{1cm} (4.12)

where $I$ is the reaction rate, in this case of one of the current components, $A$ is a scale factor, an empirical relationship between temperature and rate coefficient, and $E_a$ is the activation energy. This parameter represents the energy that must be overcome by the charge carrier to contribute to conductance. Figure 4.11(a) shows a measurement of the leakage current as a function of temperature at two different reverse bias voltages. To determine whether the diffusion or generation process is dominant, the data are fitted to the modified Arrhenius model:

$$I = AT^n e^{-\frac{E_a}{k_B T}},$$  \hspace{1cm} (4.13)

where $T^n$ accounts for the temperature dependence of the scale factor.

By taking the natural logarithm of Equation (4.13), the model is described by:

$$\ln I = \ln A + n \ln T - E_a \frac{1}{k_B T}.$$  \hspace{1cm} (4.14)

The current becomes a linear function of $1/k_B T$. Figure 4.11(b) shows both the data and the fits. The scale factor $A$, the exponent $n$ and the activation energy $E_a$ were set as
Figure 4.11: Current-temperature diagrams

(a) The leakage current as a function of temperature (I-T) at both 10 V and 100 V reverse bias. In the temperature domain from 20°C to 100°C, the 100 V data show good agreement with the temperature dependence of the generation current as described by Equation 4.2. (b) The I-T diagrams are plotted in terms of $1/k_B T$ versus $\ln I$ and fitted by the modified Arrhenius function of Equation 4.14. At 100 V, the leakage current is more dominated by generation than at 10 V.

Figure 4.12(a) shows the influence of humidity on the I-V characteristics of a sample with a visually damaged edge. An increase in leakage current is observed at approximately 15 V reverse bias for relative-humidity levels above 40%. This is likely to be caused by surface currents, especially since there is no passivation layer between the stop ring and the active area.

Figure 4.12(b) shows the leakage current at 50 V reverse bias as a function of the relative humidity for an undamaged sensor with the same edge distance. Since the humidity was not controlled in an accurate manner and measured at approximately 10 cm from the sensor, a significant error on the relative-humidity level is taken into account. Figure 4.12(c) shows the I-V characteristics of a typical undamaged sample at 5% and

### Humidity

Figure 4.12(a) shows the influence of humidity on the I-V characteristics of a sample with a visually damaged edge. An increase in leakage current is observed at approximately 15 V reverse bias for relative-humidity levels above 40%. This is likely to be caused by surface currents, especially since there is no passivation layer between the stop ring and the active area.

Figure 4.12(b) shows the leakage current at 50 V reverse bias as a function of the relative humidity for an undamaged sensor with the same edge distance. Since the humidity was not controlled in an accurate manner and measured at approximately 10 cm from the sensor, a significant error on the relative-humidity level is taken into account. Figure 4.12(c) shows the I-V characteristics of a typical undamaged sample at 5% and...
4. Active-edge sensors: electrical characterisation

Figure 4.12: Humidity dependence

(a) I-V curves of a rectangular diode (150 µm edge distance) with damaged edge for different relative-humidity values. (b) The leakage current plotted as a function of the relative humidity at 50 V reverse bias. (c) The I-V characteristics of an undamaged rectangular diode (also 150 µm edge distance) at 5 % and 40 % relative humidity.

40 % relative humidity. Here, practically no difference was observed between the I-V curves. This indicates good edge quality, the more so because the surface between the stop ring and active area was not passivated.
**Leakage current**

Results presented in the previous section concern measurements made on some of the sensor samples only. In this section, all samples are compared to each other in terms of leakage current. However, a direct comparison is not always possible, due to the different types of sensors fabricated.

For all sensors, the back side was grounded, while the leakage current was measured at the reversely biased active area. Because of the different diode junction layouts of each type of sensor, a specific active-area was chosen for testing.

For both the circular and rectangular test diodes the single active area was measured. Since the active area is entirely surrounded by the edge, these sensors are suitable for direct comparison.

For the TOTEM sensors, however, a very low single strip current was measured. To isolate the strip under test from its neighbouring electrodes, adjacent strips were biased at the same potential by a separate SMU. Since only one of the short sides of the strip was adjacent to the edge, these samples were mainly used for comparing the leakage current characteristics with that of conventional sensors. In addition, the functionality of the stop ring for each of the doping types could be studied.

The Medipix sensors were characterised by probing a large pad (\(\sim 1.5 \text{ mm}^2\)) located at one side of the structure. For the same reasons as mentioned for the TOTEM sensors, the Medipix samples were not very suitable for studying the edge-distance dependence.

The measurements were made at relative-humidity levels between 35% and 38% and at temperatures between 294 K and 296 K.

Due to die-separation difficulties, as described in Section 4.1, some of the samples’ edges were damaged and with it the stop ring’s functionality was compromised. As a consequence, some samples were excluded from further analysis. The selection criteria for further analysis were:

1. Visual inspection should show no obvious damage at the edge.
2. In case of p-type stop ring sensors, biasing the stop ring should reduce the leakage current in the active area.
3. The total leakage-current density in the active area should be below 660 \(\mu\text{A/cm}^2\). This value is based on the maximum leakage current that the amplifier circuit of a Medipix pixel can compensate in case of hole collection [94].

Table 4.4 shows the leakage-current density levels of the selected sensors at 50 V reverse bias, i.e. at approximately twice the full-depletion voltage. The current densities are all more than a factor 100 lower than the value of criterion 3. The errors are calculated by taking both the measurement accuracy of the instrument as well as the error on the active area into account.

The data have two shortcomings. The number of same-type samples with identical edge
### Table 4.4: Leakage-current density in the active area ($J_{AA}$) at 50 V reverse bias.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Stop ring type</th>
<th>Stop ring width (µm)</th>
<th>Edge distance (µm)</th>
<th>$J_{AA}$ (nA/cm²)</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTEM</td>
<td>n⁺</td>
<td>15</td>
<td>25</td>
<td>109.0 ± 6.5</td>
</tr>
<tr>
<td></td>
<td>p⁺</td>
<td>15</td>
<td>25</td>
<td>104.7 ± 6.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30</td>
<td>50</td>
<td>140.9 ± 6.7</td>
</tr>
<tr>
<td></td>
<td>p⁺</td>
<td>15</td>
<td>25</td>
<td>24.2 ± 6.1</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30</td>
<td>50</td>
<td>21.0 ± 6.1</td>
</tr>
<tr>
<td>Conv.</td>
<td>p⁺</td>
<td>15</td>
<td>495</td>
<td>4.7 ± 6.0</td>
</tr>
<tr>
<td></td>
<td></td>
<td>30</td>
<td>520</td>
<td>7.5 ± 6.0</td>
</tr>
<tr>
<td></td>
<td>n⁺</td>
<td>5</td>
<td>10</td>
<td>23.5 ± 3.1</td>
</tr>
<tr>
<td></td>
<td>p⁺</td>
<td>10</td>
<td>20</td>
<td>(1.052 ± 0.008) · 10³</td>
</tr>
<tr>
<td></td>
<td></td>
<td>15</td>
<td>30</td>
<td>33.4 ± 3.2</td>
</tr>
<tr>
<td>Medipix-2</td>
<td>n⁺</td>
<td>15</td>
<td>50</td>
<td>131.6 ± 0.8</td>
</tr>
<tr>
<td></td>
<td>p⁺</td>
<td>25</td>
<td>100</td>
<td>878.6 ± 5.0</td>
</tr>
<tr>
<td>Circular diodes</td>
<td>n⁺</td>
<td>10</td>
<td>25</td>
<td>(6.556 ± 0.035) · 10³</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25</td>
<td>150</td>
<td>114.5 ± 0.7</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25</td>
<td>300</td>
<td>28.18 ± 0.28</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25</td>
<td>300</td>
<td>101.3 ± 0.7</td>
</tr>
<tr>
<td>Rectangular diodes</td>
<td>n⁺</td>
<td>10</td>
<td>50</td>
<td>(1.1 ± 1.4) · 10⁻¹</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25</td>
<td>150</td>
<td>(0.6 ± 1.6) · 10⁻¹</td>
</tr>
<tr>
<td></td>
<td></td>
<td>25</td>
<td>300</td>
<td>(0.7 ± 1.6) · 10⁻¹</td>
</tr>
</tbody>
</table>
Results

The topology is too small to derive an accurate average value for the leakage-current density at a given edge distance. Moreover, the statistics are further limited due to the fact that sensors of different types do not allow for a one-to-one comparison, since the size of their active areas are very different. Nonetheless, the values of Table 4.4 demonstrate the good general quality of these sensors. They all show leakage-current density levels that are well below the maximum level that can be compensated by the Medipix-MXR chip. Whereas the leakage currents of the active-edge TOTEM strip sensors with p-type stop ring are $\sim 2$–5 times higher than those of their conventionally processed counterparts, the active-edge Medipix sensor with an edge distance of 30 $\mu$m shows a leakage current similar to that of the conventional one. The characteristics are compared in Figure 4.13. The conventional sensor even seems to draw slightly more current at bias voltages beyond full depletion. While the edge distance is more than a factor twenty smaller, the leakage currents are of the same order of magnitude. The p-type stop-ring active-edge technology therefore seems viable.

Supported by the fact that samples with identical edge topology show similar leakage-current densities, sensors of the same type were compared. In general, it seems that p-type stop-ring sensors show lower leakage currents than their n-type counterparts. In particular, this applies to the TOTEM strip sensors and the rectangular diodes. The n-type stop ring structures show leakage-current density levels of approximately 100 nA/cm$^2$. At 50 $\mu$m edge distance, approximate levels between 20 and 45 nA/cm$^2$ were measured for the p-type stop ring sensors. These values are comparable to those from the literature on edgeless sensors with a similar edge distance. Even lower values (down to 65 pA/cm$^2$ at 50 V) were obtained for structures with a 300 $\mu$m edge distance. Possibly, the edge distance can be reduced even further, but this study does not prove

![Figure 4.13: Proof-of-principle](image)

The leakage-current characteristic of an active-edge Medipix sensor compared to that of a conventional one. They show a similar leakage current, which indicates that edge distances can be reduced to tens of micrometers using this technology.
4. Active-edge sensors: electrical characterisation

The data demonstrate that an edge distance of 50 µm can be achieved without introducing leakage currents of unacceptable levels.

**Leakage-current components** Although a low leakage current is an important requirement for a sensor, values for the total leakage current at a certain bias voltage do not provide insight into the leakage-current behaviour and its individual current components. Since the edge of the test samples is close to the active area, it is interesting to compare the contribution of possible surface currents to the total leakage current. This is studied by decomposing the I-V curves into its main current components, as described in Section 4.3.2. In an identical way to the example fit of Section 4.3.2, the leakage-current components were studied. A substantial part of the curves, however, do not follow the relation of Equation 4.10 but show a steeper rise in the sub-depletion domain, possibly due to a dominant contribution of the surface current. Table 4.5 lists the fit-parameter values and the leakage current components at 50 V reverse bias of samples that showed successful fits to the I-V curves. In general, the surface current seems to dominate the leakage current of active-edge sensors, whereas the volume current prevails for the conventional structures. This is in accordance with our expectation, since there is only little space between the edge and the active area and there are no guard rings to absorb the surface current. Moreover, as mentioned in Section 4.1, the manufacturing process lacked deposition of a passivation layer between the active area and the stop ring. Furthermore, it seems that the active-area of p-type stop-ring sensors draws less surface current than that of those with an n-type stop ring. Since the p-type stop ring is biased, edge-effect induced currents are drained and hence do not reach the active area.

**Table 4.5:** Fit-parameter values and the leakage-current components at 50 V for samples that showed successful fits to the I-V curves. To indicate the dominant contribution to the leakage current, the ratio between the surface current and generation current is given.

<table>
<thead>
<tr>
<th>Sample</th>
<th>Stop ring type</th>
<th>Stop ring width (µm)</th>
<th>Edge distance (µm)</th>
<th>$I_{\text{gen}}$ (A)</th>
<th>$I_{\text{surf}}$ (A)</th>
<th>$I_{\text{surf}}/I_{\text{gen}}$</th>
</tr>
</thead>
<tbody>
<tr>
<td>TOTEM</td>
<td>Edgeless</td>
<td>n+</td>
<td>15</td>
<td>25</td>
<td>3.4·10^{-11}</td>
<td>3.5·10^{-10}</td>
</tr>
<tr>
<td></td>
<td></td>
<td>p+</td>
<td>15</td>
<td>25</td>
<td>6.9·10^{-11}</td>
<td>8.1·10^{-11}</td>
</tr>
<tr>
<td></td>
<td>Conv.</td>
<td>p+</td>
<td>15</td>
<td>495</td>
<td>2.4·10^{-11}</td>
<td>8.1·10^{-12}</td>
</tr>
<tr>
<td>Medipix</td>
<td>Edgeless</td>
<td>p+</td>
<td>15</td>
<td>30</td>
<td>7.2·10^{-10}</td>
<td>2.7·10^{-9}</td>
</tr>
<tr>
<td></td>
<td>Conv.</td>
<td>n/a</td>
<td></td>
<td>680</td>
<td>1.5·10^{-9}</td>
<td>7.2·10^{-10}</td>
</tr>
<tr>
<td>Rectangular diodes</td>
<td>n+</td>
<td>25</td>
<td>50</td>
<td>1.3·10^{-8}</td>
<td>1.6·10^{-8}</td>
<td>1.2</td>
</tr>
<tr>
<td></td>
<td>p+</td>
<td>25</td>
<td>50</td>
<td>8.3·10^{-9}</td>
<td>4.4·10^{-9}</td>
<td>0.53</td>
</tr>
</tbody>
</table>
4.6 Conclusion

Electrical integrity is a prerequisite for image and particle sensors. It determines their suitability as conversion material for highly sensitive detectors. In particular, a sensor’s leakage current is a determining factor in a detector’s noise performance.

In this chapter, active-edge sensors with different edge topologies were compared in terms of their electrical characteristics. The data show that their leakage current is comparable to that of conventional sensors. This demonstrates that the edge distance can be reduced drastically, while the leakage current is still at an acceptable level. Sensors with an edge distance of 50 µm and smaller show currents of less than 100 nA/cm². A one-to-one comparison of the sensors is not possible, due to the fact that the sensors are of a different type and hence the active-area configuration with respect to the edge is different for each type. In addition, there were difficulties in the manufacturing process, which results in a reduction of sample statistics. Therefore, a value for the minimum acceptable edge distance cannot be derived. Distances of the order of 50 µm seem feasible.

A distinction is observed between sensors with a p-type stop ring and sensors with an n-type ring. Sensors with a p-type stop ring show lower leakage currents in the active area. In accordance with expectations, these sensors also show lower surface currents in the active area. This is very interesting, since today’s "conventional" active-edge sensors are made without stop rings. It shows that a combination of active edge and a stop ring may be the solution to reduce the edge distance and at the same time protect the active area against unwanted edge effects.