Sensor specifications

R. Klanner and J. Zhang, Universität Hamburg
T. Rohe and J. Sibille, Paul Scherrer Institut

Last update September 21, 2010

1 Introduction

The research project P2 aims for the development and characterisation of the sensor part of silicon pixel detectors for

- the upgrade of the CMS pixel detector scheduled for 2016
- the AGIPD instrument for the XFEL in Hamburg

The main challenge of both projects is the harsh radiation environment, in which the detectors will be operated, which is, however, in both cases very different.

In order to realise the projects in the given tight time frame, we restrict on the use of presently available technologies. New findings or changes in the schedule of LHC or XFEL require a frequent review, and possibly also changes of these specifications.

2 High Energy Physics (CMS)

The specifications for the (barrel) sensors of the CMS pixel detector are listed in table 1. In addition the change of the specification for the future projects are indicated.

The specifications are driven by the two main tasks of the CMS pixel detector:

- Provide three unambiguous space points of every track to allow an effective pattern recognition in the dense track environment close to the LHC interaction point. This requires a high detection efficiency of each module in order to provide a sufficient number of track seeds.
- A precise measurement of the track position for the identification of displaced vertices. This is the most important criteria to tag b-jets and τ-leptons. To those measurements, the innermost layer (which suffers most from radiation damage) contributes most.

property	present	Phase I (2016)	Phase II (2020)
wafer			
thickness	$285 \pm 15\,\mu$m	$250 \pm 15\,\mu$m	$200 \pm 15\,\mu$m
flatness	$40\,\mu$m	$40\,\mu$m	$40\,\mu$m
material	DOFZ	DOFZ or mCz	DOFZ or mCz
orientation	$\langle 111 \rangle$	$\langle 111 \rangle$	$\langle 111 \rangle$ or $\langle 100 \rangle$
doping	P	P	P or B
resistivity	$3 - 5\,$kΩcm	$3 - 5\,$kΩcm	$> 1\,$kΩcm
pixel cell			
pitch $(r - \varphi)$	$100\,\mu$m	$100\,\mu$m	$75\,\mu$m
pitch (z)	$150\,\mu$m	$150\,\mu$m	$100\,\mu$m
biasing	punch through	punch through	punch through or poly
V_{pt}	$> 3\,$V	$> 3\,$V	$> 3\,$V or > 1MΩ
$C_{\mathrm{interpixel}}$	$< 100\,$fF	$< 80\,$fF	tbd
sheet resistance pixel implant	$< 500\,\Omega/\square$	$< 500\,\Omega/\square$	$< 500\,\Omega/\square$
isolation	p-spray	p-spray	tbd
module properties			
leakage current	$< 2\,\mu$A	$< 2\,\mu$A	$< 2\,\mu$A
breakdown $(\Phi = 0)$	$> V_{\mathrm{depl}} + 50\,$V	$> V_{\mathrm{depl}} + 50\,$V	$> V_{\mathrm{depl}} + 50\,$V
breakdown $(\Phi > 10^{15}\,\mathrm{n_{eq}/cm^2})$	$> 600\,$V	$> 1\,$kV	tbd
increase within 15 h	$< 30\,\%$	$< 30\,\%$	$< 30\,\%$

Table 1: Specifications for the CMS BPix-Sensors

The concept is to use an n-in-n sensor with high voltage capabilities in order to keep the efficiency high, also after irradiation and to use the analogue pulse height information of each pixel (if it is above a certain threshold) to obtain the best possible spatial resolution.

2.1 Wafer properties

The wafer properties reflect the chosen sensor concept. In order to get the highest possible signal at moderate voltages after substantial hadron irradiation, an n-in-n sensor was chosen for the present system. The collection of electrons has the following advantages:

- Large Lorentz angle causing high charge spread important for analogue charge spread
- Electrons are less prone to trapping

- Highest electric field (after $\Phi > 10^{14}\,\mathrm{n_{eq}/cm^2}$) is close to the collecting electrode

Using a P-doped (n-type) wafer requires a cost driving double sided processing, which allows for a guard ring concept having all sensor edges on ground potential. In future upgrades, especially in case much large detector areas, a much cheaper single sided sensor will be preferred. Therefore a B-doped (p-type) wafer is mentioned for the phase II upgrade. However the problems in module construction arising from the high electrical potentials at the sensor edges are presently not solved.

The thickness of 285 µm for the present detector was chosen because it was the standard of the wafer polisher used at that time. A lower thickness at that time would have caused an significant cost increase. This leads to a signal height of above 20 000 electrons (MPV) per minimum ionising particle. After irradiation induced decrease of the trapping time, the "active" thickness is reduced anyhow and using sensors thinner does not cause lower signals for hadron fluences exceeding $10^{15}\,\mathrm{n_{eq}/cm^2}$. The processing technology of thin wafers seems more advanced now, and even double sided processed wafers can acquired without huge extra costs.

Thinner sensors result also in a smaller material budget (if all other possibilities to reduce the material are exhausted) and therefore also in a better tracking accuracy.

The resistivity of the wafer has to be adjusted to the thickness in order to assure that the unirradiated sensor can be fully depleted at a comfortable voltage. More important than the actual value of the resistivity is uniformity of the wafers. A small spread of the full depletion voltage makes it easy to group modules together to the same power supply. Therefore it was required that all sensors were processed on wafers from the same ingot. This requirement should be kept.

The CERN-RD48 and later the RD50 collaboration has found out that silicon which is enriched with oxygen has favourable properties in respect to radiation hardness. Therefore the present sensors were processed on DOFZ material. In the meanwhile Cz and mCz-silicon which have naturally a very high oxygen content are commercially available in the resistivities required for sensor processing. Also there are some restrictions in the processing of those wafers (to prevent the formation of thermal donors) the material has shown to be suitable for sensor production.

2.2 Pixel cell

The pixel dimensions are defined by the requirement of the single track resolution. In the CMS pixel detector the spatial resolution is reached by interpolating between neighbouring pixels if a particle induces a signal in several pixels. In the direction perpendicular to the magnetic field of CMS

$(r-\varphi)$ this is caused by the Lorentz drift of the signal charge. In the new detector, which is biased at 150 V the number of pixels above threshold per track is about two, which is the optimum for the interpolation. Therefore a spatial resolution of about 14 µm is reached with a pixel pitch of 100 µm.

With increasing fluence of charged hadrons, the internal electric field in the sensor will change and require a higher bias voltage to obtain sufficient signal charge. The Lorentz angle which determines the charge sharing between neighbouring pixels is a function of the electric field and will therefore decrease. A slow increase of the bias voltage will therefore cause a decreasing fraction of two pixel clusters in the $r-\varphi$ direction. Eventually a spatial resolution of $\frac{\text{pitch}=100\,\mu\text{m}}{\sqrt{12}} \approx 30\,\mu\text{m}$ will be reached. A spatial resolution of about 20 µm, which is presently assumed as just acceptable, is reached at a fluence of $1.2 \times 10^{15}\,\mathrm{n_{eq}/cm^2}$ using a bias voltage of 600 V. A better spatial resolution of the highly irradiated modules can only be reached if the pixel pitch in the $r-\varphi$-direction is reduced. This, however, requires a complete redesign of the readout electronics, which is not possible within the timescale up to 2016. Therefore a reduction is only foreseen for the phase II upgrade.

In the direction parallel to the magnetic field (z), the situation is more complex. The radius of the layers is much smaller than their length, resulting in a large variation of the impact angle of the tracks. In the central region of the detector ($\eta \approx 0$), the impact angle of the tracks is close to 90° and therefore the cluster size in z-direction is basically one. This leads to a spatial resolution in the low-η-range of $\frac{\text{pitch}=150\,\mu\text{m}}{\sqrt{12}} \approx 40\,\mu\text{m}$. With increasing incident angle the fraction of two pixel clusters increases which also leads to a better spatial resolution. The best value of down to 15 µm is reached at a pseudo rapidity of $\eta \approx 0.5$ were the average cluster size is exactly two. For higher η the cluster size increases to large values and the resolution gets slightly worse. As the pixels are shorter (150 µm) than the thickness of the sensors (285 µm), the charge deposited is smaller by a factor of about two. If the charge collected in the region with long clusters is in addition reduced due to trapping the probability that one of the pixels in the cluster stays below the threshold increases. As cluster which has a "hole" is reconstructed with a very large position error, the spatial resolution in z degrades significantly. A reduction of the pitch in this direction will even worsen this effect. Therefore a reduction of the threshold of the readout chips is an important focus of all developments (but not part of this project).

The layout of the pixel cell was optimised for a good high voltage performance after the irradiation induced changes of the surface properties. Therefore the moderated p-spray technique was chosen for inter pixel isolation. The present design is rather conservative with large implant dimensions which leave a gap between the pixel implants of only 20 µm. This in addition lead to a homogeneous drift field for the signal charge but in contrary to a quite large inter pixel capacitance of about 80–100 fF a bias voltage of 150 V.

In order to reduce the capacitance, sensor layouts with larger gaps are under investigation. However it has to be assured that the more important properties (high voltage stability, signal collection, etc.) do not suffer.

For testing the sensors prior to bump bonding, a punch through biasing structure is implemented. The specifications made in table 1 are made to assure that this structure does not compromise the performance of the readout chip. However, this structure displays an area insensitive for particle detection. If the impact of this in a much reduced pixel size is still negligible has to be investigated. Therefore a poly silicon biasing with a resistance between neighbours of at least 1 MΩ , which displays a technological challenge, might be an alternative.

2.3 Module performance

The limits in leakage current and breakdown voltage are defined to monitor the quality of the production and to prevent faulty sensors from entering the production.

3 Photon detection at the XFEL

The AGIPD (Adaptive Gain Integrating Pixel Detector) is is a classical Hybrid Pixel Array Detector, with a silicon-sensor bump-bonded to a readout ASIC. Each pixel in the ASIC contains an analogue pipe-line for storing images at the 5 MHz XFEL repetition rate during the 600 micro-second bunch train, and a variable gain input stage in order to cover the required dynamic range. The images stored in the ASICs are readout, digitised and written to mass storage during the 99 millisecond inter-bunch spacing.

The most challenging requirements for the sensor part are the following:

- The high flux of 3×10^4 10 keV photons per 100 fs and pixel. For such photon fluences the local density of electron-hole pairs is of order $10^{13}\,\mathrm{cm}^{-3}$, much larger than typical doping concentrations of a few $10^{12}\,\mathrm{cm}^{-3}$, and a plasma forms in the sensor, which erodes mainly by ambipolar diffusion. Once the charges are separated, strong electrostatic repulsion results in a kind of "charge explosion". Compared to the response to e.g. single photons, the plasma erosion and charge repulsion cause a change of the pulse shape (plasma delay), an increased lateral spread of the collected charge, and possibly a non-linear response due to electron-hole annihilation. The details depend in a sensitive way on the spatial distribution of the photon flux, the angle of incidence and the photon energy. The phenomenon is known from silicon sensors used for the detection of ions and nuclear recoils.

property	value
wafer	
thickness	$500, \mu$m
flatness	$40\,\mu$m
material	FZ
orientation	$\langle 111\rangle$ or $\langle 100\rangle$
doping	P
resistivity	$\approx 5\,\mathrm{k\Omega cm}$
passivation	tbd, SiO_2 and Si_3N_4 ?
pixel cell	
pitch	$200 \times 200\,\mu\mathrm{m}^2$
biasing	DC no punch through
$C_{\mathrm{interpixel}}$	$< 100\,$fF
sheet resistance	
pixel implant	$< 500\,\Omega/\square$
module properties	
dead area (edges)	$< 1\,$mm
leakage current	$< 10\,$nA per pixel
breakdown	$> V_{\mathrm{depl}} + 50$
increase within 15 h	$< 30\,\%$

Table 2: Specifications for the AGIPD sensors

- The high integrated flux of photons of about 10 MGy do not lead to a significant crystal damage of the silicon material as in the high energy physics, but induces surface damage which is not yet properly investigated. It affects the inter pixel isolation and capacitance and depends on the crystal orientation, composition of the passivation layers, and processing details.

A standard p-in-n sensor is foreseen which is a simple and robust device. So large devices (above $\approx 80 \times 30\,\mathrm{mm}^2$) can be produced on relatively large wafers (150 mm) with a good yield.

3.1 Wafer properties

The sensor concept of the AGIPD detector is driven by the need for a robust and simple device, which displays a high yield and can be integrated into modules using a very simple IV-test of the guard rings only. This yields to a so called p-in-n sensors consisting of a P-doped (n-type) wafer with B-implants (p-type) as collection electrodes. They do not need a special isolation implant. As there is no crystal damage from hadron radiation, it is not necessary to use especially oxygen enriched material.

However, the radiation damage induced by the photons has to be taken into account. The radiation induced changes affect mainly the surfaces. Therefore the composition of the passivation layers has to be chosen with care. Investigation of surface damage is ongoing.

The thickness is chosen to 500, μm in order to provide a good interaction probability for 12 keV photons (favours thick wafers) and at the same time keep the parallax errors, signal diffusion, and depletion voltage within limits (favour thin wafers).

3.2 Pixel cell

The size of the pixel cell is defined by the required spatial resolution and the smallest possible pitch reached by the readout chip. The present value of $200 \times 200\,\mu\mathrm{m}^2$ represents a compromise between this limits.

The pixel cell will consist on a simple rectangular p^+ implant with a metallisation and contact vias. A biasing structure is not foreseen. Those devices can be produced with a yield high enough, that a test of the guard ring current is sufficient. The exact geometry of the implant is not yet decided. Criteria are the interpixel capacitance and the reaction to surface damage.

3.3 Module properties

As the photons are absorbed in the sensor, it is not possible to built a multi-module detector without insensitive area. In order to keep this area sufficiently small ($< 10\,\%$ of the total detector area), a minimisation of the guard rings are targeted. The value of 1 mm given in table 2 is conservative, a reduction to 0.5 mm seems possible.

The current limit given per pixel is driven by the tolerance of the readout chip for leakage current. In practise a much lower limit will be enforced the new sensors as a quality control measure.

4 Conclusions

Specifications for the sensor parts of the CMS-pixel phase I upgrade detector and the XFEL-AGIPD instruments are given. The investigation of the damaging mechanisms is ongoing and will require a frequent review of these numbers.