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Small pitch pixel sensors for the CMS Phase II upgrade

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The CMS collaboration has undertaken two sensor R&D programs on thin n-in-p planar and 3D silicon sensor technologies. To cope with the increase in instantaneous luminosity, the pixel area has to be reduced to approximately $2500 \mu\text{m}^2$ to keep the occupancy at the percent level. Suggested pixel cell geometries to match this requirement are $50 \times 50 \mu\text{m}^2$ or $25 \times 100 \mu\text{m}^2$, leaving little space for design choices and a possible biasing scheme. Monte Carlo studies comparing the hit resolution for these two scenarios are presented.

CMS has initiated the production of test-sensors with the envisaged pixel geometries. Status, progress, and prospects of this effort are discussed.

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I. MOTIVATION

The foreseen upgrade to the high-luminosity phase of the Large Hadron Collider (HL-LHC) is expected to result in a further increase of the luminosity to $5 \times 10^{34} \text{ cm}^{-2}\text{s}^{-1}$, producing a total integrated luminosity of 3000 fb^{-1} of collisions [1]. This leads to exceptional demands for the experiments located at the LHC. The detectors have to withstand a harsh radiation exposure (fluences up to $2 \times 10^{16} \text{ neq cm}^{-2}$) as well as an increased particle density. Hence, all experiments are preparing upgrades of the detectors for the high-luminosity phase. Currently, more than 200 m^2 of planar silicon sensors are used in the CMS experiment [2]. This technology has proven to be very reliable and predictable and is considered to be the best choice for the outer regions of a future CMS tracker. The CMS experiment also intends to use planar silicon sensors for a large fraction of the pixel detector.

For the innermost layers, two candidate technologies are investigated in the CMS R&D effort, thin planar ($< 200 \mu\text{m}$) and 3D sensors (introduced in [3]). Both approaches make use of short drift paths, thus minimizing the impact of charge carrier trapping. Furthermore, the lower voltage required to operate both types of sensors (and especially the 3D sensors) is beneficial for the power consumption after irradiation.

Because of the increased luminosity, the cell size of future

HL-LHC pixel sensors has to be downscaled to an area of about $2500 \mu\text{m}^2$. Candidate pixel sizes under investigation are $25 \times 100 \mu\text{m}^2$ and $50 \times 50 \mu\text{m}^2$. Compared to the current CMS barrel pixel design, these dimensions allow little space for design choices and a biasing scheme like a punch through dot with a bias rail (Figure 1).

Fig. 1. Illustration of the required pixel dimensions of future CMS pixel sensors compared to the current CMS BPix design.

II. THE UPGRADE OF THE CMS TRACKING SYSTEM FOR PHASE II

The design concept for the new CMS tracker [4], [5] is based on requirements to maintain efficient tracking under high luminosity conditions. With respect to the current tracker, the basic changes are: increased granularity to maintain hit occupancies in the percent range, reduced material budget in the active region, delivery of outer tracker data to the level 1 trigger to significantly reduce the input rate to the high level trigger, and radiation tolerant silicon modules that will withstand 10 years of running at high luminosity. The overall baseline tracker design is shown in Figure 2. The CMS coordinate system is defined in [2]. To aid forward jet reconstruction in the presence of high pile up, the angular coverage of the CMS tracking system is extended significantly up to a pseudorapidity of $|\eta| = 4.0$, mainly by adding forward pixel stations. This will significantly improve the physics performance in key areas like vector boson fusion and vector boson scattering. The pixel barrel detector will cover approximately the same volume as the Phase I detector. The number of pixels will increase significantly due to the

need to go to six times smaller pixel sizes. The tracker will use two-phase CO₂ cooling to remove heat from sensors and the electronics. This choice makes it possible to operate and maintain the tracker at -20°C, hereby reducing the effects of radiation damage to the silicon sensors. The material budget is also significantly reduced compared to liquid cooling.

Fig. 2. Layout of the CMS tracking system for the HL-LHC. Outer tracker layers with modules consisting of two back-to-back strip sensors (2S modules) are shown in red, layers with modules consisting of a macro-pixel and a strip sensor (PS modules) are shown in blue. The pixel detector is depicted in green.

III. FINE PITCH PIXEL SENSORS

CMS will likely reduce the pixel area by a factor of six with respect to the current detector. This can either be implemented in square pixels ($50 \times 50 \mu\text{m}^2$) or rectangular pixels, for example $25 \times 100 \mu\text{m}^2$. A simulation study, which did not take into account the effects of radiation damage, was carried out by CMS comparing these two scenarios. Single muon Monte Carlo tracks (μ^+ and μ^-) were generated and processed through the CMS detector simulation and reconstruction. The transverse muon momentum, p_T , was required to be above 0.9 GeV and the momentum less than 200 GeV. In the detector simulation pixel detector modules were implemented in these two geometries. The study was repeated with two sensor thicknesses, 100 μm and 150 μm , respectively. Three thresholds were applied in the simulation at the pixel level (1000, 1500 and 2000 electrons, respectively). The pixel readout chip under development by the RD-53 collaboration for Phase II for both ATLAS and CMS aims at a minimum threshold around 1000 electrons [6]. Hit residuals were calculated by comparing the reconstructed with the Monte Carlo generated hit position. Figure 3 shows the hit resolution in $r-\phi$ as a function of the pseudorapidity η for $25 \times 100 \mu\text{m}^2$ pixels, the same quantity is shown in Figure 4 for $50 \times 50 \mu\text{m}^2$ pixels. Figure 5 shows the hit resolution in z as a function of the pseudorapidity η for $25 \times 100 \mu\text{m}^2$ pixels, the same quantity is shown in Figure 6 for $50 \times 50 \mu\text{m}^2$ pixels. The $r-\phi$ -resolution for the rectangular pixel geometry is better than that for square pixels since the pixels are oriented with the long side in the direction of the beampipe (z). Higher thresholds in general lead to a degradation of the spatial resolution. A strong degradation can be seen at large η in case of square pixels for a threshold of 2000 electrons. This effect can be traced back to the breakage of clusters at large angles when pixels with low charge fall below threshold. The z -resolution is in general better for square pixels because their size in z is reduced by

a factor of 2. However, square pixels are more susceptible to cluster breakage for higher thresholds. Since $r-\phi$ is typically the coordinate to be measured with higher precision in a particle detector in a collider experiment, and due to the threshold-effect at large angles, this study reveals a preference for rectangular pixels of $25 \times 100 \mu\text{m}^2$. This study needs to be repeated with radiation damage effects and simulated noise, both of which will impact the resolution and the efficiency.

Fig. 3. Hit resolution in $r-\phi$ for $25 \times 100 \mu\text{m}^2$ pixel size for different thresholds and sensor thicknesses. Red: threshold=1000e, blue: threshold=1500e, black: threshold=2000e; open symbols: 100 μm sensor thickness, filled symbols: 150 μm sensor thickness.

Fig. 4. Hit resolution in $r-\phi$ for $50 \times 50 \mu\text{m}^2$ pixel size for different thresholds and sensor thicknesses. The symbols are the same as in Figure 3.

IV. SUBMISSIONS FOR SMALL PITCH TEST SENSORS

CMS has initiated a production of planar n-in-p pixel sensors on 6" wafers with a variety of different geometries, pixel isolation technologies (p-spray, atoll p-stop, common p-stop), biasing schemes (common punch through: punch through biasing common to two pixel columns) and bump bond patterns. Also a "bricked" arrangement of pixel sensors,

Fig. 5. Hit resolution in z for $25 \times 100 \mu\text{m}^2$ pixel size for different thresholds and sensor thicknesses. The symbols are the same as in Figure 3.

Fig. 6. Hit resolution in z for $50 \times 50 \mu\text{m}^2$ pixel size for different thresholds and sensor thicknesses. The symbols are the same as in Figure 3.

where every second pixel row is shifted by half of the pitch, has been implemented on the wafer. An example of the

Fig. 7. Layout of $25 \mu\text{m} \times 100 \mu\text{m}$ pixel cells with "common punch through" and p-spray pixel isolation.

structures implemented is presented in Figure 7.

At present, no readout chip compatible with $50 \times 50 \mu\text{m}^2$ or $25 \times 100 \mu\text{m}^2$ pixels is available, although there are ongoing efforts to produce prototype chips for this or a similar pixel area in the near future. Therefore, small pixel designs have

been implemented on these test wafers compatible with such a new readout chip as well as with the CMS Phase I chip PSI46dig, which has a pixel size of $100 \times 150 \mu\text{m}^2$. In the latter case, small pixels are implemented next to large pixels to keep the overall geometry compatible. An example of such a layout for testing is shown in Figure 8.

Fig. 8. Layout of $50 \mu\text{m} \times 50 \mu\text{m}$ pixel cells surrounded by larger cells to be compatible with the PSI46dig readout chip.

V. THIN EPITAXIAL SENSORS AS A CANDIDATE

Reducing the active thickness of planar pixel sensors has several potential advantages for highly irradiated sensors:

- Smaller voltages are needed to reach high electric fields, resulting in sufficient charge collection;
- Less volume and a smaller operation voltage might result in smaller bulk currents and thus in less power (cooling) and less noise;
- A smaller active thickness reduces the impact of particle trapping;
- High electric fields can result in charge multiplication due to impact ionization, hereby increasing the signal.

The obvious drawback of thin sensors is the reduced signal for non-irradiated sensors. Therefore, measurements on highly irradiated prototype sensors were used to find the optimal sensor thickness. Due to the lower radiation tolerance of the current CMS readout chip compared to the requirement for HL-LHC, bump bonded pixel sensors could not be irradiated to very high fluences. On the other hand, to bump bond a sensor after irradiation would cause unwanted annealing due to the high temperature bump bonding process. Hence, the measurements described here [7], [8] were done using $80 \mu\text{m}$ pitch prototype strip sensors [9] produced by Hamamatsu photonics (HPK) and irradiated up to fluences equivalent to the innermost layer of the pixel detector. The irradiation was carried out at the CERN proton synchrotron (PS) [10] (24 GeV proton momentum) and at the Los Alamos LANSCE facility [11] (800 MeV proton momentum, here only for fluence $1 \times 10^{15} \text{ neq cm}^{-2}$). Several materials were investigated (float-zone (FZ), magnetic Czochralski (MCz) and epitaxially grown (Epi) sensors) in different active thicknesses (100 μm and 200 μm). The main focus here is on sensors with a 100 μm thick epitaxial layer (1-1.5 k Ωcm) grown on low-ohmic substrate. All results presented in this section are for p-bulk sensors. Non-irradiated

and irradiated sensors were evaluated in the DESY testbeam with 5 GeV electrons. The device under test (DUT) was read out using the ALiBaVa readout system [12], while beam electrons were tracked with an EUDET beam telescope [13]. A five-strip cluster is defined in the DUT by identifying the strip with the higher pulseheight on both sides of the impact point of the reconstructed telescope track and adding the pulseheights of two neighbors on each side. This unbiased method is independent of threshold cuts and still yields reliable results even when the signal-to-noise is low. The DUT was kept cold (-20 to -27°C). Non-irradiated sensors were measured at $+20^\circ\text{C}$. Figure 9 shows the five-strip-cluster charge distribution for an irradiated epitaxial strip sensor with a $100\ \mu\text{m}$ active thickness irradiated to $1.3 \times 10^{16}\ \text{neq cm}^{-2}$. At this fluence, the signal is not separated from the noise, therefore a simultaneous fit to the signal (Landau convoluted with a Gaussian) and the noise (second Gaussian) is performed as can be seen in Figure 10.

Fig. 9. Charge distribution for five-strip clusters for a $100\ \mu\text{m}$ thick epitaxial sensor irradiated to $1.3 \times 10^{16}\ \text{neq cm}^{-2}$. The bias voltage was 800 V, the sensor was cooled to -27°C .

Fig. 10. Fit to the charge distribution for five-strip clusters for a $100\ \mu\text{m}$ thick epitaxial sensor irradiated to $1.3 \times 10^{16}\ \text{neq cm}^{-2}$. The bias voltage was 800 V.

The most probable value (MPV) of the Landau curve in the fit is shown in Figure 11 as a function of bias voltage for $100\ \mu\text{m}$ epitaxial sensors and a $200\ \mu\text{m}$ MCz sensor. The error bars include a statistical contribution from the fit as well as systematic errors due the conversion of ADC counts into electrons, and due to a temperature correction of the gain. One can see a decrease of the collected charge with fluence and an increase with voltage. At the highest fluence

($1.3 \times 10^{16}\ \text{neq cm}^{-2}$) the collected charge is still around 5000 e for the epitaxial sensor. The corresponding charge for the $200\ \mu\text{m}$ thick MCz sensor at the highest possible voltage is similar. The fact that there is no larger signal in a thicker sensor is likely due to a combination of charge carrier trapping and higher electric fields in the thin sensor which might lead to charge multiplication. The extracted collected charge differs from measurements taken with pixel devices due to the difference in the combination of the electric field and the weighting field. However, a relative comparison within the radiation tolerance of the different materials and thicknesses is possible. An important figure of merit for a pixel sensor

Fig. 11. Collected charge (Landau MPV based on five-strip clusters) as a function of bias voltage for strip sensors before and after proton irradiation. The Landau MPV of a non-irradiated $100\ \mu\text{m}$ thick sensor is $\approx 7500\ e^-$.

is the single pixel efficiency for a given threshold. While the charge distribution will look different for a pixel sensor, it is still instructive to turn the individual charge distributions of the strips with the maximum pulse height in a cluster into strip efficiencies. Due to the higher noise contribution, 95% was chosen instead of 99%. Figure 12 shows the threshold needed for 95% efficiency as a function of bias voltage for different fluences. At the highest fluence, the threshold for the epitaxial sensor at 800 V is still around 2000 electrons. The pixel readout chip under development by the RD-53 collaboration aims at a minimum threshold around 1000 electrons [6]. With

Fig. 12. Thresholds for 95 percent single strip efficiency as a function of bias voltage for strip sensors before and after irradiation.

measurements on different devices we also derive benchmark parameters (leakage current as presented in Figure 13, operating voltage, power consumption) as a function of the

temperature and the irradiation in order to define requirements for a future read out chip and cooling systems. The thin epitaxial sensors show rather large leakage currents, increasing strongly with voltage. The leakage currents shown are not normalized to the sensor volume. The strongly increasing

Fig. 13. Leakage current as a function of voltage for strip sensors ($2.5 \times 0.5 \text{ cm}^2$) irradiated up to $1.3 \times 10^{16} \text{ neq cm}^{-2}$.

leakage current together with an increase in charge collection efficiency as a function of voltage even exceeding unity as seen in Figure 14 for pad diodes is a hint for charge multiplication. This hypothesis is also supported by the increase in noise seen in Figure 15 for strip sensors. The increase in noise and leakage current might reduce the advantage of a sensor with charge multiplication.

Fig. 14. Charge collection efficiency (CCE) for 100 μm thick p-bulk Epi diodes as a function of bias voltage measured using an infrared laser (1060 nm).

VI. 3D SENSORS

3D sensors are candidates for the innermost layer of the pixel detector for the Phase II upgrade. The advantage of 3D silicon detectors is that the path length for signal creation is decoupled from the charge collection length. A relatively thick sensor leads to a large number of electron-hole pairs while the charge collection length is kept short by implementing readout columns transverse to the silicon surface. Disadvantages of 3D in comparison to planar pixel sensors are a higher pixel capacitance leading to higher noise, a dead region around the columns, and larger production costs.

Fig. 15. Single strip noise as a function of bias voltage for strip sensors irradiated up to $1.3 \times 10^{16} \text{ neq cm}^{-2}$.

CMS has implemented 3D sensors on a wafer processed by CNM [14], [15] for the ATLAS IBL [16] project. The pixel size is $100 \times 150 \mu\text{m}^2$, compatible with the PSI46dig readout chip. The layout can be seen in Figure 16 [17]. Testbeam measurements reveal hit inefficiencies for normal incidence when a column is hit (Figure 17) while at an incidence angle of 25° , these inefficiencies disappear (Figure 18). In CMS, this inefficiency would be reduced due to the Lorentz-angle in the magnetic field. A joint submission of ATLAS, CMS and LHCb is under way at CNM for 200 μm thick p-bulk silicon. Small 3D pixel sensors compatible with the PSI46dig readout chip and with R&D chips under development are implemented on the wafer. Among others, the aims of this run are to study small 3D pixel pitches and large aspect ratios (thickness to column diameter). First test results are expected at the beginning of 2016.

Fig. 16. Geometry of 3D sensors.

VII. SUMMARY AND CONCLUSIONS

For the high luminosity phase of the LHC, CMS will replace its entire central tracker in order to maintain efficient tracking under very demanding conditions. The pixel detector will be similar in overall volume to the Phase I detector but it is planned to extend the angular coverage significantly. The granularity of the pixel sensors needs to be increased in order to deal with high track occupancy. CMS is considering to

Fig. 17. Detection efficiency for perpendicular incidence for 2x2 pixel cells. The pitch is 150 μm in x and 100 μm in y (local sensor coordinates).

Fig. 18. Detection efficiency for 25 degree incidence for 2x2 pixel cells. The pitch is 150 μm in x and 100 μm in y (local sensor coordinates).

reduce the area of each pixel by a factor of six. Preliminary simulation studies show that rectangular pixels with the longer side along the direction of the beam pipe (z) are preferred over square pixels. For the innermost pixel layer(s) thin planar sensors and 3D silicon sensors are being considered. Testbeam studies with n-in-p strip sensors implemented on 100 μm thick epitaxial silicon show that these devices still collect around 5000 electrons at the highest fluence studied, $1.3 \times 10^{16} \text{ neq cm}^{-2}$. 3D silicon sensors are considered as a technology for the innermost layer. R&D programs on 3D sensors are under way at INFN (Italy) and CNM Barcelona. First results with pixel sizes compatible with the Phase I CMS readout chip are promising and results from an R&D run aiming at small pixel cell sizes are expected soon.

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