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A detector response model for CMOS Monolithic Active Pixel Sensors

C. Dritsa*
IPHC Strasbourg, GSI Darmstadt, Goethe University Frankfurt
E-mail: c.dritsa@gsi.de

M. Deveaux
Goethe University Frankfurt

CMOS Monolithic Active Pixel Sensors (MAPS) have demonstrated excellent performances in terms of charged particle detection. Due to their excellent spatial resolution ($1-5\ \mu$m), their light material budget (0.05 % X_0) and their advanced radiation tolerance ($3 \cdot 10^{13}\ n_{eq}/cm^2$), the pixels are foreseen for a use in various vertex detectors in nuclear and particle physics experiments like CBM, STAR and potentially the ILC. Accurate detector simulations are needed to design these vertex detectors and to demonstrate their ability to measure the observables relevant for the physics goals of the experiments. In the context of the development of the CBM-Micro Vertex Detector, we developed a detector response model conceived for MAPS sensors. The model is described and its performances are compared with real data acquired in a beam test performed at the CERN-SPS.

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*Speaker.

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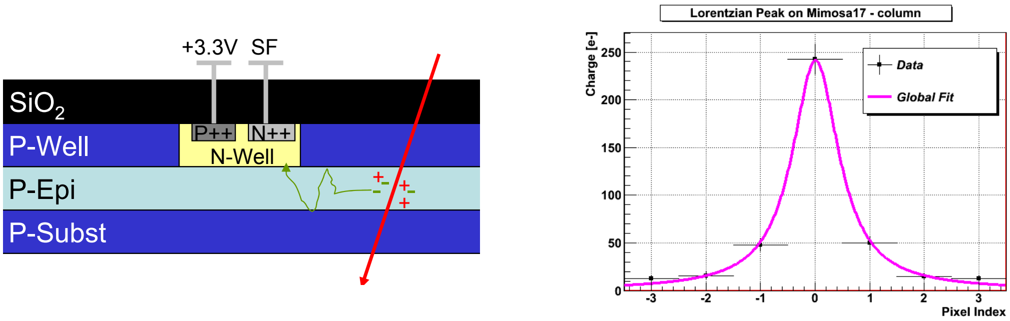

Figure 1: Left panel: MAPS operation principle. Right panel: Lorentzian fit on experimental data. The data points correspond to the most probable value of the charge per pixel in the central column. The central pixel (30 μm pitch) is indicated by the index 0.

1. Introduction

The Compressed Baryonic Matter experiment (CBM) [1] will be one of the core experiments of the future FAIR facility [2] at GSI, Darmstadt. The experiment will study nuclear matter in the regime of highest baryonic densities with various rare probes, among them open charm. Reconstructing those particles requires a Micro Vertex Detector (MVD) which is formed from detector layers that should provide excellent spatial resolution, (≤ 5 μm), very low material budget ($\leq 0.3\%$ X_0) and advanced radiation tolerance ($\geq 10^{13}$ n_{eq}/cm^2) [3]. Therefore, Monolithic Active Pixel Sensors (MAPS), are the foreseen technology for the first generation MVD [4]. Since in CBM open charm production will occur close to the production threshold, a high collision rate of $10^5 - 10^6$ s^{-1} is ambitioned for the corresponding measurements. This implies that the detector would need a time resolution of 1-10 μs to separate the individual collisions. This time resolution is challenging to reach for MAPS, as it is expected that they will not have a time resolution better than ~ 30 μs for the first generation MVD. However, given the excellent granularity of those sensors, it is believed that one can reach the ambitioned minimum collision rate of 10^5 s^{-1} by tolerating a moderate pile-up of events in the detector. Precise and realistic simulations are necessary to validate this approach and to optimize the design of the MVD accordingly. In particular, it has to be studied, if the expected high detector occupancies will lead at some point to a significant number of merged clusters, which might reduce the quality of the track and secondary vertex reconstruction in CBM.

In order to obtain conclusive results, a fine tuned detector response model for MAPS is needed. This model has to simulate accurately the average number of significant pixels per cluster, as well as the shapes of regular and merged clusters of particles impinging the sensors with all incident angles. The latter is needed as the occupancy of the CBM-MVD is dominated by the high number of δ-electrons knocked out from the target by the primary beam. Being deflected by the field of the dipole magnet of CBM, a substantial fraction of those low momentum particles impinge the MVD with angles above 60°.

In this work, we present a detector response model for MAPS, which is suited for simulating the questions mentioned above. Moreover, we compare the performances of the simulation model with measured data acquired at the CERN-SPS with a beam of 120 GeV/c pions. The sensor under test was a MIMOSA-17, with a 30 μm pixel pitch and a 12-bit external ADC.

2. MAPS, operation principle and simulation model

MAPS [5] consist of three layers formed by a moderately p-doped epitaxial layer, which is located between two highly doped zones: the substrate and the p-well implantations (see Figure 1, left). The doping levels of both layers are roughly three to four orders of magnitude higher than the one of the epitaxial layer, which introduces potential barriers at the region boundaries. Free electrons generated by an impinging particle in the epitaxial layer diffuse thermally in this layer but cannot leave it because of the above mentioned barriers. Regularly implanted n-wells collect the electrons passing in their vicinity and direct them to an on-pixel preamplifier.

In a first attempt to simulate the response of MAPS, we tested a detector response model [6] used in simulations for the International Linear Collider (ILC). Being initially developed for depleted detectors, this model simulates simultaneously the drift of the charge carriers in the electric field of depleted detectors and the expansion of this cloud by thermal diffusion. As expected from literature, a good choice of model parameters allowed reproducing with good accuracy the response of MAPS in terms of average pixel multiplicity in a cluster. However, we noticed that the approach shows weaknesses in providing at the same time a realistic picture of the charge sharing. This feature was feared to bias the CBM-MVD simulations as the simulation of cluster merging requires a good description of the charge deposit also for the less significant pixels in the outer crowns of the cluster[1].

To overcome this limitation, the charge distribution mechanism was modified. This led to a different approach, derived from the above mentioned simulation model. We model the interaction of particles with the material by generating charge in ionization points along the particle trajectory in the epitaxial layer. This charge is afterwards distributed over the pixels. Currently, the assumption is made that the epitaxial layer is uniform and therefore the diffusion of the generated electrons is independent from their starting point. So far, this approach is similar to the previous one. The modification consists in distributing the charge according to a measured Lorentz distribution. The latter is derived from experimental data as following: first, all clusters created by impinging particles are identified. The clusters have by construction 7×7 pixels, and the pixel with the highest signal charge is located by definition in the middle (index 0). Next, for each pixel in the central column[2], the charge distribution is fitted with a Landau function. The most probable value (MPV) of the latter is plotted as a function of the pixel index in the column (see Figure 1, right panel). Finally, those data points are fitted with a Lorentz function. The experimental data on the cluster shape were obtained from measurements with tracks at normal incidence.

The total charge initiated by the track is generated as a random number according to the Landau distribution measured for tracks at normal incidence. Inclined tracks are simulated by scaling the total charge according to the length of the particle trajectory in the epitaxial layer.

[1]Pixels at the border of the clusters do usually not collect enough signal charge to impact significantly the cluster reconstruction. However, as in the case of close particle hits, they receive signal from both particles, they were assumed to play an important role in cluster merging.

[2]The direction of the column is defined as the one perpendicular to the read-out direction of the sensor.

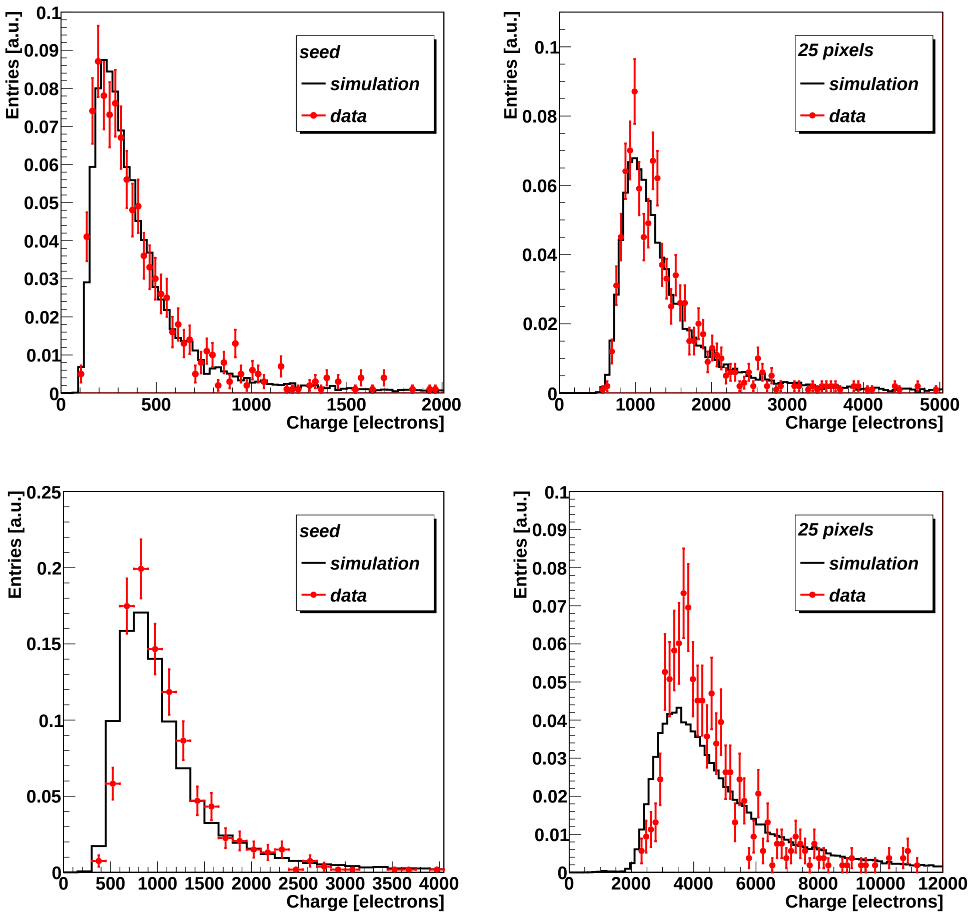

Figure 2: Landau distributions of the accumulated charge in the seed and on 25 pixels, for 0° (top panel) and 75° (bottom panel) particle incident angle.

As input from measured data is needed, the model is not able to predict the properties of MAPS but it can reproduce accurately their response profiting from a rich data base of the properties of different MAPS prototypes obtained in numerous beam tests. The simulator was complemented with a clusterisation algorithm, which allows reconstructing clusters independently of their shape. Moreover, it provides the option to simulate MAPS with analogue or digital readout (ADC of 1 up to N bits, where N>> 1).

3. Evaluation of performance

Data simulated with the model have been compared with data acquired at the CERN-SPS with a 120 GeV/c pion beam. The evaluation includes the cluster charge and the average number of significant pixels in a cluster.

A comparison of the total charge distribution in the pixel with the highest charge (seed) and in a cluster of 5×5 pixels is shown in Figure 2, for simulated and measured data. The model, which was tuned with 0° data (top panel of Figure 2), performs a satisfactory prediction of the charge

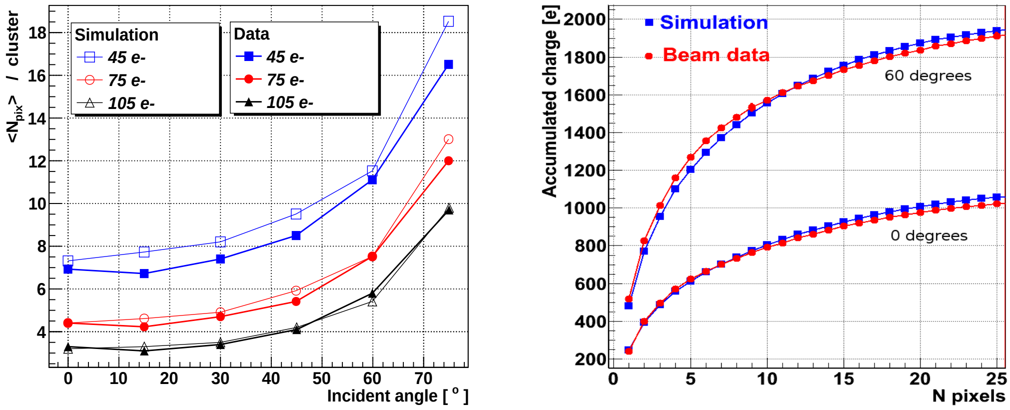

Figure 3: Left panel: Average number of significant pixels ($< N_{pix} >$) per cluster as a function of the incident angle for simulated (open symbols) and real (full symbols) data. Three different thresholds are used to select significant pixels: 45, 75 and 105 electrons. Right panel: The accumulated charge, Q_N, as a function of the number of pixels in the cluster. Two incident angles are compared: 0° and 60°.

distribution of clusters produced by particles with larger incident angles (bottom panel of Figure 2). Figure 3, left, depicts the average number of significant pixels in a cluster for different thresholds, as a function of the particle incident angle for measured and simulated data. Three different values of charge threshold are used for identifying a significant pixel: 3×noise, 5×noise, 7×noise, i.e. 45, 75, and 105 electrons for a measured noise of the sensor amounting to 15 electrons. A very satisfactory agreement, i.e. within 10%, of the pixel multiplicity is observed.

The simulated and measured charge in the pixels of a cluster are compared on the right hand side of Figure 3. This plot accounts for the fact that the total signal charge generated by an impinging particle is distributed over a cluster formed from M $(= 5 \times 5)$ pixels. To obtain the plot, we sum the signal charge collected by a subset of the N<M pixels showing the highest charge in one cluster. For every value $1 \leq$ N $\leq$ M, this sum is filled into a separate histogram H_N. After all clusters are analyzed accordingly, each of those histograms contains a Landau distribution. This distribution is fitted for all histograms. The most probable value of the signal charge of the subset of N pixels, Q_N, is obtained by fitting the Landau distribution observed in the histogram H_N. In the figure, Q_N is plotted against N, which provides information about the charge sharing inside the cluster. For example, for the tracks at normal incidence, the seed pixel contains roughly 30% of the total charge in the cluster while a group of 10 pixels contains already almost the total charge of the cluster. We show the result of comparison for two incident angles: 0° (tracks perpendicular to the sensor plane) and 60°. One observes that the charge repartition in the cluster is well described by the model.

4. Summary and Conclusion

We developed and tested a detector response model for MAPS which is adapted to simulating the CBM-MVD. The model parameters were tuned according to data measured in a beam test at the CERN-SPS for tracks at normal incidence on the sensor surface. The model predictions for those tracks as well as for inclined tracks (up to 75°) were compared with measured data. The model describes within 10% accuracy the most crucial parameters for the foreseen simulations, which are the pixel multiplicity and the charge sharing of the pixels in the cluster. The software has thus become a regular component of the CBMRoot simulation [7] framework.

Acknowledgments

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