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Spatial resolution analysis of micron resolution silicon pixel detectors based on beam and laser tests

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ABSTRACT

Pixel sensors with micron resolution are being developed by several groups, and this development comes hand in hand with the development of new resolution enhancement methods specially suited to the new sensors. This paper summarizes the results of our study of hit reconstruction methods used in analysis of Depleted P-Channel Field Effect Transistor (DEPFET) beam test data.

The study is based on data of DEPFET beam tests at CERN in 2006 and 2007, and on laser tests using a pulsed 682 nm laser. In beam test data analysis, we used a new method to separate the contributions of intrinsic resolution, multiple scattering and track uncertainty to impact point prediction error. We compared several methods of hit reconstruction for pixel detectors, based either on beam test tracks or on laser matrix scans for a range of laser pulse energies. We show about 20% improvement in the resolutions calculated from the data of two DEPFET beam tests with different detector setups. We also show that impact point correction derived from laser tests can be applied in tracking.

1. Introduction

A new generation of track detectors for high energy physics is being designed to allow track reconstruction with sub-micron precision. Pixel detectors with micron resolution are a basic prerequisite of such designs. The Depleted P-Channel Field Effect Transistor (DEPFET) structures are a good example of such micron resolution pixel detectors [1]. With such precise detectors, however, the determination of spatial resolution from beam test measurements becomes complicated because multiple scattering contributes significantly to tracking errors. This is further complicated if detectors with different (and unknown) resolutions are used as telescopes, as in the case of DEPFET beam tests.

Similarly to strip detectors, positions of space points in pixel detectors are usually corrected using η-correction (homogenization of the impact point distribution, more in Ref. [2]) in both directions. However, this approach has a serious limitation. Firstly, it assumes independence of corrections in x on y and vice versa. Secondly, pixel detectors with integrated electronics on each pixel may contain areas with different charge-collecting properties.

The present paper is a summary of a detailed study of precision of track reconstruction on several DEPFET structures with pixel dimensions between 22 and 36 μm. We studied several hit reconstruction methods on a sample of beam test data and a series of laser scans. Two methods of impact point position calibration based on beam test tracking and laser scan are compared with the traditional combination of η-corrections in both dimensions.

2. Methods

This section summarizes the measurements and data analysis procedures used in this study.

2.1. Detector description

We used DEPFET sensors manufactured in MPI [1] with active readout structures located on the sensor surface. The tested sensors were test samples intended to verify the properties of

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different structures, so their resolutions differed and changed as their working settings were optimized. This made analysis complicated and initiated the development of improved resolution analysis methods. Common properties of detectors were: pixel structure 64×128 columns, thickness $450\,\mu m$, common clear gate version, pixel size between 22 and $36\,\mu m$ and bias voltage 200 V for all detectors. As we worked with experimental samples, in some cases only a part of the sensor sensitive area was available. Same samples with the best resolution have S/N (cluster charge/pixel noise) higher than 110. We used detectors produced with high and medium energy implantation technology. For more details, we refer to Ref. [1].

2.2. Charge distribution calculations

To study the differences in charge sharing between beam tests and laser measurements, we used the approach outlined in Ref. [3]. Briefly, we calculated the charge distribution on the detector surface as follows: (i) the initial distribution of charge created by a traversing particle or by laser light was segmented into small cells. (ii) The charge from each cell was allowed to diffuse as it was drifted by electric field inside the silicon bulk towards the detector surface. (iii) The distribution on the detector surface was calculated as a sum of charge distributions arising from individual cells. The electric field inside the detector was approximated by electric field of p–n junction.

2.3. Beam test

This study includes evaluation of two beam tests at CERN SPS with 180 GeV π^+ and with five detectors in different arrangements (Fig. 1).

The 2006 beam test was focused on testing high energy implantation type of DEPFETs in a geometry favorable for fine analysis of resolution with minimization of multiple scattering. The results of this test were used to check the reliability of different hit reconstruction methods and to estimate the best achievable precision of DEPFET in the beam.

The 2007 beam test used a different type of DEPFET with medium energy implantations and a different geometric arrangement supporting tilting of two detectors. One detector on position 2 (Fig. 1) used in this beam test was tested by laser beam and was used to compare several methods of hit reconstruction, including, in particular, impact point reconstruction based on laser tests.

2.4. Laser test

Laser test was used to check functionality of DEPFET matrices before beam tests. After the beam tests, laser test was used for fine inter-pixel response characterization using the settings of the 2007 beam test.

The tests were carried out using red (682 nm) light. Infrared 1065-nm light penetrating the silicon should better mimic the ionization particle passage, but reflections from inner structures seriously complicate interpretation of the results. Schematic of the setup is shown in the right panel of Fig. 1.

For impact point reconstruction, we carried out a set of measurements including pixel region identification and high statistics scans of 20×20 points on a grid of $2.5\,\mu m$ for a wide range of laser beam powers (Fig. 2). The test readout used trigger from the laser in the same arrangement as for beam tests. Each point was probed by 50 pulses to eliminate laser noise and obtain a precise pixels response. Laser power was controlled, monitored and calibrated to energies generating the same charge per laser pulse as a typical particle in a beam test. Pulse duration was ≈ 3 ns, much shorter than the collecting time of $\approx 1\,\mu s$.

2.5. Analysis

We used several methods going beyond the standard beam test analysis (for example, Ref. [4]). These include track finding using a PCA filter, robust alignment, and resolution calculations taking into account multiple scattering and avoiding infinite energy extrapolation. For details, we refer to Ref. [5].

We studied the following variants of impact point reconstruction: (i) no η-correction, only center-of-gravity (COG) estimate, (ii) standard 1D η-corrections [2] applied independently in both directions, and (iii) (for one detector) 2D impact point correction calibration based on laser test (Fig. 3).

The laser calibration was calculated as follows: Using the results of a laser scan, we calculated the difference between the true position of a laser beam (based on position setting of an XY

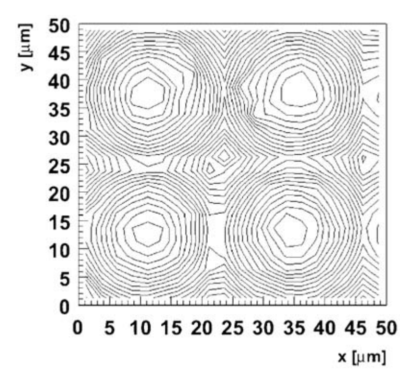

Fig. 2. A typical cluster seed distribution as determined by a laser scan. The displayed area is 2×2 pixels of $24 \times 24\,\mu m$. The difference between the maximum and minimum points is 400–800 ADU.

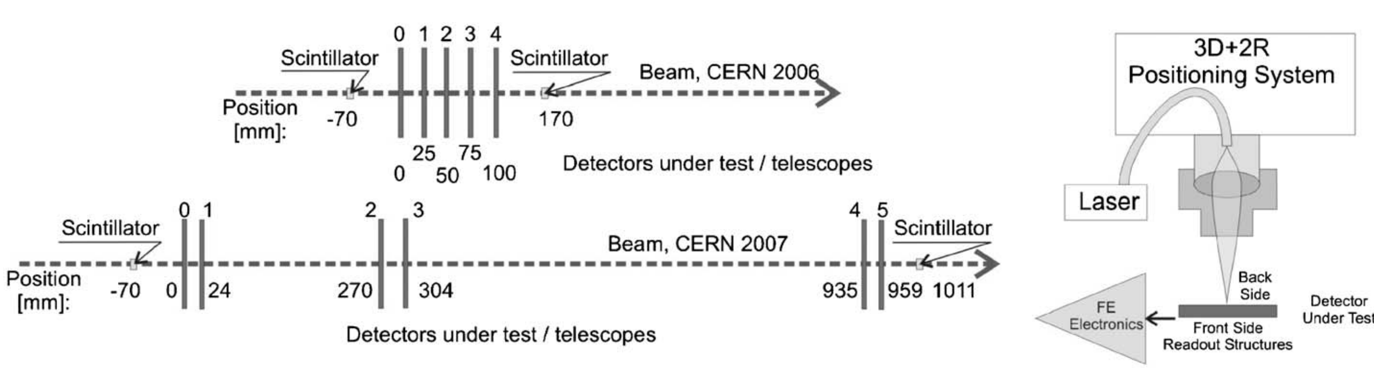

Fig. 1. Geometries of the CERN DEPFET beam tests in 2006 (top left) and 2007 (bottom left), and of the laser scanning setup (right).

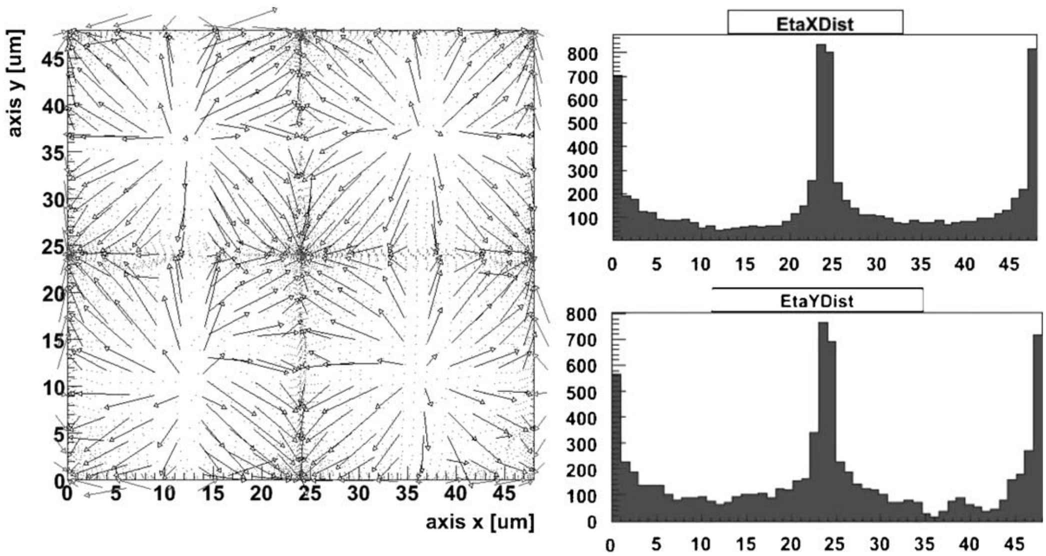

Fig. 3. Laser test: an example of a 2D impact point correction field (left), X (top right) and Y (bottom right) projections of hit distribution within pixels.

stage) and the position reported by the detector. We then constructed a Delaunay triangulation of the correction map for x and y coordinates and found the correction for beam test hits by interpolating in the triangulated surface [6].

3. Results and discussions

3.1. Detector resolutions

Table 1 summarizes resolutions for the DEPFET detector in position 2 used in the 2007 beam test. We list resolutions for different impact point correction methods and also report the resolution of the telescope system at the detector plane and the contribution of multiple scattering to the telescope resolution.

The calculated resolutions of detectors are stable parameters and do not differ (within experimental error) in the geometries of the 2006 and 2007 beam tests. Also, the resolution does not depend on position of a detector in the setup (the rightmost two detectors in Fig. 1 were swapped in the 2007 beam test). The only parameter which is affected by unfavorable geometry or lower statistics is the error of resolution.

Thus, the resolutions calculated by our method are a useful tool in evaluation of other analysis methods, such as the impact point reconstruction methods described in the next section.

Laser test was carried out on one of the modules used in the 2007 beam test. The test comprised a set of measurements including pixel region identification and high-statistics detailed scan of a 2×2 pixels region. The measured residuals were used for the determination of an exact 2D impact point position calibration and for direct detector resolution measurement. The detector resolutions as determined by laser tests are, within experimental error, equal to the tracking resolutions.

3.2. Impact point reconstruction

As seen from Table 1, the calculated resolution of a detector depends on impact point reconstruction method used.

In the absence of a feasible "full" 2D η-correction algorithm, the best available variant of η-correction applicable for pixel detectors is the combination of independent 1D η-corrections in both directions. This method is conceptually simple, but restrictive: it assumes that corrections in x and y are independent.

Table 1
Resolutions for the 2007 DEPFET beam test (CERN SPS) module in position 2 for different methods of impact point reconstruction.

Method	x resolution (μm)	y resolution (μm)
COG (no η)	4.35 ± 0.28	4.20 ± 0.16
Beam test η	3.34 ± 0.27	3.40 ± 0.16
Laser test calibration	3.41 ± 0.27	3.62 ± 0.17
Telescope error	3.63 ± 0.13	2.11 ± 0.10
Multiple scattering	0.71	0.71

We also report the resolution of the telescope system at the DUT plane and the (RMS) contribution of multiple scattering to the telescope resolution.

This η-correction remarkably (by more than 20%) improves detector resolutions for all detectors and both coordinates. For example, the correction reduced the resolution of the best detector in the 2006 beam test setup from 1.11 ± 0.15 to $0.83\pm 0.18\,\mu$m.

A search for a method that could provide good impact point position correction for pixel detectors and, at the same time, be able to detect areas of charge collection inefficiency within pixels, inevitably leads to methods which we call "impact point position calibration", to distinguish them from η-correction methods. These methods rely on experimental determination of corrections to centroid estimates.

Such determination can be based on tracking, where the corrections are calculated as mean difference between track intersection and centroid estimate for a given position on the detector, or on laser scans, where we have independent information about the position of the laser beam.

In Fig. 3 we show a calibration map based on a laser scan. The map is a vector field of displacements between actual and measured (COG) positions of laser spot. Fig. 4 shows a calibration map constructed from the data of a (low-statistics) beam test run. The map shown in this figure is a vector field of displacements between hit positions forecast by tracks and COG estimates. The resolutions for track calibration correction are not presented in

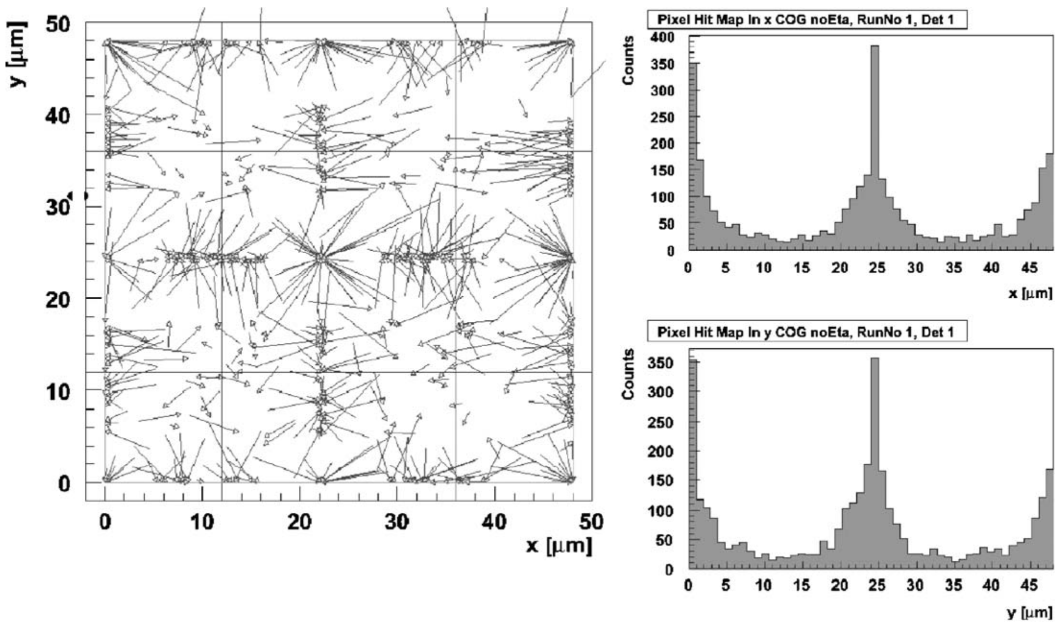

Fig. 4. Beam test: an example of a 2D impact point correction field (left), *X* (top right) and *Y* (bottom right) projections of hit distribution within pixels.

Table 1, since we did not have sufficient statistics for the selected detector in the 2007 beam test.

To be usable, the field has to be smoothed and an interpolation method is needed to calculate corrections for beam test hits. A special complication arises due to hits that do not induce charge sharing in one or both directions—these must be treated separately.

The basic advantage of laser calibration is a detailed information about response and local resolution from every point in a pixel, and very precise impact point correction due to cheaply achievable high statistics. A disadvantage is a different mechanism of charge creation and, consequently, a slightly different profile of collected charge distribution, as described in the following section.

3.3. Charge distribution calculations

The mechanisms of charge creation and its sharing among sensitive cells of the sensor determine the precision of a detector and methods of hit reconstruction. Charge sharing among detector cells arises due to diffusion of charge carriers in silicon bulk and drift by electric fields.

We studied the differences in charge sharing between beam tests and laser measurements. These measurements differ by the mechanism of charge creation and, consequently, by initial charge distribution.

A charged particle crossing the silicon bulk generates electron–hole pairs along its track. The generated charge drifts in the electric field and is collected on the detector surface (see Figs. 5 and 6). The final distribution of collected charge for a particle, reconstructed using our calculations, has a pointed, clearly non-Gaussian shape with $FWHM \approx 1.3\,\mu m$ (particle track perpendicular to detector plane, detector thickness 450 μm, bias 200 V, temperature 20 °C, collected charge ≈ 5.1 fC).

A laser beam creates charge in a region dependent on the wavelength of light: 650 nm light penetrates few microns deep into silicon, 950 nm light about 300 μm and 1050 nm light loses about 30% energy when traversing 450 μm of silicon. Based on the

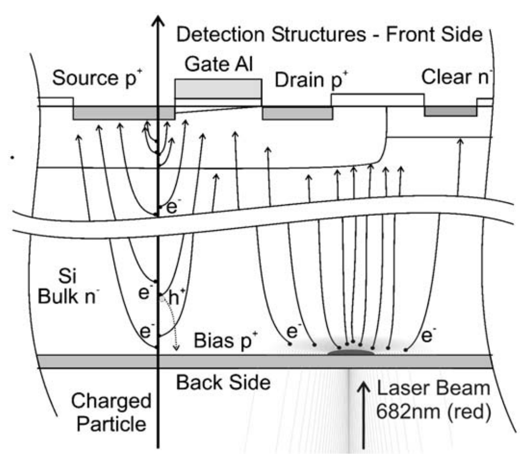

Fig. 5. Schematic of charge creation by a particle traversing a silicon detector (left) and by a red (682 nm) laser beam (right).

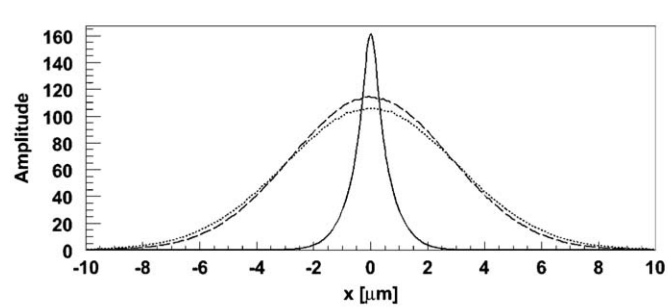

Fig. 6. Simulated charge distribution on the detecting surface generated by a particle traversing the detector (solid line), by a red (682 nm) laser beam (dashed line), and by an infrared (1065 nm) laser beam (dotted line). The particle track and laser beam are perpendicular to detector surface. The laser produces 4× more charge than the particle, spot width is in the text.

depth of penetration, the charge is created in a column with a profile copying that of the beam and density exponentially decreasing with penetration (see Figs. 5 and 6 as an example).

The particle-generated charge distribution is narrower and, consequently, more sensitive to local variations of charge-collecting fields than the charge distribution induced by a laser with a spot width $\sigma \approx 2.8\,\mu m$. Additional diffusion from charge diffusion and drift by electric fields is $1.4\,\mu m$. Thus, in general, we will see more charge sharing with a laser beam than with particles.

4. Conclusions

The studied methods of hit reconstruction using impact point position calibration from laser tests and reconstructed tracks from beams gives improvement of pixel detector resolution more than 20%. The best of the tested DEPFET structures consistently achieve sub-micron resolution in the fine coordinate.

The laser calibration function is a useful tool for mapping detector precision and could serve as a process quality monitoring tool in case of mass production of modules for a sub-micron semiconductor tracker.

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