Nuclear Instruments and Methods in Physics Research A 650 (2011) 230–234

Contents lists available at ScienceDirect

Nuclear Instruments and Methods in Physics Research A

journal homepage: www.elsevier.com/locate/nima

A grazing angle technique to measure the charge collection efficiency for CMOS active pixel sensors

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ARTICLE INFO

Available online 21 December 2010

Keywords:
Charge collection efficiency
CMOS APS
Grazing angle

ABSTRACT

Recently, CMOS Monolithic Active Pixels Sensors have become strong candidates as pixel detectors to be used in high energy physics experiments. A very good spatial resolution and an excellent detection efficiency could be obtained with these detectors. Beside spatial resolution and detection efficiency, an important parameter to be investigated is the charge collection efficiency (CCE) as a function of the distance from the detector surface. In this paper a new approach to measure the CCE profile by means of ionizing particles is proposed.

1. Introduction

CMOS Monolithic Active Pixel Sensors can be used as charged particle tracking devices, integrating on the same silicon substrate a radiation sensitive detector element with its front-end readout electronics [1–3]. Following the mainstream of microelectronics technologies, CAD tools are used for their design, and modern submicron or deep submicron commercial CMOS processes can be adopted for their fabrication. After production the device is directly ready to be used without any use of complicated and expensive post processing (e.g. bump-bonding with a dedicated readout chip). Typically, prototypes of monolithic active pixel sensors were fabricated using a CMOS process option featuring on top of bulk substrate a thin lightly p-doped silicon epitaxial layer grown on a heavily p++ doped thick ($\sim$300 μm) supporting structure. On top of the epitaxial layer, structures of n+ wells are formed. The detector is only partially depleted in the proximity of the n-well/p-epi junction (1–2 μm in depth), so the charge is collected mainly through a thermal diffusion mechanism. The detector active volume is limited mostly to the epitaxial layer only and the charge collection efficiency (CCE) tends to decrease towards the sensor bulk, because of the small lifetime of charge carriers inside a p++ substrate. In this work a new method to precisely measure the CCE profile by means of ionizing particles almost parallel to the sensor plane is proposed.

2. Grazing angle technique

The most direct way to accomplish the measure of the CCE profile is to generate a known amount of electron/hole pairs at a given depth and then to measure the pixel response. However, this is not an easy measurement because it requires an accurate and complex setup. Various methods have been proposed in the past, mainly for microstrip devices, among which a method using an IR laser entering from a polished side of the silicon bulk, focused at different depths under the sensitive region [4] and a method using charged particles incident at a small angle on the sensor surface (which is our starting point as well) [5,6].

In all the previous cases the most relevant problem is the obtainable spatial confinement for the charge generation, which is several micrometers at best.

In our modified grazing angle approach, the charged particle crosses several pixels, each one at a different depth (see Fig. 1), depositing a known amount of energy and producing a voltage drop (ΔV) at each photodiode. For a given incidence angle, the nth pixel in the track is always crossed by an incident particle at the same depth. For each pixel position a signal distribution could be built modeled by a Landau–Vavilov function. The MPV (Most Probable Value) for each pixel position will depend on the generation depth and could be used to build the CCE profile function.

The track will be detected with a sharper definition near the sensor surface and a more unfocused one in depth (worse S/N and worse spatial resolution), as can be seen in Fig. 2, where the online display of two simultaneous tracks entering the detector is visible. The pixel signal evolution along the track is consistent with track 1 entering from the surface side and track 2 from the back side. In other words, brightest pixel at the right hand side of track 1 could be ascribed to

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[1] Supported by a grant from the Regione Umbria, Italy (POR FSE 2008).

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doi:10.1016/j.nima.2010.12.122

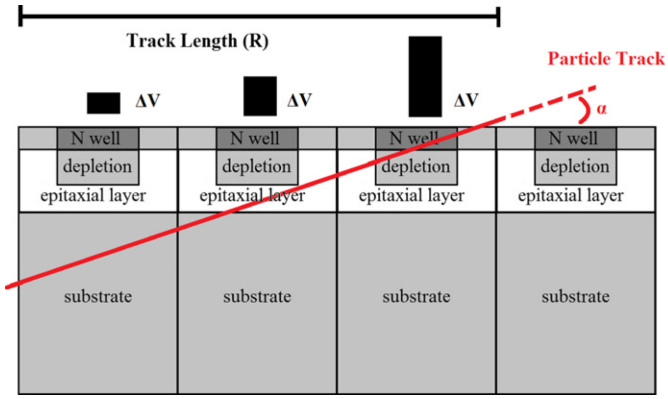

Fig. 1. Schema of grazing angle method: several pixels are hit by the same track.

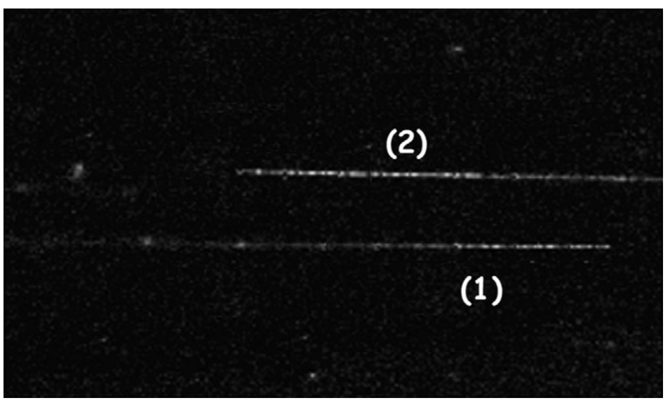

Fig. 2. Online display of two simultaneous tracks entering the sensor from opposite sides (100 MeV electrons coming from the right). Track entering from sensor surface (1) and from sensor back (2).

closer-to-the-surface charge generation and therefore greater charge collection efficiency.

The incident angle (α) is strictly related to the track length (R) by the expression $R = d/\tan(\alpha)$, where d is the sensitive layer of the sensor, often unknown. To control, within a small error, the charge generation depth particles with the same length (in pixel unit) are selected.

3. Test setup

To test the validity of this method a MICRON MT9V011 CMOS Sensor [7] featuring $5.6 \times 5.6\ \mu m^2$ pixel size, with 640×480 pixels matrix and 4 μm epitaxial layer has been used. The readout of the sensor is assured (Fig. 3) by the Demo2 board and the MT9SH06 evaluation board, with an USB line to power the system, to control the sensor and to receive the data. The sensor under test has no microlenses over the pixels and is run in monochromatic mode to equalize the pixel response. The Single Pixel Noise, measured in absence of external stimuli, is equal to 3.6 ADC. The sensor was exposed to 100–500 MeV electron beam at Laboratori Nazionali di Frascati (LNF), Rome (Italy) and 12 GeV protons at CERN, Geneva (Switzerland) Proton Synchrotron (PS). To have tracks lenghts up to 100 pixels a small incidence angle was used.

The grazing angle choice has been dictated by the sensor geometrical constraints: the maximum sensitive region could be guessed, as a first approximation, at about twice the epitaxial layer thickness. Defining the maximum grazing angle as the angle at which tracks of 100 pixel length are possible, we obtain an incidence angle of 0.8°. The sensor has been mounted on a rotational stage,

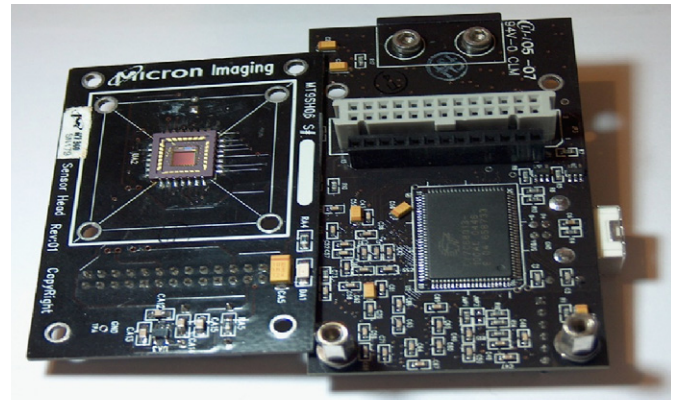

Fig. 3. MT9V011 sensor, the evaluation board (left) and the Demo2 DAQ board (right).

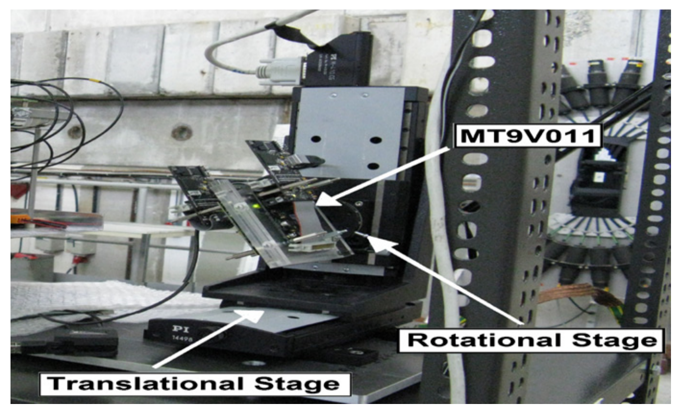

Fig. 4. Test Setup at CERN Proton Synchrotron.

with 1 mrad minimum step (Fig. 4). The spatial position of the matrix has been chosen to have the rows almost parallel to the incoming beam direction.

3.1. Track finding algorithm

A track finding algorithm has been implemented to select good tracks and to reject background signals (e.g. noisy pixels, short tracks) [8]. To obtain a better track spatial definition, the neighboring pixels of each hit pixel pertaining to a row orthogonal to the beam direction are checked: if their signals are greater than a defined threshold (2 times the pixel noise), the pixels are included in the track.

A very good track separation capability has been obtained. Two different tracks with a distance of only few pixels, can be actually recognized (Fig. 5). This is mandatory to select clean tracks for the analysis and to reject tracks with secondary emissions.

4. Technique description

The first step of our method is the automatic selection of tracks entering from the sensor surface with respect to the ones entering from the sensor backside. Defining the track start as the pixel with the lowest absolute row coordinate, we could plot for each track the pixel response as a function of the pixel position with respect to the track start. The slope of the linear fit is the pixel response slope (Fig. 6).

Tracks entering from the surface will have negative pixel response slope because the pixel response is at its maximum at low pixel coordinate and then tends to decrease towards zero with

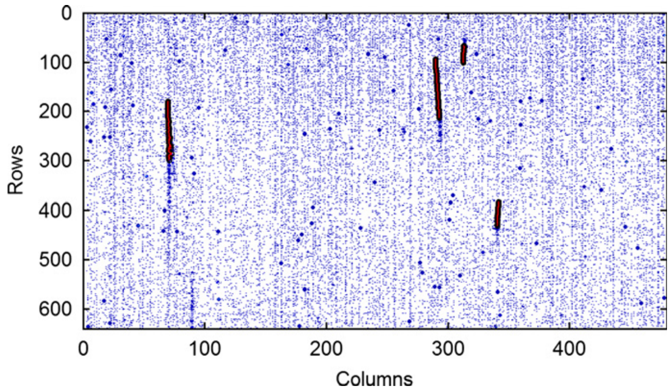

Fig. 5. Frame with four identified tracks.

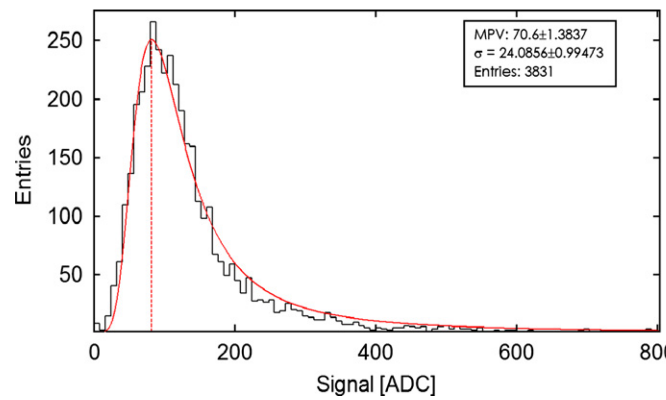

Fig. 8. Signal distribution of the all 1st pixels.

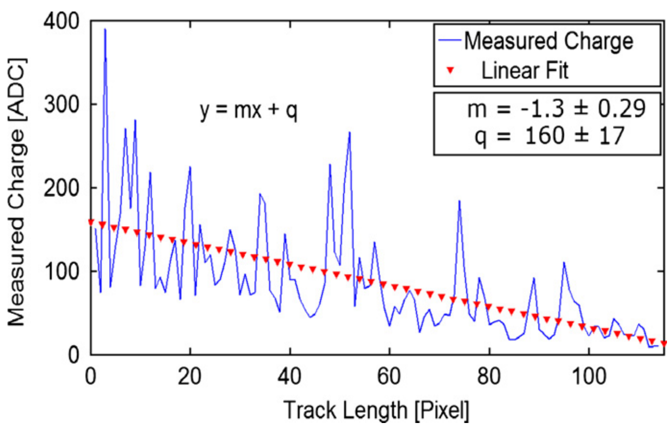

Fig. 6. Pixel response of one track entering from the surface with linear fit.

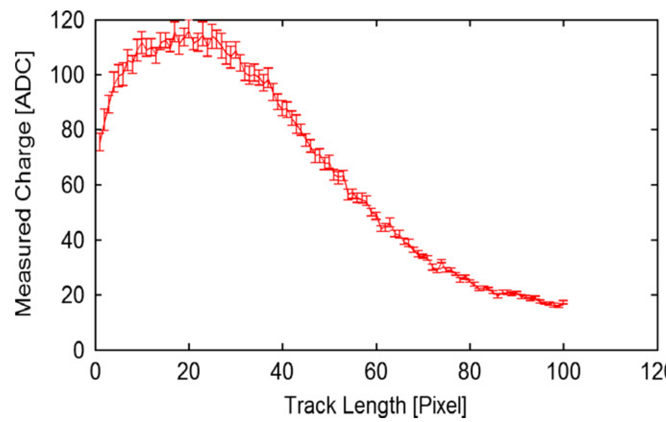

Fig. 9. Charge collection efficiency profile for MT9V011 sensor.

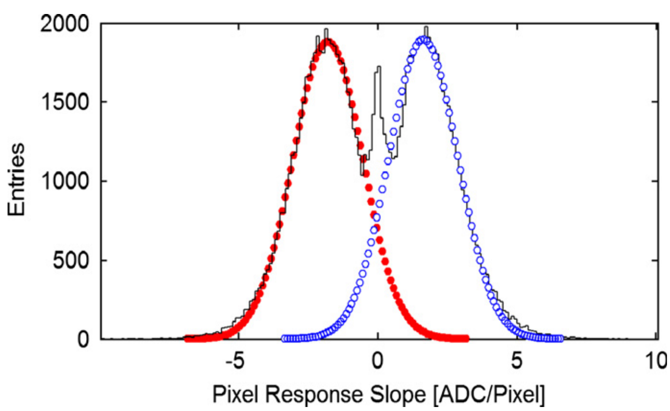

Fig. 7. Distribution of the Pixel Response Slope measured with tracks entering form the sensor surface (filled circle) and from the sensor back (open circle).

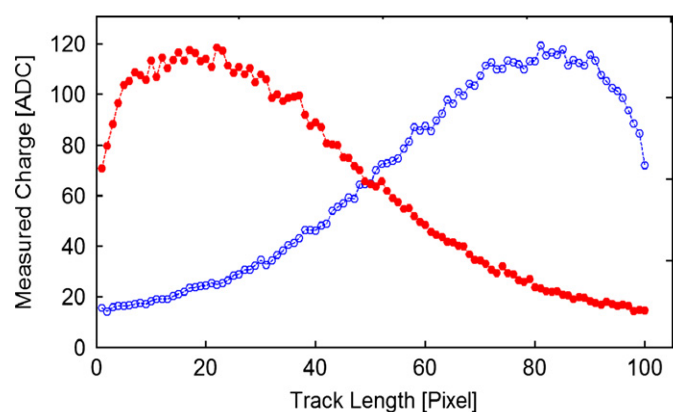

Fig. 10. Charge collection efficiency profiles measured with tracks entering form the sensor surface (filled circle) and from the sensor back (open circle).

increasing pixel coordinate. For tracks entering from the back the reverse holds good. The distribution of pixel response slopes is shown in Fig. 7. It is possible to notice the two fitted Gaussian distributions, which represent the two different directions of incoming tracks (around the nominal direction of the beam, assumed as zero angle reference). The peak around zero represents all the incoming tracks parallel to the sensor surface, not selectable for the following analysis.

The second step is to collect all the tracks entering from one direction (for instance from the surface) with the same length (for instance 100 pixels) and to build a signal distribution for each pixel position, beginning from the first pixels of the tracks to the last ones. In Fig. 8 is shown the signal distribution for the 1st pixel, well modeled by the Landau–Vavilov distribution, from which we can extract the MPV and its associated error.

In Fig. 9 is plotted the distribution of MPV as a function of the pixel position along the track. Position 0 is the track start (point closest to the sensor surface) and position 100 is the track end. It is evident the modulation of the response as a function of the pixel position along the depth of the track.

In Fig. 10 are reported the two profiles obtained using the tracks coming from the sensor surface (filled circle) and from the sensor backside (open circle). The high symmetry shows that the track finding algorithm is working very well.

We checked that the method does not depend on track length. In Fig. 11 are shown three profiles normalized to the track length, obtained with three different track length values (25, 50 and 100 pixels). The curves overlap very well, the only difference being a better "sampling" of the profile when longer tracks are chosen.

The final step in order to obtain a quantitative measure of the collection depth is to translate the horizontal scale unit from pixel units to length units (micrometers). For this purpose the following procedure has been used. The total generated charge for an inclined track could be written as

$$Q_{gen} = \sum_{i=1}^{Npixel} Q_i \frac{\Delta R_i}{\sin\alpha} = \frac{1}{\sin\alpha} \sum_{i=1}^{Npixel} Q_i \Delta R_i$$

where Q_i is the released charge per length units in the ith pixel, ΔR_i is the pitch of the ith pixel and α is the track incident angle on the sensor surface.

The total measured charge for an inclined track could be written as

$$Q_{meas} = \frac{1}{\sin\alpha} \sum_{i=1}^{Npixel} p_i Q_i \Delta R_i$$

where p_i is the charge collection efficiency for the ith pixel of the track. The term $\sum_{i=1}^{Npixel} p_i Q_i \Delta R_i$ could be evaluated using orthogonal tracks, where $\alpha = 90^\circ$ ($\sin\alpha = 1$) and Q_{meas} is equal to the MPV of the Landau–Vavilov fit.

$$Q_{meas} = Q_{ort} = \sum_{i=1}^{Npixel} p_i Q_i \Delta R_i.$$

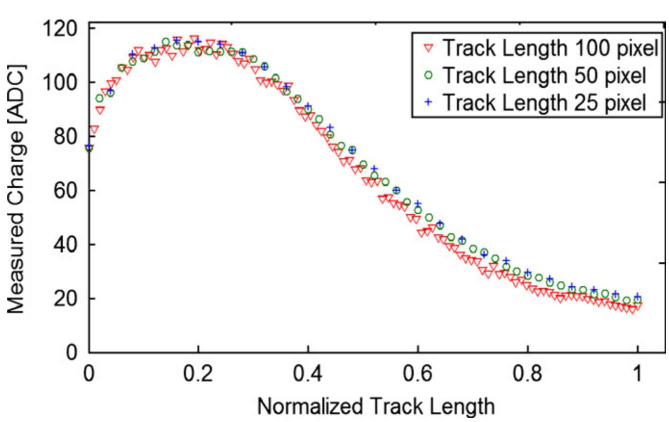

Fig. 11. Charge collection efficiency profiles measured with different track lengths.

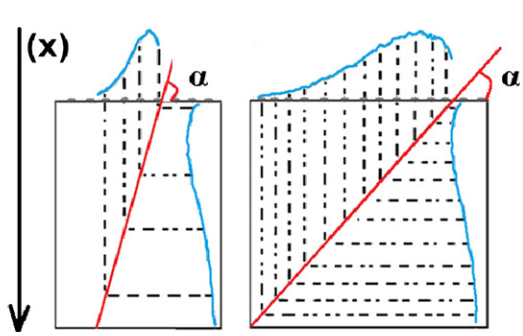

Fig. 12. Scheme of charge collection efficiency profile measurement using grazing particles.

For particles at different incidence angles it is then straightforward to obtain the value of α for each track, $\alpha = \arcsin(Q_{ort}/Q_{meas})$ and hence the extraction of the depth scale of the CCE profile. Fig. 12 illustrates how using longer tracks yields a finer sampling of the CCE, allowing a more detailed measurement.

5. Results

The result for sensor MT9V011 (4 μm epi-layer) is shown in Fig. 13. In the vertical scale is reported the signal per unit track length. The horizontal scale starts from 0 (silicon surface) and goes toward negative values (silicon bulk).

The profile could be divided roughly in three parts:

A. the first 1 μm, where the charge collection efficiency is not complete, most likely due to the presence of the pixel architecture and p-wells regions (hosting the pixel transistors);
B. from 1 to 3.5 μm, where there is a plateau in efficiency, corresponding to the epitaxial region;
C. from 3.5 to 12 μm where the efficiency decreases due to the increasing distance of the charge creation region from the epitaxial region.

Another Micron sensor (MT9V032) featuring different epilayer thicknesses (12 μm) has been tested and preliminary results are shown in Fig. 14.

The shape of the collected charge is very similar to that of the previous sensor profile. Also in this case the CCE is not complete in the first 1 μm. The only difference is the wider plateau due to the

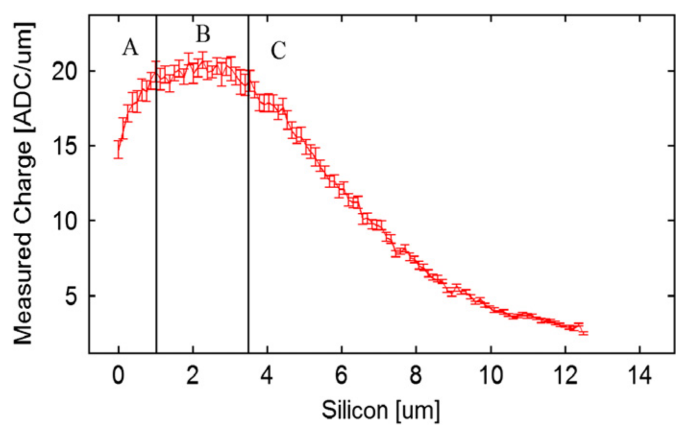

Fig. 13. Charge collection efficiency profile for MT9V011 sensor.

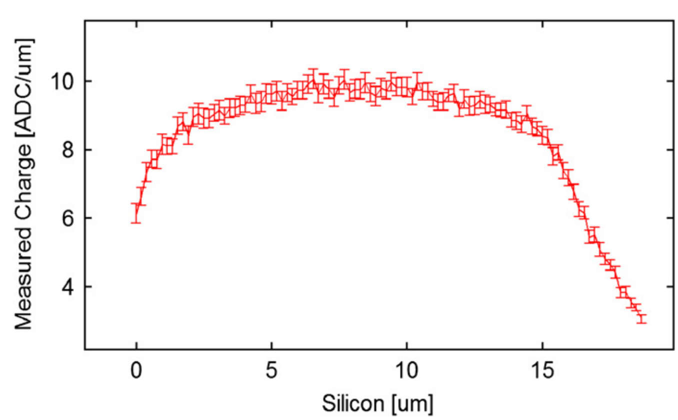

Fig. 14. Charge collection efficiency profile for MT9V032 sensor.

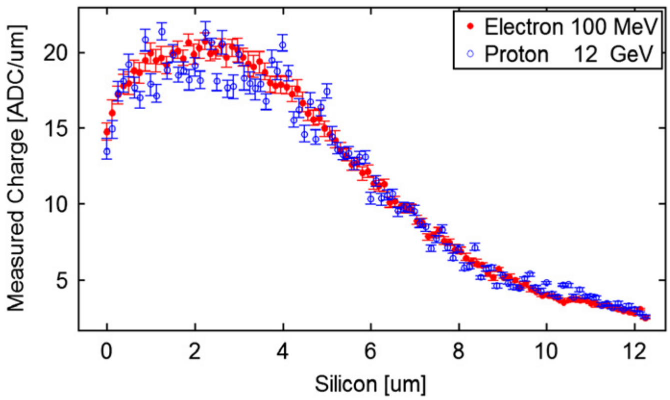

Fig. 15. Charge collection efficiency profile for MT9V011 sensor using 100 MeV electrons (filled circle) and 12 GeV Protons (open circle).

thicker epitaxial layer. It is important also to note that using different particle beams, with different energies, the profile does not change. In Fig. 15 are reported the two profiles for sensor MT9V011 obtained using 100 MeV electrons (Beam Test Facility at LNF) and 12 GeV protons (Proton Synchrotron at CERN). No difference is visible in all the measured domain.

This result is of paramount importance because it shows how multiple scattering does not significantly affect the measure of the CCE profile and therefore both high or medium energy facilities can be used for this measurement.

6. Conclusions

A comprehensive methodology based on the grazing angle technique to measure the charge collection efficiency of pixel sensors has been developed. By means of this method it is possible to measure the charge collection efficiency profile in great detail (e.g. 80 nm sampling granularity already achieved). Only one sensor with sufficient segmentation is required and there is no need of external information. In order to perform this measurement, medium momentum charged particles (e.g. 100 MeV electrons) could be employed, considerably extending the number of usable beam test facilities.

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