Charge Collection Measurements

in single-type column 3D Sensors

M. Scaringella*, A. Polyakov, and H. F.-W. Sadrozinski
SCIPP, UC Santa Cruz, CA 95064 USA
M. Bruzzi, C. Tosi
Dipt. Energetica, Univ. of Florence
Via S. Marta 3, I-50139 Firenze, Italy
M. Boscardin, C. Piemonte, A. Pozza, S. Ronchin, and N. Zorzi
ITC-irst, Divisione Microsistemi, Via Sommarive 18,
I-38050 Povo (Trento), Italy
G.-F. Dalla Betta
DIT, Università di Trento,
Via Sommarive 14, I-38050 Povo (Trento), Italy

Abstract

We report on charge collection studies on 3D silicon detectors of single-type column n-implants in p-substrate, configured either as strip or as pad detectors. The charge is generated by penetrating beta particles from a ^{90}Sr source which, together with a scintillation counter, serves as an electron telescope. The charge collection as a function of bias voltage is compared with the depletion thickness derived from the measured C-V characteristics.

Keywords: 3D detector, silicon detector, charge collection

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1. Introduction

For the future luminosity upgrade [1] proposed for the Large Hadron Collider (LHC), pixel detectors will have to survive fluences of fast hadrons in excess of 10^{16} cm^{-2} 1 MeV equivalent neutrons [2]. Since charge trapping during the drift is the main limitation for the application of silicon detectors in that regime, 3D detectors [3] with their shorter collection length are a promising candidate as silicon pixel sensors. In particular, 3D detectors with columns of both n-and p-doping are considered to be especially radiation hard [4]. An alternative is represented by 3D detectors of single-type column n-implants in p-substrate [5]. The principle of the single-type column 3D sensors is shown in Fig. 1. Their advantages over standard 3D of Ref [3] are mainly ease of manufacturing: etching and column doping are performed only once and the processing is single-sided with no need for a carrier wafer. Their disadvantage is the larger extension of low-field regions, leading to an increased hole trapping.

Thus the single-type column 3D detectors are not considered as detectors for the sLHC, but they represent ideal structures to study the manufacturing steps and to support simulations of electrical characterization and charge collection process for this kind of devices. For example, the agreement of the charge collection efficiency as a function of bias voltage (CCE) with the depleted thickness derived from capacitance-voltage measurements (C-V) can be investigated.

2. Devices

The devices are made on p-type wafers, either float zone (FZ) of 500 μm thickness and resistivity of $\rho >$ 5.0 kΩ·cm or Czochralski (Cz) of 300 μm thickness and resistivity of $\rho >$ 1.8 kΩ·cm. The holes were etched by CNM-Barcelona, and the processing into detectors was done by ITC-irst.

The columns are all n^+ type, 150 μm deep, spaced by 80 or 100 μm pitch. The columns are connected together on the surface by n^+ and/or metal layers to form pads or strips.

3. C-V Measurements and expected Depletion Behavior

Figure 2 shows the capacitance-voltage curves for a strip detector made on a 500 μm FZ substrate: both measurements, i.e., backplane capacitance in Fig.2(a) and interstrip capacitance in Fig.2(b), can be divided into two different regions [6]. In voltage range I (bias < ~7V), the depleted region grows laterally starting from the columns and the capacitance is large. In this range the inefficiency of the detecting tracks should be large and proportional to the fraction of undepleted area, but the collected charge should be about constant, given by the depth of the depleted area around the columns (~ 2fC). The detector is still not depleted at 180 V bias, where breakdown occurs. In voltage range II (bias > ~7V), the region between columns is fully depleted, and proceeds in planar-diode like fashion towards the back plane. The detector should be fully efficient. Similar considerations hold for Cz substrates, for which, due to the lower thickness, full depletion is reached at about 40V (see Fig.4).

4. Charge Collection Studies

Charge collection studies were performed with a ^{90}Sr source and a scintillation counter trigger with two different setups for single pad and microstrip detectors.

a. Pad with Analog Readout

The AC-coupled pad sensors from both FZ and Cz substrates were read out with an analog data acquisition (DAQ) at Università di Firenze. The DAQ is characterized by a 250ns shaping time and a ENC=500e$^-$. Figure 3 (a) shows the pulse height distribution of a 3D pad detector made from a Cz substrate at 6V bias. The peak is at 23.2 mV, using a calibration of 500 e$^-$/mV, it gives a charge of 11.6ke$^-$ expected for a thickness of 160μm, close to the column depth. At high voltages, the histogram of both the 3D FZ and Cz Si pad detectors show a very peculiar feature: the appearance of a second peak between the noise and the main Landau distribution. This effect, shown for a FZ Si detector biased with 50V in Fig. 3b, can be explained as due to those electrons impinging directly on the column holes perpendicularly to the detector surface and then travelling into the column void. Their signal is lower than that of the electrons impinging on the detector bulk, as it is originated only by the drift into the depleted region beyond the column holes. For this reason, the most probable value of the pulse height has been determined by Landau de-convolution only in the low bias voltage range, while at high bias the most probable value taken is the maximum of pulse height spectrum. The study on the thicker FZ detector has been performed up to 150V due to the onset of breakdown at higher bias, thus it could not be fully depleted.

Fig. 4 shows the charge collection efficiency CCE as a function of the bias together with the normalized reciprocal of the bulk capacitance, that in a planar diode, being proportional to the depleted region, should match the bias dependence of the CCE. Clearly the reciprocal capacitance and the charge collection efficiency have a very different bias dependence: this effect will be discussed in more detail in section 5.

b. Strips with Binary Readout

The AC-coupled strip sensor from a FZ substrate, with 80 μm pitch and about 2 cm length, was read out with binary DAQ [7] at UC Santa Cruz. The shaping time was about 100 ns. The efficiency was measured as a function of the threshold charge for each value of the bias voltage. The median pulse height corresponds to the 50% efficiency point, and the most probable pulse height is the maximum in the pulse height spectrum constructed by differentiating the efficiency spectrum as a function of the threshold charge. For a fixed threshold charge value, the efficiency is defined as the ratio of the number of in-time coincidences between scintillator triggers and strip hits and the total number of triggers. The efficiency for 1 fC threshold is shown in Fig. 5 as a function of bias voltage. As predicted above, the efficiency varies only below ~ 7V (Region I) where the area between columns is only partially depleted. Note at even at zero bias, the efficiency is not zero, indicating that the region between the columns is partially depleted. In Region II, with bias > 7 V, the efficiency approaches a value close to 100 %, i.e., the area between columns is full depleted and the small inefficiency is due to the finite width of the columns.

The comparison between the collected charge as a function of bias voltage in FZ 500 μm microstrip and pad detectors is shown in Fig. 6. Good consistency is found between the median and most probable pulse height of the binary strip measurement. The agreement between the bias dependence of the charge collected on the strips with ~100ns and on the pad with 250 ns shaping time is good. As seen before in Fig. 4, there is a finite charge collected at a bias of 0V, indicating that the detector is partially depleted in voltage region I.

5. Interpretation

The collected charge Q is proportional to the thickness d of the depleted region. In planar detectors, the backplane capacitance C extracted from C – V measurements allows to predict the charge collection. Since the capacitance C ~ 1/d, one would expect that Q ~ 1/C. In addition, for uniform doping density in planar detectors, the depleted region is proportional to the square root of the voltage. Both trends are compared with the measurements in Fig. 7, which shows the evolution of the measured median charge with bias voltage and the expectation from 1/C and sqrt(V), both normalized at the 150V bias point. As expected, the prediction valid for planar detectors fails to describe the data. In contrast, a very good description is given by a function which takes into account the two-stage depletion mechanism: this is a constant in the region between the columns and a 1/C dependence in the remainder of the detector (Q = 1fC + const/C).

6. Conclusions

The measured voltage dependence of the charge collection in single-type column 3D sensors has been measured for strip detectors with ~100 ns shaping time and pads with 250ns shaping time, and found to be the same.

The studies of charge collection and backplane capacitance as a function of bias voltage confirm the simple picture of the depletion in single-type column 3D sensors: there is rapid depletion between columns (< 10 V) and a slow, planar-diode like depletion beyond that. The bias voltage dependence of the charge collection is steeper than that predicted from 1/C or sqrt(V), which are typical for planar devices. Using an analog electronic read-out, we observed in the high voltage range a satellite peak in the Landau distribution , which we explain as due to those electrons traveling down the column holes perpendicularly to the detector surface. The double peak feature could be minimized by opportunely tilting the detector, to reduce the path of the electron into the column void: this phenomenon will be investigated in detail in a forthcoming paper.

7. Acknowledgments

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8. References

* Corresponding author. Tel.: 39+(055); Fax: 39+(055); e-mail: scaringella@gmail.com.

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Figure Captions

Fig. 1: Scheme of the charge collection process in single-type column 3D detectors

Fig. 2: Bias voltage dependence a) of the back plane capacitance ($1/C^2$ from C-V) and b) of the interstrip capacitance (Cint-V) of the single-type column 3D detector. Both show two different regions: in region I depletion occurs between the columns, and in region II, the depletion proceeds from the depth of the columns to the back plane.

Fig. 3 Pulse height distribution of the 3D pad detector (a) from a Cz substrate at 6V bias. The Landau distribution is peaked at 23.2 mV, corresponding to a depleted thickness of 160μm, close to the column depth. (b) FZ substrate at 50V. An extra peak is observed between the peaks of the noise and the Landau distribution.

Fig. 4 Bias voltage dependence of the charge collection efficiency CCE and the reciprocal of the body capacitance 1/C in the single-type column 300μm thick 3D pad sensor. Both CCE and 1/C are normalized to unity at a bias of 50V.

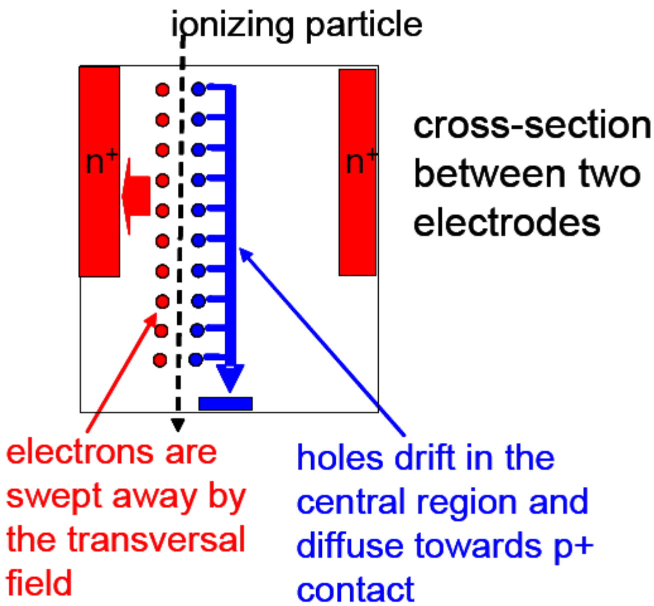
Fig. 5: Bias voltage dependence of the efficiency in the single-type column 500μm thick 3D strip sensors.

Fig. 6: Bias voltage dependence of the pulse height in single-type column 500μm thick 3D strip and pad sensors. The median and most probable pulse height of the strips are shown together with the analog signal of the pad sensor, normalized at a bias voltage of 60 V.

Fig. 7: Bias voltage dependence of the collected charge in single-type column 500μm thick 3D strip sensors. The median of the collected charge is compared to three different functions: Q ~ 1/C, Q ~ sqrt(V) and Q ~ 1fC + const/C, of which the latter describes the data well.

Figures

Fig. 1



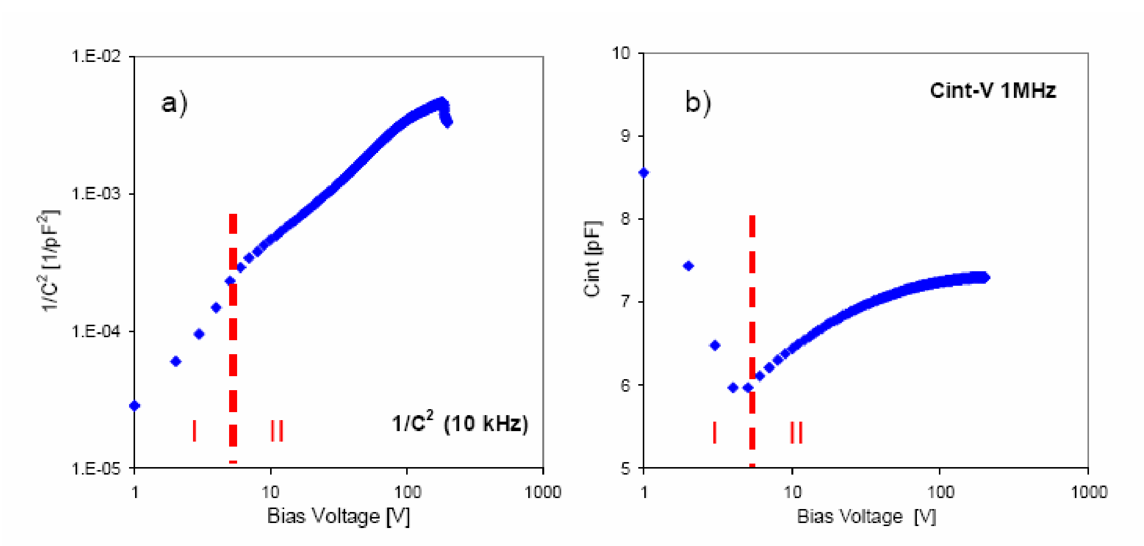


Fig. 2

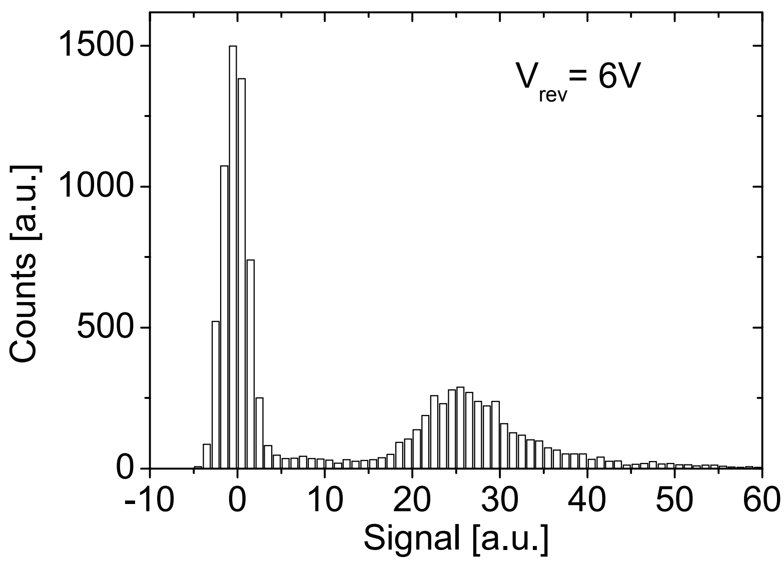


Fig. 3a

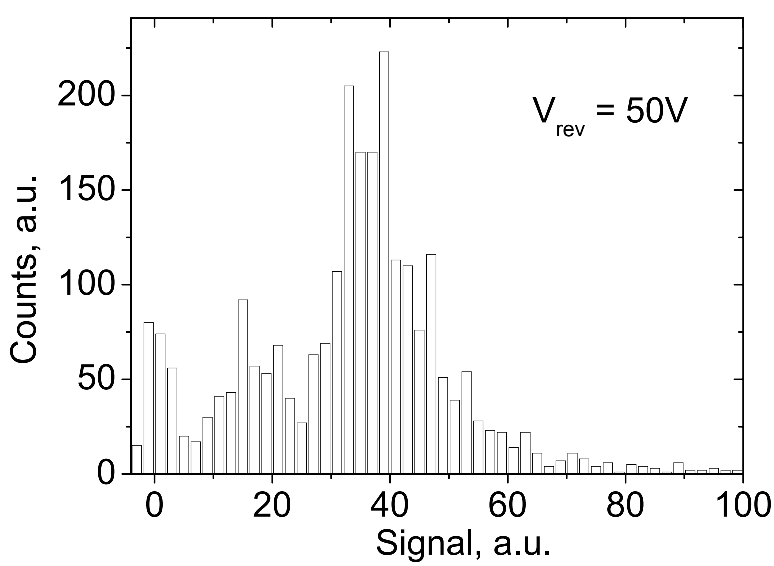


Fig. 3b