Charge Collection Measurements in single-column 3D Sensors

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Abstract

We report on charge collection studies on 3D silicon detectors of single column n-implants in p-substrate, configured either as strip or 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.

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} neq/cm^2 [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 are 3D detectors of single column n-implants in p-substrate [5]. The principle of the single-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 existence of low-field regions, leading to increased hole trapping.

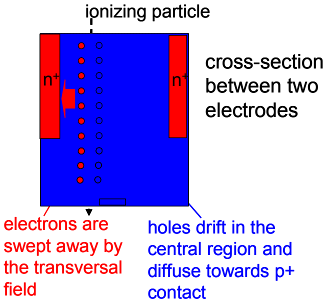

Fig. 1: Scheme of the charge collection in single-column 3D detectors

Thus the single-column 3D detectors are not considered to be the detectors for the sLHC, but are ideal devices to study and manufacturing steps and to support device simulations and understanding of the charge collection process. 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 float zone (FZ) wafers of 500 μm thickness and resistivity of $\rho > 5.0$ k·Ωcm. The holes were etched by CNM-Barcelona, and the processing into detectors was done by ITC-irst.

The columns are all n+ type of 150 µm depth on 80 and 100 µm pitch between them . The columns are connected to form pads or strips.

3. C-V Measurements and expected Depletion Behavior

The C-V and Cint-V measurements (Fig. 2) can be divided into two different regions [6]. In voltage range I (bias < ~7V), the region between the columns is slowly depleted starting from the columns. The capacitance is large. The inefficiency of detecting tracks should be large and, proportional to the fraction of undepleted area, but the collected charge should be about constant, given by the depleted area around the columns (~ 2fC). 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.

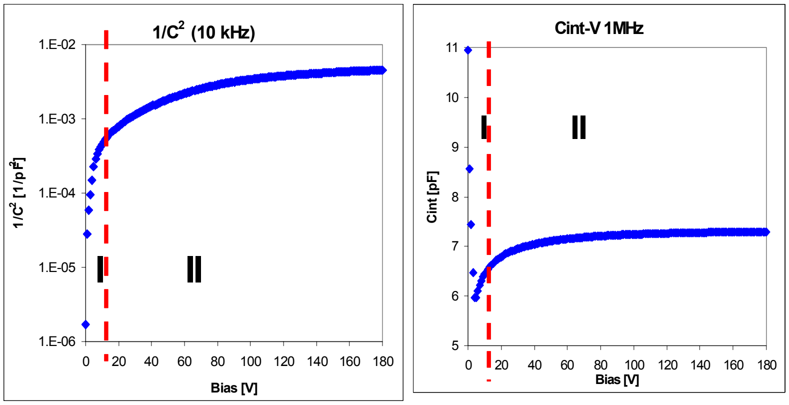

Fig. 2: Bias voltage dependence of the back plane capacitance ($1/C^2$ from C-V, left) and interstrip capacitance (Cint-V, right) of the single-column 3D detector. Both show two different regions: in region I depletion occurs between the columns, and in region II, the depletion proceeds from the depth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

4. Charge Collection Studies

Charge collection studies were performed with a ^{90}Sr source and a scintillation counter trigger.

a. Pads with Analog Readout

The DC-coupled pad sensor are read out with analog DAQ at Universita di Firenze. The DAQ is characterized by a 2.4 µsec shaping time. The deconvolution software provided by NIKHEF extracts the parameters of a Landau distribution, but at high bias voltage a discrepancy between the pulse height at the maximum and the extracted parameters is observed (Fig. 3) . The most probable value of pulse height is determined by Landau de-convolution only in the range 0-60V. At 70-150V the most probable value taken is the maximum of pulse height spectrum.

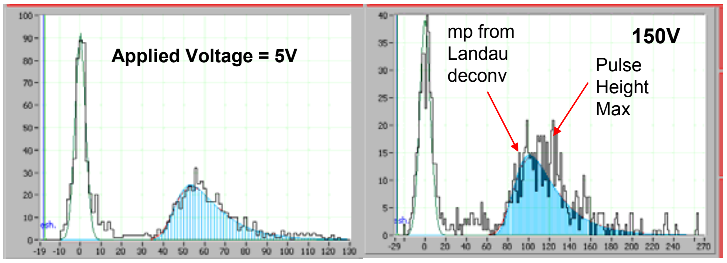

Fig. 3: Pulse height distributions for low (left) and high bias of the 3D pad detectors.

Fig. 4 shows the extracted pulse height as a function of the bias, indicating that the pulse height (and thus the depleted thickness) increases up to the highest voltages reached before breakdown.

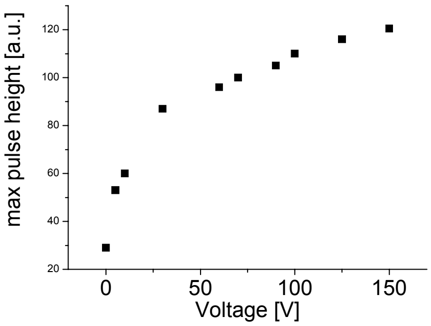

Fig. 4: Bias voltage dependence of the collected charge in single-column 500µm thick 3D pad sensors.

b. Strips with Binary Readout

The AC-coupled strip sensor, 80 µm pitch of about 2 cm length are read out with binary DAQ at UC Santa Cruz. The shaping time is about 100 ns. Both the efficiency and the pulse height (median and most probable) are measured. Fig. 5 shows the efficiency (ratio of trigger-strip hit coincidence and triggers) 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.

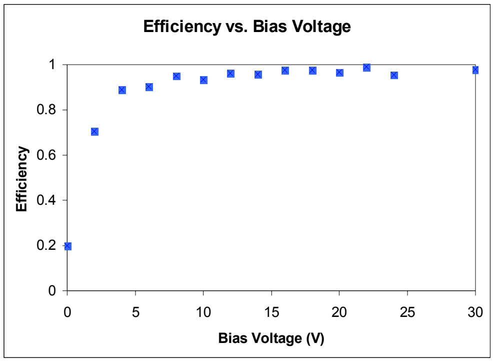

Fig. 5: Bias voltage dependence of the efficiency in single-column 500µm thick 3D strip sensors

The collected charge is shown in Fig. 6. Again the increase with the bias is shown. Good agreement is found between the median and most probable ("most likely") of the binary strip measurement. Also the agreement between charge collected on the strips with ~100ns and pads with 2.4µs shaping (called "FIML" in the graph) 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 the voltage region I.

5. Interpretation

The collected charge Q depends on 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, the depleted region is proportional to the square root of the voltage. Both trends are shown in Fig. 7, which reports 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. Of course, the predictions valid for planar detectors fail to describe the data. On the contrary, a very good description is given by a function which takes into account the double 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).

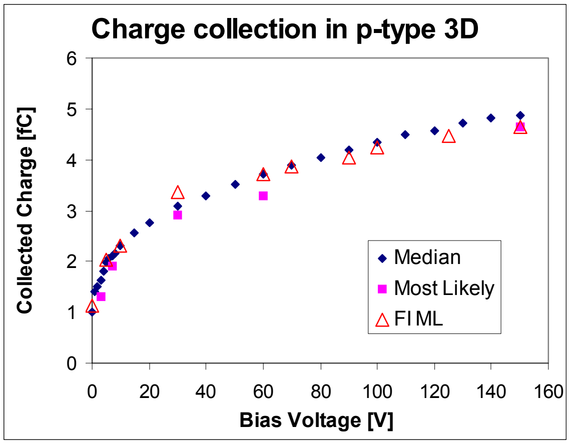

Fig. 6: Bias voltage dependence of the pulse height in single-column 500µm thick 3D strip and pad sensors. The median and most likely pulse height of the strips are shown together with the analog signal of the pads ("FIML") shown in Fig. 4, normalized at 60 V.

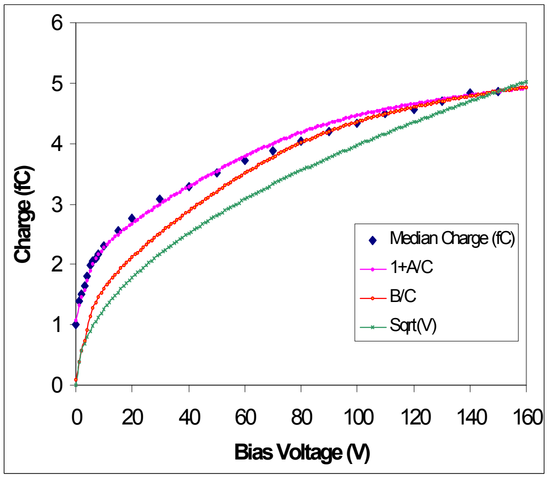

Fig. 7: Bias voltage dependence of the collected charge in single-column 500µm thick 3D strip sensors. The median is compared to three different functions: Q ~ 1/C, Q ~ sqrt(V) and Q ~ 1fC + const/C, of which the latter describes the data well.

6. Conclusions

The measured voltage dependence of the charge collection in single-column 3D sensors is the same for SSD with ~100 ns shaping time and pads with 2.4 µs shaping time.

The studies of charge collection and backplane capacitance as a function of bias voltage confirm the simple picture of the depletion in single-column 3D sensors: there is rapid depletion between columns (< 10 V) and a slow, planar-diode like depletion beyond that. The collected charge is larger than that predicted from 1/C or sqrt(V), which are typical for planar devices.

7. Acknowledgments

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8. References

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