Available online at www.sciencedirect.com

ScienceDirect

Nuclear Instruments and Methods in Physics Research A 579 (2007) 633–637

NUCLEAR INSTRUMENTS & METHODS IN PHYSICS RESEARCH Section A

www.elsevier.com/locate/nima

Study of the signal formation in single-type column 3D silicon detectors

Claudio Piemonte[a,*], Maurizio Boscardin[a], Luciano Bosisio[b], Gian-Franco Dalla Betta[c], Alberto Pozza[a], Sabina Ronchin[a], Nicola Zorzi[a]

[a] ITC-irst, Divisione Microsistemi, 38050 Povo di Trento, Via Sommarive 18, 38050 Povo di Trento, Italy
[b] INFN and Physics Department, University of Trieste, Via A. Valerio 2, 34127 Trieste, Italy
[c] INFN and ICT Department, University of Trento, Via Sommarive 14, 38050 Povo di Trento, Italy

Available online 29 May 2007

Abstract

Because of their superior radiation resistance, three-dimensional (3D) silicon sensors are receiving more and more interest for application in the innermost layers of tracker systems for experiments running in very high luminosity colliders. Their short electrode distance allows for both a low depletion voltage and a high charge collection efficiency even at extremely high radiation fluences. In order to fully understand the properties of a 3D detector, a thorough characterization of the signal formation mechanism is of paramount importance. In this work the shape of the current induced by localized and uniform charge depositions in a single-type column 3D detector is studied. A first row estimation is given applying the Ramo theorem, then a more complete TCAD simulation is used to provide a more realistic pulse shape.

PACS: 29.40.Wk; 85.60.Bt; 85.60.Ha

Keywords: Radiation detectors; 3D silicon detectors; Device modeling

1. Introduction

The interest in three-dimensional (3D) solid-state particle detectors is continuously growing especially in those applications requiring extraordinary radiation resistance. 3D detectors have been introduced in 1997 by Parker et al. [1] and since then a few research laboratories around the world started developing the technology for their fabrication (see as an example Refs. [2,3]). ITC-irst (Trento), in collaboration with INFN, is one of the groups involved in this development. So far, three batches of 3D detectors have been successfully produced at ITC-irst with a simplified approach, referred to as single-type column 3D (3D-STC) [4,5], featuring columnar electrodes of only one doping type. The simplification of the fabrication process, needed at the beginning to get acquainted with the technological difficulties, induces a certain deterioration of the performance with respect to a standard approach, as reported in Ref. [4]. In particular, the carrier motion is no longer fully transversal presenting also a vertical component that causes reduction of the detector speed.

Besides tuning the fabrication technology, what is very important at this stage of development is the study and evaluation of the performance of the 3D detector, first by means of simulations and then by experimental characterization. This is the reason why we carried out this study on the signal formation in 3D-STC detectors. Our analysis is based on calculations (application of the Ramo theorem) and TCAD simulations. The combined use of these two methods allows the origin of each signal component to be effectively traced.

2. Methods and structure

The evolution of the signal has been estimated in two ways. First, a row calculation has been performed using the Ramo theorem [6]. This method requires the calculation of electric and weighting fields which, in case of 3D detectors,

*Corresponding author. Tel.: +39 0461314428; fax: +39 0461302040.
E-mail address: piemonte@itc.it (C. Piemonte).

0168-9002/$ - see front matter © 2007 Published by Elsevier B.V.
doi:10.1016/j.nima.2007.05.261

cannot be easily expressed in an analytical form. For this reason they have been calculated using a TCAD simulator. According to the definition, the weighting field has been extracted solving the Laplace equation with the following boundary conditions: potential 1 to the electrode of interest and 0 to all the others. Since TCAD simulators solve only the Poisson equation, the semiconductor has been replaced with a perfect dielectric in order to have a null charge density in the device. Subsequently, the electric field has been calculated solving the Poisson equation within the semiconductor at the desired bias voltage. It should be noted that both distributions are calculated only on the mesh points, i.e., the points used to discretize the structure. The signal evolution can now be easily extracted solving the Ramo theorem for each grid point and calculating the time needed for the carrier to travel from one point to the following according to the direction and intensity of the velocity vector.

The second method used to estimate the current shape is by direct TCAD simulation. In this case, the static bias condition is calculated solving both the Poisson and the continuity equations. Then, a certain amount of charge is injected (locally or along a straight line) and the time domain response is calculated integrating in time the continuity and the displacement current equations.

Both methods should be used because they give mutual information. The first approach (Ramo theorem) allows a step-by-step reconstruction of the signal shape associating the current amplitude to the movement of the electron/hole in a certain position. It naturally gives a simplified solution because single carriers can be treated. On the other hand, the second approach provides a realistic estimation of the signal giving the possibility to include different types of charge deposition and other physical phenomena such as carrier diffusion.

With both methods a TCAD simulator is needed. In this work the software package ATLAS [7] by Silvaco has been used.

The structure considered in this work consists of a set of 250 μm deep columnar electrodes located at distance of 80 μm in both x and y directions (Fig. 1). The 7 μm radius columns are of the same doping type (n-type). The p-type bulk, 300 μm thick, is contacted from the backside. As reported in Ref. [4], such structure requires the use of a 3D simulation. The computational time in three dimensions increases dramatically with respect to 2D and only structures limited in size can be simulated. Due to the particular geometry and the bias condition, a basic cell consisting only of a square with the columns at the corners can be considered for the calculation of the electric field. On the other hand, the computation of the weighting field of one column would require a more extended structure, because not all the field lines end on the first neighboring electrodes. Nevertheless, some simulations have been performed verifying that the error induced considering a cell limited to four columns (the same used for the electric field) is very small. Thus, for all the simulations, static and dynamic, a square cell of $80 \times 80\,\mu\text{m}^2$ has been used (see Fig. 1).

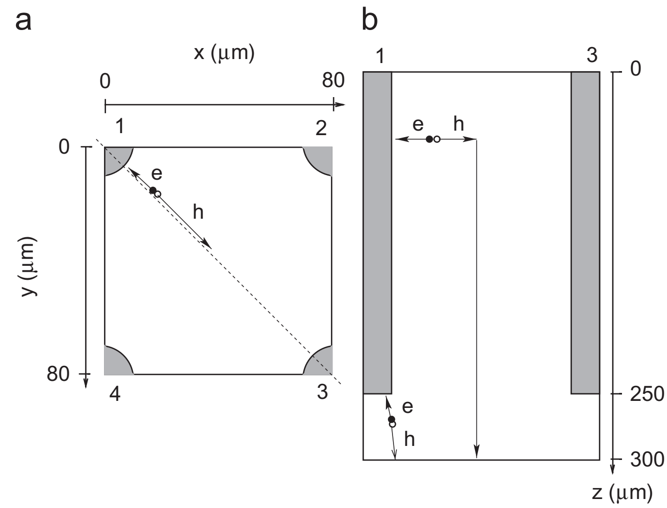

Fig. 1. Sketch of the simulated cell: (a) horizontal and (b) vertical cross-sections.

3. Estimation of the signal shape using the Ramo theorem

Two regions with different field shapes can be identified in the z direction (Fig. 1b). The first extends for the whole column depth whereas the second is located below the columns. The collection mechanism in the two cases is completely different. In the first zone, the electron drifts from the generation point to the nearest column moving in the x–y plane, whereas the hole reaches the middle region between the columns moving on the same plane and then slowly drifts vertically towards the backplane.

In the second zone, if fully depleted, both the electron and the hole experience a high electric field and move mainly on the z direction similar to standard planar diodes. Of course, we are interested in understanding the signal formation in the first region which is characteristic of this 3D sensor.

As already evidenced, the movement has a horizontal and a vertical component that can be treated separately. The magnitude of the electric and weighting fields on the x–y plane along the diagonal of the square cell are shown in Fig. 2 (the calculations are performed with a substrate doping concentration of $5 \times 10^{12}\,\text{cm}^{-3}$ and a bias voltage of 16 V). The E field is null in the central point and grows with opposite sign moving toward the two columns. The W field is strongly peaked on the read-out column but features also a smaller peak on the opposite column due to the bunching of the field lines. Fig. 3 shows the currents induced on the two columns by an electron generated in three different positions, namely at 15 (a), 30 (b) and 50 μm (c) from the centre of column 1, on the diagonal.

The shape of the currents can be easily understood from the shape of the fields. In particular, the signal grows as the