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Simulation of 3D diamond detectors

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ABSTRACT

3D diamond detectors present an interesting prospect for future Particle Physics experiments. They have been studied in detail at beam tests with 120 GeV protons and 4 MeV protons. To understand the observations that have been made, simulations have been carried out using Synopsys TCAD in order to explain the movement of charge carriers within the sample, as well as the effects of charge sharing. Reasonable agreement has been observed between simulation and experiment.

1. Introduction

As the LHC enters into the high luminosity domain, increasingly high requirements will be put on the radiation hardness of the detectors used, particularly the semiconductor tracking detectors closest to the interaction points. There are two approaches that can increase the radiation hardness of these detectors:

1. Use of a more radiation tolerant geometry, such as that employed in 3D detectors, increasing radiation hardness as the inter-electrode distance is reduced, meaning that charge carriers are less likely to get trapped. 3D silicon detectors have already been successfully produced and make up 25% of the IBL [1] (the new innermost layer of the ATLAS detector at the LHC).
2. Use of chemical vapor deposition (CVD) diamond, which has already been used for radiation and beam monitoring in BaBar, Belle, CDF and the LHC experiments [2]. Diamond has a high bond strength (43 eV needed to displace an atom, 13.6 eV for silicon). Diamond also has a large band gap (5.5 eV compared to 1.12 eV for silicon) resulting in a low leakage current even after a high irradiation dose.

The aim of 3D diamond detectors is to combine these two approaches by producing diamond detectors with graphitic microwires acting as electrodes drilled into the diamond bulk [3,4], thus producing detectors that are more radiation resistant than either of the two approaches can achieve individually, meaning they would be better able to carry on functioning in high radiation environments, such as future LHC upgrades.

3D diamond detectors also present interesting prospects for applications in other fields such as medical physics. A 3D geometry allows the detector to be operated at a low voltage for an equivalent performance, while diamond has the advantage of being a non-toxic tissue equivalent material.

2. Device simulation

Simulations were performed using Synopsys TCAD [5], a semiconductor device simulation package, to understand the behavior of single crystal (scCVD) and polycrystalline (pCVD) 3D Diamond detectors.

In order to simulate a device, it is first of all necessary to create a mesh, modeling the device as a discrete set of nodes. Boundary conditions, such as the electrode voltage, are then applied to the device, and a quasistationary simulation is used to find the steady state behavior.

Once the steady state behavior of the device has been determined, some charge is injected into the device to simulate the charge deposited by a particle hit. A time dependent (transient) simulation is then performed on the device to compute the signal observed at the electrodes due to a charged particle hit.

The behavior of the device is modeled by iteratively solving the governing equations of semiconductors (the continuity equations for electrons and holes, as well as the Poisson equation). A field dependent mobility model was also included [6], the parameters used for this model were those measured by Pernegger et al [7].

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Simulations were performed in order to better understand the observed behavior of single crystal (scCVD) 3D diamond detectors at test beams using 120 GeV [8] and 4 MeV [9] protons, while more simulations are required to understand the behavior poly-crystalline (pCVD) devices during measurements using 120 GeV protons [10].

3. 3D single crystal minimum ionizing particle (MIP) simulations

To better understand observations made using a scCVD 3D Diamond detector at a test beam with 120 GeV protons [8], a 2×2 array of cells was simulated (as shown in Fig. 1 with electrodes connected along the Y -direction to match the properties of the device used), with a 150 μm pitch and a 500 μm detector thickness to match the characteristics of the detector used during the experiment.

Experimental data shows that the charge collection was mostly uniform throughout the detector, with some cells having a greatly reduced signal due to a missing or broken readout electrode.

However it was also observed that in some regions located around bias columns, signals with a negative polarity were observed in the cells adjacent to those containing the hit.

Simulations were performed to understand this phenomenon; the observations were recreated when a finite charge lifetime of 70 ns was introduced to simulate the effect of charge trapping. Regions where negative charges were observed in cells adjacent to the particle hit formed in the simulation around the position of missing or broken bias columns. The signal as a function of position due to a hit in the adjacent cell is shown in Fig. 1. The region where the highest signal is observed is due to charge sharing between cells as this is the region of the cell closest to the electrode where the signal is measured, meaning that for hits in this region, some of the charge has been generated in the neighboring cell. This result shows good agreement with the experimental data [8].

These observations were explained by considering the weighting field in a 3D detector (Fig. 2). Ramo's theorem states that the instantaneous current induced at an electrode depends on the component of the weighting field in the direction in which the charge is traveling [11]. As a result of this, in a 3D configuration, it is clear that for a hit in the neighboring cell, charge carriers would have to cross regions where the component of the weighting field in their direction of motion points in opposite directions. Hits at certain positions will therefore result in charge carriers generating bi-polar signals for hits in these regions. These signals normally result in no overall charge collection, however a significant amount of trapping will result in some left over signal, and this can be either positive or negative depending on the position of the hit relative to the electrode.

Normally charge collection in 3D scCVD diamond detectors is very fast, and a large enough number of charge carriers reach the electrodes before they are trapped, meaning that any residual signals would be small and hence difficult to detect. However in this experiment, a missing bias column results in an extended low field region as shown in Fig. 3. This greatly increases the time taken for charge collection to occur, thus allowing more trapping to occur, and the residual signals to become significant.

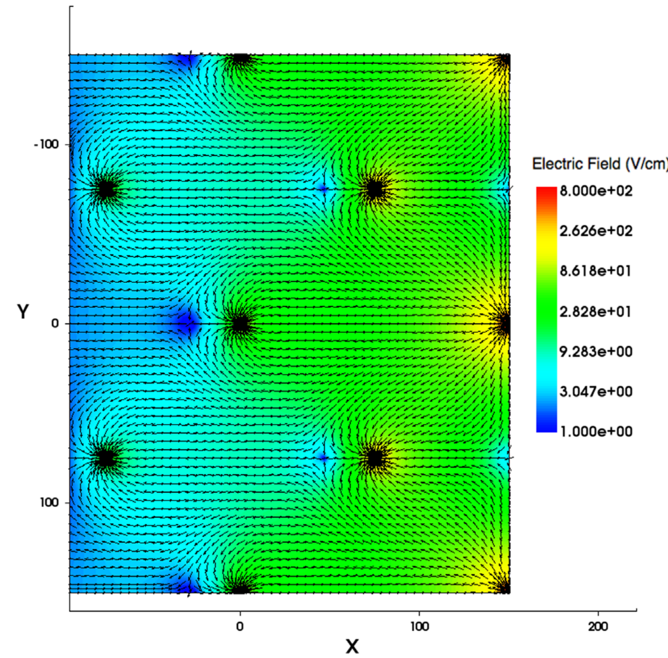

Fig. 2. Image showing the magnitude and direction of the weighting field due to the right-most set of connected signal columns, which determines the measured signal according to Ramo's theorem [11].

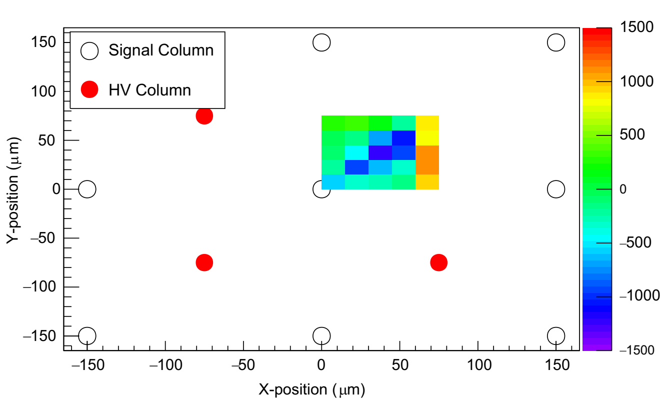

Fig. 1. Plot showing the simulated charge collected by the right-most line of signal columns due to hits in the quarter cell between (0,0) and (75,75) when a bias columns is missing from (75,75). The columns are connected together along the Y -direction to match the geometry of the detector used in the experiment.

4. 3D single crystal TRIBIC simulations

Time Resolved Ion Beam Induced Current (TRIBIC) measurements are a technique that can be used to produce spatially resolved Transient Current (TCT) measurements [12] in order to map the electric field and the mobility of a detector. Measurements using this technique were performed on a 3D scCVD sample (shown in Fig. 4) using 4 MeV protons [9].

The sample used in the experiment consisted of square cells with a size of 120 μm and had a detector thickness of 500 μm, whereas a 4 MeV proton stops after ≈80 μm [13] in diamond, producing a Bragg peak. The track was therefore modeled in the simulations using a combination of two tracks with different amounts of energy deposited per unit length; a track extending from the surface of the sample to a depth of 80 μm with a small amount of charge deposited per unit length, and a short track centered around 80 μm in depth with a high charge density; the combination of the two summing to the total charge deposited by a 4 MeV proton, with the bulk of the charge deposited at a depth of 80 μm. The mesh used also had a sample thickness of 500 μm and the area simulated comprised a quarter cell, which meant

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