3D detectors—state of the art

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Available online 10 January 2006

Abstract

3D detectors, with electrodes penetrating through the silicon substrate were fabricated, and characteristics such as speed, radiation hardness and edge sensitivity were studied. The signal shape was observed using a fast, low-noise transimpedance amplifier. The rise time of the signal obtained for a minimum ionizing particle was faster than 3 ns at room temperature. This is in agreement with earlier calculations of 3D sensors that showed the charge collection time to be between 1 and 2 ns. Similar tests were performed on detectors after exposure to proton beams with doses ($1.8 \times 10^{15}$ 24 GeV protons/cm$^2$) equivalent to those expected after 10 years at the innermost layers of the ATLAS experiment at the large hadron collider (LHC). Edge sensitivity was measured at the advanced light source at Lawrence Berkeley Laboratory, using an X-ray micro-beam. The detectors were measured to be efficient up to less than 10 mm from their physical edges. Results presented in this paper confirm the suitability of this design for possible future LHC upgrades, where the integrated fluence is expected to increase by a factor of 10. Moreover, their speed characteristics have placed them as potential candidates for the CERN linear collider (CLIC) where the bunch-crossing separation can be as short as 1.2 ns.

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PACS: 29.40.Gx; 29.40.Wk; 41.85.—p; 87.66.Pm

Keywords: 3D detectors; Fast charge collection; Active edge; Radiation hardness

1. Introduction

Near-term and future experiments in high-energy physics and molecular biology will require radiation hard and fast detectors without insensitive border regions (edgeless) to cope with the increasingly stringent research requirements. The unique geometry of 3D detectors, schematically sketched in Fig. 1, covers many of these requirements and presents several advantages over conventional planar silicon detectors.

In particular, radiation hardness and speed have become increasingly important for possible future upgrades of the large hadron collider (LHC) at CERN [1]. A luminosity upgrade (SLHC) of a factor 10, foreseen after 2012, is meant to improve the accuracy of the Standard Model and the new parameters, which are predicted to be discovered at the initial phase of the LHC experiments. The necessary increased statistics will be obtained not only by increasing the luminosity but also by reducing the bunch crossing to possibly half of the current one. In this new scenario, the radiation levels will increase by a factor of 10 compared to the present level, exposing the innermost tracker’s layers to an integrated fluence equivalent of $\sim 10^{16}$ 1 MeV neutrons/cm$^2$ in 10 years of operation.

Besides the SLHC, there is also motivation for further studies on topics such as supersymmetry and measurements that may be unravelled by the LHC. These studies and measurements necessitate $e^+e^-$ colliders of energy up to at least 3 TeV, such as the CERN Linear Collider (CLIC) [2] where the corresponding bunch crossing might subsequently be reduced to $\sim 1.2$ ns. The full pulse width of a
typical signal induced from a conventional 300 μm thick planar silicon device from a minimum ionizing particle’s energy deposition is typically 25 ns. New technology must, therefore, be developed for the near-future requirements.

In molecular biology, protein crystallography is used to identify protein structure using X-ray diffraction at synchrotron light sources. The X-ray diffraction pattern produced by low-energy X-rays (~13 keV) scattered by the protein crystal is recorded by high spatial resolution detector. Phosphor screens with fibre optic demagnification to CCD sensors have been successfully used for this type of research, but alternatives are required to improve speed, sensitivity, linearity and large area coverage at a limited cost. Standard planar silicon detectors have been considered, but they suffer from intrinsic limitations for this application. One example is the typical dead border surrounding the sensor’s active area of about 100 mm² (which might increase to 500–1000 mm² in some cases). This insensitive area is required because of the need for guard rings required to control the surface leakage current by keeping the electric field uniform and intercepting the current before the first signal electrode [3]. This dead area leaves behind important information of the diffraction pattern.

In 3D detector, where electrodes penetrate through the entire bulk, the edge is normally made into an electrode. Moreover, as the inter-electrode distance is normally much smaller than the wafer thickness, the maximum collection path and depletion voltage can be made much smaller for a comparable signal to noise ratio that is achieved in planar detectors [4,5].

This paper discusses some of the recent 3D detector’s results in view of desirable performance characteristics: speed, radiation hardness and edgeless capabilities.

2. Speed—fast charge collection

In 3D sensors, the inter-electrode distance can be smaller than the wafer thickness resulting in shorter average drift lengths. By Shockley–Ramo theorem, [6] the signal current from the detector arises because of the motion of charge carriers after they are formed by incident radiation. An ionizing particle generates charge carriers along its path as it traverses the silicon bulk. In a planar detector, each charge along the ionization path is at a different distance with respect to the collecting electrode, so the peak signal induction occurs at different times. On the contrary, in a 3D detector the ionization path is parallel to the collecting electrodes, as shown in Fig. 2. All charges along the path are at almost the same distance from the collecting electrodes. Ignoring some diffusion spreading, the arrival of all the charges is simultaneous, inducing a signal with a faster rise time as compared to a planar silicon detector. Moreover, the cylindrical shape of 3D detector’s electrodes forces the electric field lines to terminate on cylindrical geometries rather than circular ones of generally smaller areas. This results in a higher average field for any given maximum field in the drift path of ionization charges and the drift velocity consequently increases. These differences allow 3D detectors to be very fast. In addition, another feature, which takes advantage the innovative 3D design, is the possibility for drift time corrections to improve the accuracy of signal timing by reading out simultaneously from both n+ and p+ electrodes, since both types of electrodes can be accessed from the top surface of the detector.

Initial calculations were performed to study the effects of induced charges from a minimum-ionizing particle on 3D detectors [5]. The simple simulation consisted of a square cell with a p-electrode at the centre as the collecting electrode, surrounded by eight neighbouring n-type electrodes displaced at equal distance around the cell. These simulations showed a signal peaking time of 0.5 ns with a return to baseline at 1.5 ns. This is over a factor of 10 faster than a signal obtained from a planar silicon detector with 2D electrodes, which takes about 25 ns to return to the baseline, neglecting any amplifier delays [7].

Measurements were made using a 0.25 μm CMOS technology low-noise transimpedance amplifier [8] to study and compare the pulse shape of the induced signal in a 3D detector with those obtained from calculations. At optimal biasing conditions, the amplifier showed a rise time of 3 ns at room temperature and an rms noise of 350e⁻ when
was measured to be 30 V but a bias voltage of 40 V was used in the measurement to allow some over depletion. Signals induced by a minimum ionizing electron from a 90Sr source were recorded using a fast digital oscilloscope (Agilent 54516C) with a sampling rate of 2 Gsamples/s and a bandwidth of 500 MHz. Raw tracks, shown in Fig. 3, were recorded both at room temperature and 130 K.

The pulse shape reconstructed from the oscilloscope trace is shown to be solely dependent on the response of the readout electronics. An indication of the true 3D response at the output of the amplifier has been obtained by simulation. A simulated 3D-induced signal pulse was used as the input to the simulated amplifier using the same bias setting as mentioned earlier. The result was compared with the observed tracks produced by a minimum ionizing electron from a 90Sr source. The pulse shape reconstructed from the oscilloscope trace is compared with the observed signal (dotted) produced by a minimum ionizing particle from a 90Sr source.

have a minimum rise time of less than 1.7 ns at room temperature, much closer to the predicted charge collection time of 3D detectors obtained from simulation.

3. Radiation Hardness

Radiation hardness of planar silicon detectors remains a challenge if the LHC is to be upgraded. New silicon detectors are yet to be developed in order to meet this extreme radiation level. Defects are formed in the silicon lattice due to radiation damage and several macroscopic effects occur including increase in leakage current and depletion voltage. The calculated effective drift lengths are 150 μm for electrons and 50 μm for holes at −20 °C after irradiation with a fluence of 1015 n/cm². Both are significantly short when compared to the electrode distance of a conventional 300 μm thick planar silicon detector, reducing the charge collection efficiency. Several different approaches have been studied to provide a solution to fulfill the future requirements. The inter-electrode spacing of a 3D detector can at present be made to be as short as 50 μm. This is comparable to the reduced calculated effective drift lengths while keeping the wafer thickness at 250–300 μm to maintain a good signal-to-noise ratio, making 3D detector radiation tolerant. Moreover, as compared to a planar detector, the voltage required to maintain full depletion remains lower because of the shorter inter-electrode distance.

Some 3D detectors were irradiated with a fluence that is equivalent to the lattice damage expected after 10 years of operation at the innermost B layer of the ATLAS detector (1 × 1015 55 MeV protons/cm²) [14]. Performance studies were made and the depletion voltage was found to be around 105 V for a detector with a cell size of (100 × 134) μm². This is at least a factor of 7 lower than that of a 300 μm planar oxygenated detector irradiated with the same fluence. An
induced signal obtained at room temperature after the same fluence of 24 GeV protons using the measurement set up and a similar detector electrode spacing as those described in Section 2 is shown in Fig. 5. Successful detection of minimum ionizing particles is still possible.

4. Active edge

The same processing procedure performed to fabricate the electrodes was used to etch, dope, and fill a trench all around the detector bulk, making it into an active-edge electrode. In this way, the electric field can extend to within a few microns of the physical edge of the detector when a bias voltage is applied. The technique employed to fabricate edges using plasma etching offers several advantages: the sides are smooth and cracks or chips caused by conventional sawing or dicing of the detector are prevented. This is in contrast with traditional planar silicon processing, where the depleted (operational) region, when reverse biased, must be kept away from the physical edge since the dangling bonds there and on the chips and cracks can short the electrodes. This problem was traditionally solved by allowing extra ‘dead’ space between the active electrode and the physical edge. Space must also be allocated for a ‘guard ring’ electrode(s) that controls the voltage drop and sinks the surface leakage current generated at the edge of the device, covering a region from about 100 μm to 1 mm.

A preview of active-edge sensors performance was made [15] by replacing the cylindrical electrodes of 3D detectors by a wall electrode to give a preview of active-edge sensors performance. Fabrication steps were described in [4] and [15]. The near-cell-edge performance of these sensors was expected to give a realistic estimate of the active edge electrodes. The efficiency was measured to be within a few μm from the wall electrodes using an infrared light-emitting diode.

In 2003, active-edge detectors were successfully fabricated and were tested using an X-ray micro-beam at the advanced light source (ALS) at Lawrence Berkeley Laboratory and the insensitive edge was measured to be less than 5 μm [16].

5. Conclusions

3D detectors were successfully fabricated. Their proposed advantageous characteristics including speed, radiation hardness and active edge were tested and demonstrated. Rise time of signal induced in the detector was measured to be 3 ns at room temperature, with the observed speed limited primarily by the readout electronics. Even after irradiation with a fluence of $1 \times 10^{15}$ protons/cm², low leakage current and depletion voltage were maintained and successful detections of minimum ionizing particles were observed. Active-edge detectors was measured to be efficient up to a few μm from their physical edges, making possible zero dead edge when tiled or shingled in an array. In the near future, further studies are foreseen on performance characteristics by using faster electronics based on 0.13 μm CMOS technology and more detailed tests on radiation hardness in particular for active-edge sensors are foreseen.

References