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Recent trends in 3D Detectors

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Abstract

A new type of 3-D sensor has been developed using double sided processing with the aim of simplifying the production process. The results of strip and pixel devices from the first production run are presented. The devices fully deplete at 8 V. Tests on a beamline at the Diamond Synchrotron demonstrate much reduced charge sharing in the 3-D devices compared to planar devices. 3-D sensors also potentially have application in the harsh radiation environment of the LHC experiment upgrades. The optimal spacing between electrodes for this application has been simulated, and a cell dimension of 50-100 μm found to be optimal. The work is placed in the context of other types of 3-D architecture detectors and the work of other groups on the commercial fabrication of devices is briefly reported.

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(a) (b) (c)

Figure 1: Alternative architectures for 3D detectors. (a) Two variants of Single-sided Single Type Column sensors. (b) Single Sided Double Type Column sensors. (c) Double Sided Double Type Column sensors. The blue and red lines represent opposite doping types, the light blue area the lightly doped substrate, and the black line a metal layer.

1 Introduction

Semiconductor particle detectors usually have a planar structure, with n- and p-type electrodes on their front and back surfaces. The 3-D detector architecture replaces these planar electrodes with doped columns passing through the thickness of the substrate. This structure has significant advantages for applications such as high energy physics experiments and the detection of X-rays.

In a planar detector the substrate thickness determines the spacing between the electrodes: typically a few hundred micrometres. In a 3-D detector, the electrode spacing can be greatly reduced: the pitch between columns can be as little as 50 μm. This leads to a significant reduction in the device's collection time and full depletion voltage. As a result, 3-D detectors can tolerate the charge trapping and increase in effective doping concentration caused by high levels of radiation damage.

The 3-D architecture was proposed by Parker *et al.* more than a decade ago [1], yet no large scale system has been realised or used in an experiment. This paper explores recent trends that are helping to make full detector systems based on 3-D realisable. Simplifications of the detector design are reported concentrating on the "double sided" architecture proposed by G. Pellegrini *et al.* [2] and the results obtained by the authors. In addition the prospects for commercial device fabrication are reviewed. A brief review of the work conducted by other groups is provided in section 6.

3-D detector work has also received greater impetus from the plans for the upgrades of LHC experiments. The designs of detectors close to the beam (e.g. LHCb Vertex Locator, ATLAS b-layer) and for forward physics (FP420) lead to harsh radiation requirements for these systems. The plans for an upgrade to the LHC, increasing the luminosity by a factor of ten, will require detectors with a radiation tolerance greater than 10^{16} 1 MeV neutron equivalents / cm^2 (n$_{\mathrm{eq}}$). For X-ray imaging applications, 3-D detectors have the advantage of reduced charge sharing, as demonstrated in section 5. An additional benefit of 3D detectors is that the fabrication tools used to produce the columns can also be used to add an active edge electrode to the sensor, reducing the dead area at the edge to as little as 5 μm [3]. Hence, active edges make it possible to tile the sensors over a large area, with minimal dead space between them.

2 3D Detector Types

The electrodes in 3-D detectors are fabricated by etching holes in a silicon substrate, typically with deep reactive ion etching, and then filling them with polysilicon [4, 5]. This makes 3-D detectors considerably more complicated to produce than planar detectors. In significant part this has prevented the widespread take-up of the 3-D architecture. One of the main difficulties is to integrate the etching and doping of the n and p columnar electrodes into the fabrication sequence.

3-D detectors can be fabricated either as pixel devices or, by ganging the pixel elements together, as strip devices. Results on both are presented here.

In recent years a number of alternative 3-D like device architectures have been proposed with the aim of simplifying fabrication. These can be classified according to whether the columns are etched from one-side of the device, or both sides, and whether the columns are of one doping type only, or both p- and n-type. These concepts are illustrated in figure 1.

Single Sided Single Type Columns – semi-3D detectors. Semi-3D detectors combine a planar electrode of one doping type with 3-D pores extending some distance in to the wafer of the other doping type. Devices have been suggested and fabricated by FBK [6] and Li [7] with the planar electrode on either the opposite or the same side of the device from which the columns are etched. The fabrication of these devices is much simplified and they may provide a useful first step to allow new manufacturers to demonstrate working devices utilising micromachining technology. However, simulation and test results on strip devices show they suffer from charge loss in the central region between columns, negative signals induced on neighbouring columns, and slower charge collection times.

Single Sided Double Type Columns – original 3D devices. Standard 3D devices [1] have columns of both doping types that extend through the full thickness of the wafer. These devices are generally mounted on a carrier wafer during fabrication to reduce the risk of them cracking due to thermal stress or edge damage. (The carrier wafer is also essential to the active edge process described in [8].)

Double Sided Double Type Columns – new 3D. In the new 3D architecture [9] discussed here, columns of one doping type are etched from the front-side of the device, and the other type etched from the back side. Neither set of columns passes through the full thickness of the substrate. The columns etched from the front-side are used for readout, and the columns on the back side are connected together and used to bias the detector. The set of columns on the back side can be easily connected together by etching windows in the oxide layer then coating the entire back surface with metal. Having the bias contact on the back side, rather than the front-side as in the original 3-D design, also makes it easier to couple the detector to standard readout electronics.

3 Simulation

The double sided 3-D detector structure has been simulated and optimised using the ISE-TCAD finite element semiconductor simulation package [9, 10]. In the first devices the columns extend to 250 μm from each surface. Throughout most of the device the electrostatic behaviour matches that of a standard 3-D detector. However, the regions near the front and back of the detector deplete more slowly and have a lower electric field. Initially, the depletion region grows cylindrically outwards from the n+ column, like in a standard 3-D device, reaching the p+ columns at a few volts. At this point most of the device volume is completed. Full depletion of the substrate down to the base of the device is reached around 8V. The depletion voltage of a planar detector fabricated on the same substrate is around 50V.

Simulations have been performed that model the behaviour of different 3-D detectors at Super-LHC radiation-damage levels. The spacing of the electrodes in the 3-D device strongly influences the depletion voltage, the average collection efficiency and uniformity of the collection across the pixel. While a smaller column spacing leads to higher collected charges, using a small column spacing also increases the fraction of the pixel occupied by the columns and the rapidly increasing capacitive noise limits the signal-to-noise ratio. This is shown in figure 3 For detectors operating at 10^{16} n_{eq}, the best trade-off is likely to be achieved by using 4-6 columns in the 50×400 μm pixels currently used by the ATLAS collaboration. Overall, the simulation results show improved depletion and charge collection behaviour compared to planar detectors.

For X-ray imaging, the most important advantage of the 3D structure is reduced charge sharing, as demonstrated by simulation studies [11]. Firstly, the fast charge collection in a 3D detector means that there is less time for the cloud of charge carriers to spread by diffusion. Secondly, the electric field pattern in the device causes the carriers to drift horizontally towards the readout columns, away from the pixel boundaries.

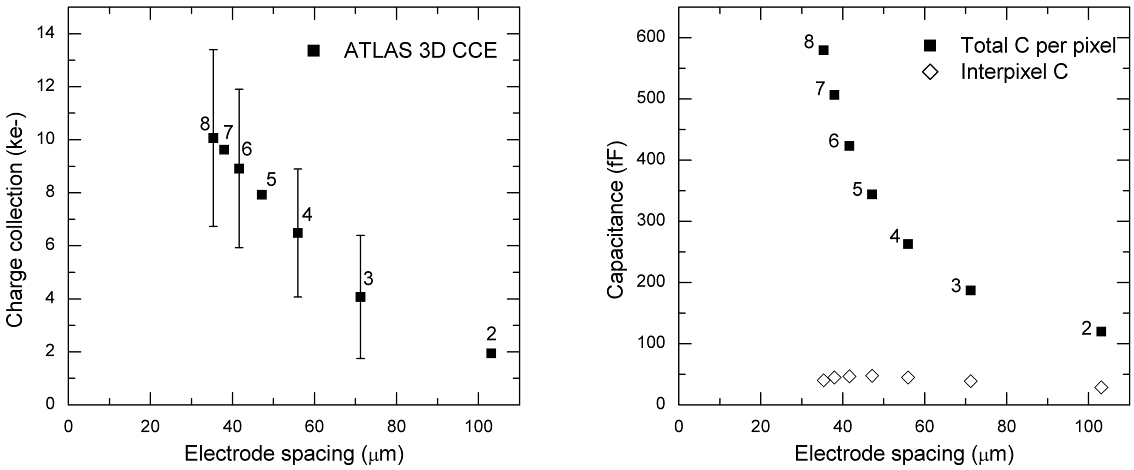
4 Fabrication

The production of the double sided double type 3-D sensors is described in [12]. 10 μm diameter holes were produced with a 250 μm depth using the inductively coupled plasma etching process. Hence, the overlap of the two column types from each side of the wafer is 200 μm. The electrodes within the holes were formed by partially filling with a thick polysilicon layer and doping with boron and phosphorus. The temperature of the process was controlled to limit the diffusion of the dopant, the junction is formed at a distance of about 2 μm into the silicon.

The first production run of 3D devices with p-type readout was completed in 2007, and a second run including n-type readout is currently underway. The devices produced include test structures, pads, strip detectors, and pixel detectors. Pixel devices with layout compatible with Medipix2, Pilatus and ATLAS pixel read out chips were produced.

5 Test Results

The 80 μm pitch strip devices have been tested by wire bonding to the 40MHz sampling time front-end chip of the LHCb silicon detectors [13] and using data acquisition readout and data processing software based on that of the LHCb Vertex Locator. Source tests were then performed. Charge distributions were obtained and fitted with a Landau convoluted with a Gaussian, and a preliminary signal:noise ratio of 15:1 was obtained. Comparison with a planar sensor shows significantly reduced charge sharing on the 3D sensor. Devices have



(a) (b)

Figure 2: (a) Simulated charge collection in different ATLAS pixel layouts at 10^{16} n_{eq} fluence. The data points give the average collection efficiency, and the "error bars" give an estimate of the variation in the charge collection with lateral position. This variation was only calculated for the 8-, 6-, 4- and 3-column devices. The simulated applied bias was 150 V in all cases, and the charge deposited was 80 electron hole pairs per micron. (b) Capacitance per pixel and interpixel capacitance in different ATLAS pixel layouts. No bulk damage was included in these simulations.

been irradiated with neutrons at the J. Stephan Institute's Triga research nuclear reactor [14] at Ljubljana, Slovenia to 5×10^{15} n_{eq} and are currently under test. IV results compatible with simulation are obtained.

Pixel devices have been bump bonded to a Medipix2 chip. The Medipix2 readout chip [15] is a single photon counting chip specifically designed for X-ray detection, and has a 256 by 256 array of square, 55 μm pixels. Hits are counted above a variable threshold, and individual pixel flat field corrections may be applied. The Medipix2 chipboards were read out using Medipix2 USB interfaces, produced by IEAP, Czech Technical University, Prague [16]. The devices were tested at the Diamond Light Source synchrotron and results are reported in [17]. A spectral scan was performed with a 15keV X-ray beam. Images were taken with a range of threshold values varying from above the beam energy down to the noise level. The total counts in each image was then differentiated to obtain the differential spectrum. The results for the 3-D sensor (with a a bias of 21.5 V) and a planar sensor (with a bias of 100 V) with identical readout are shown in figure 3. By fitting a Gaussian to the peak distribution the total number of non-charge shared hits was extracted. The total number of photons detected by each sensor was estimated by setting the low threshold to half the beam energy. The 3-D sensor has a substantially lower proportion of charge-shared hits; from an average of results at three different beam energies a value of 23% was extracted for the 3-D sensor to be compared to 39.5% for the planar sensor.

6 Other 3D groups

There is currently significant worldwide activity in 3-D sensors, with the technology being developed commercially or semi-commercially by a number of groups. The University of Glasgow and the Diamond Light Source have also been collaborating with ICEMOS Technology Ltd, a first production run of 3-D sensors was completed in early 2008 [18]. 27:1 aspect ratio holes were produced, and despite problems with wafer fragility and metal layer deposition, test structures showed lateral depletion between columns at 4V. The Universties of Hawaii, Stanford and Manchester are collaborating with SINTEF on the production of 3-D sensors, and are also investigating the use of 3-D sensors in fast timing applications for triggering [19]. VTT have produced single sided single type devices [20] and have also bonded them to Medipix2 and plan a full 3D run at the end of 2008. FBK first developed the single sided single type devices [6] and have recently completed their first production run of double sided double type devices which laterally deplete at 2 V.

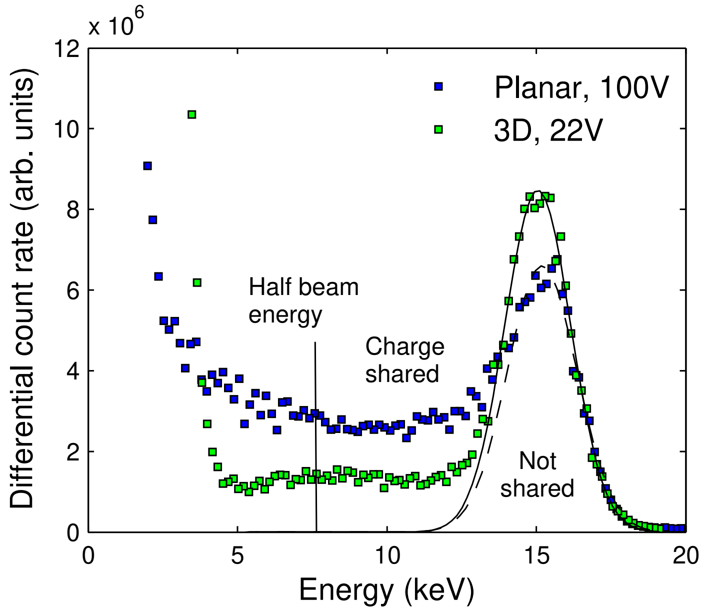


Figure 3: Comparison of 15 keV beam spectra measured by 300 μm double sided double type 3D and planar sensor with Medipix2 chip. Smaller charge sharing is observed on the 3D than the planar device.

7 Conclusions

Initial fabrication of 3-D devices was centred on university laboratories, more recently the technology has been transferred to commercial and semi-commercial facilities. Commercial production offers the prospect of using 3-D sensors in large scale systems. Potential applications include upgrades to the LHC experiments, where radiation tolerances of 10^{16} $\mathrm{n_{eq}}$are required. Simulations show that the inter-column pitch can be optimised for a trade-off between the devices capacitance (and hence noise performance) and the collected signal.

Double-sided double-type 3D sensors have been developed by CNM and the University of Glasgow with the aim of simplifying the production of 3D sensors. The results for both strip and pixel devices from the first production run at CNM have been shown. The devices deplete at 2V laterally and full-deplete at 9V. The charge sharing in 3-D sensors is seen to be significantly reduced from that of planar sensors, this has potential benefits for X-ray applications with single photon counting chips.

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