PoS PROCEEDINGS OF SCIENCE

New Beam Test Results of 3D Pixel Detectors Constructed With poly-crystalline CVD diamonds

The RD42 Collaboration

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As nuclear and high energy facilities around the world strive for higher and higher energies and intensities, more radiation tolerant technologies are required to withstand the increasing radiation doses. Chemical Vapour Deposition (CVD) diamond is an excellent candidate for this purpose. Detectors out of this material are already established in the highest irradiation regimes for the beam condition monitors at the LHC. The RD42 collaboration is leading an effort to use CVD diamonds also as sensor material for the future tracking detectors. We present a novel detector design - namely 3D Detectors - based on poly-crystalline CVD diamond sensors with a pixel readout. The fabrication of these 3D detectors as well as their working principle is shown. We measured the efficiency and signal response of two 3D diamond detectors with $50 \times 50\,\mu$m cell sizes using readout chip technologies currently used at CMS and ATLAS.

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1. Introduction

The radiation levels of the High-Luminosity-LHC (HL-LHC) are expected to be a big challenge for the future detectors. By 2028 experiments must be prepared for an instantaneous luminosity of $7.5 \cdot 10^{34}\,\mathrm{cm^{-2}\,s^{-1}}$. In this environment the innermost tracking layer at a transverse distance of $\sim$30 mm to the interaction point will be exposed to a total fluence of $2 \cdot 10^{16}\,\mathrm{n_{eq}/cm^2}$ which corresponds to a total dose of the $\mathcal{O}(10\,\mathrm{MGy})$ [1]. After such a large dose, all detector materials become trap limited with a schubweg, the average drift distance before a free charge carrier gets trapped, below 75 µm. The expected lifetime of the current planar silicon tracking detectors would be about one year in such and environment.

Due to the properties of Chemical Vapour Deposition (CVD) diamond, such as the displacement energy of 42 eV/atom and the band gap of 5.5 eV, the RD42 collaboration is investigating it as a possible detector material [2]. Compared to analogous silicon detectors, various studies have shown that diamond is at a minimum three times more radiation hard [3], collects the charges at least two times faster [4] and conducts heat four times more efficiently [5].

By now the technology of diamond detectors is well established in high energy physics. Many high energy physics experiments are already using Beam Condition Monitors or Beam Loss Monitors based on CVD diamonds [6, 7, 8].

The RD42 collaboration is studying a novel detector design in diamond, namely 3D detectors. The 3D concept reduces the drift distance an electron-hole pair must undergo to reach an electrode below the schubweg of an irradiated sensor without reducing the amount of created electron-hole pairs.

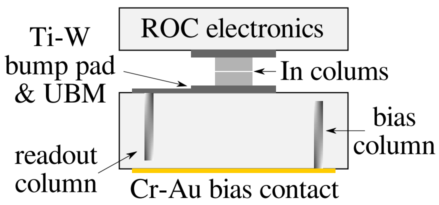
2. 3D Pixel Detectors

By placing column-like electrodes inside the detector material, the 3D geometry reduces the drift distance of a charge created by ionising particles compared to a planar device. More details about the working principle can be found in [9], [10]. All devices discussed in this article were constructed with poly-crystalline Chemical Vapour Deposition (pCVD) diamond.

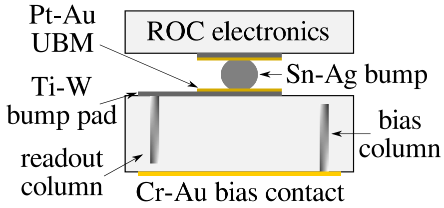
2.1 Fabrication

In order to manufacture the electrodes in diamond, columns were fabricated using a 130 fs laser with a wavelength of 800 nm which converts the diamond into a electrically resistive mixture of different carbon phases [11]. A Spacial Light Modulator (SLM) was used to correct aberrations during fabrication to achieve a column yield of $\gtrsim$99.8 %, a column diameter of 2.6 µm and a resistivity of the columns of the order of $0.1 \sim 1\,\Omega\,\mathrm{cm}$ [12]. The columns are not drilled completely through the diamond, but with a gap of 15 µm to the opposite surface to avoid high voltage breakthrough. So far the largest fabricated device has about 4000 3D cells, where one cell consists of four bias electrodes and one readout electrode in the centre. Thus $\sim$7000 columns had to be drilled to build such a device.

The detector was constructed by connecting the bias columns with a metallisation on the bottom surface and the readout columns with a metallisation on the top surface. The sensor was then bump bonded to the readout electronics as shown in Figure 1 on the following page. The detectors described herein were connected to two different readout chips (ROCs), which is why different bonding processes, as shown in Figures 1a and 1b, had to be developed. For both of these detectors a 3D cell size of $50\,\mu m \times 50\,\mu m$ was chosen. Since the layout of the ROCs has a different pixel pitch several cells were ganged together. Photographs of the assembled 3D detectors on the ROCs are shown in Figure 2.

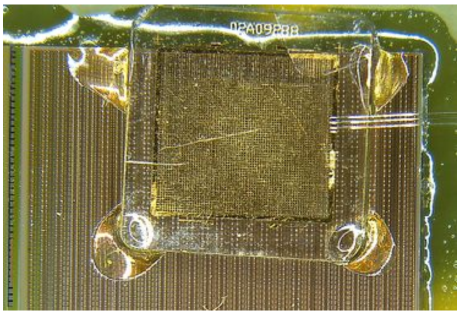


(a) CMS PSI46dig

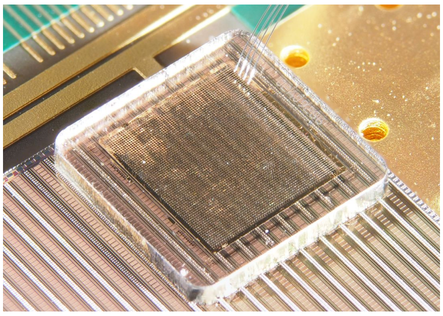


(b) ATLAS FE-I4B

Figure 1: Bump Bonding and metallisation for two different ROCs.



(a) CMS PSI46dig



(b) ATLAS FE-I4B

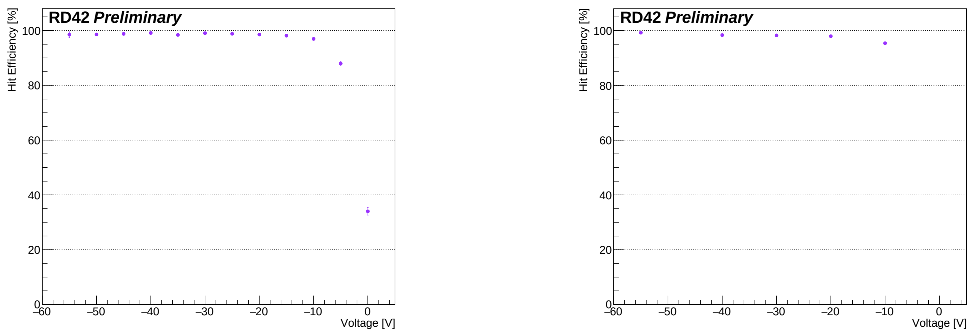
Figure 2: Fully assembled 3D pixel detectors.

2.2 PSI46digV2.1respin readout

The first 3D pixel detector prototype was connected to the PSI46digV2.1respin ROC [13] with a 3×2 cell ganging to match the pixel pitch of $150\,\mu m \times 100\,\mu m$. The 3D sensors were bump bonded to the ROC at the Nanofabrication Lab at the Princeton University with indium. This was achieved by putting equal height indium columns on both ROC and the sensor and then pressing them together.

This detector was tested both in beam lines at Paul Scherrer Institut (PSI) and the SPS facility at CERN. The preliminary beam test results show that, relative to a planar silicon device, the efficiency within a selected fiducial area was 99.2 %. Where the hit efficiency was defined as the percentage of hits in the 3D pixel detector when a particle track traversed the detector. This exact value was measured at both beam test facilities. The fiducial area was selected such as to exclude non-working 3D cells found by visual inspection, which can happen due to broken or missing columns or due to metallisation issues. A small mismatch between a 3D and a planar device is expected due to a region inside the cells where the electric field is low [14] and due to the relative inefficiency of the columns themselves. The area of the 3D columns compared to the whole cell is 0.4 %.

Figure 3 shows that the efficiency of the detector plateaus at a voltage of 30 V. The measurements at both facilities also agree well. This demonstrates that the device already operate well at comparably low voltages.



(a) PSI. (b) CERN SPS.

Figure 3: Hit efficiency vs. bias voltage.

The preliminary analysis of the pulse height distribution for the measurements at CERN yields a mean value of ∼14 ke. The precise pulse height calibration of the ROC is currently being studied.

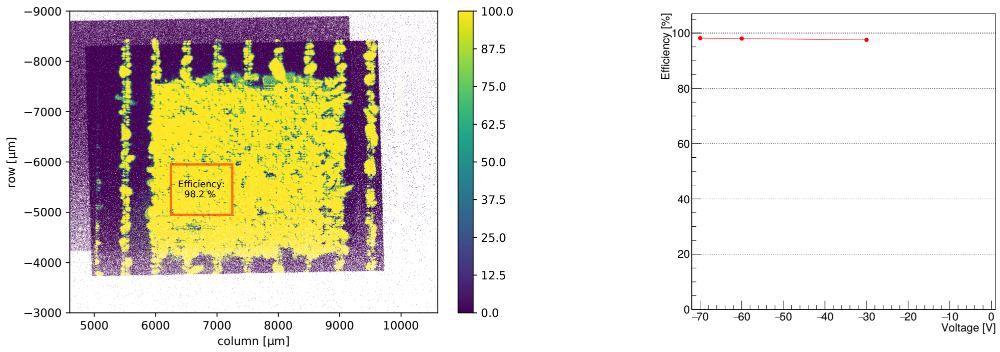
2.3 FE-I4B readout

The second prototype was connected to the FE-I4B ROC [15] with a 5×1 cell ganging due to the pixel pitch of 250 μm × 50 μm. The bump bonding was performed at IFAE-CNM in Barcelona by an adapted process with tin-silver bumps. Using a high resolution beam telescope, with a spatial resolution of 3 μm at the device under test, the efficiency could be mapped to the spatial coordinates.

The first results are shown in Figure 4 on the next page. The analysis yields an efficiency of 98.2 % in the contiguous fiducial area (Figure 4a on the following page). As shown in Figure 4b on the next page, the detector reaches the same efficiency for all tested voltages. The efficiency being lower than 99 % is most likely due to issues with the bump bonding or the metallisation as indicated by the inefficient patches in the efficiency map. The preliminary pulse height in the fiducial region was ∼14 ke which is consistent with the result of the first prototype. The precise pulse height calibration for the FE-I4B ROC is in the process of being performed.

3. Conclusion

There is progress in the development of radiation tolerant particle detectors based on pCVD diamonds. The working principle of 3D diamond pixel detectors was proven for cell sizes of 50 μm × 50 μm and column diameters of 2.6 μm. The largest device had a number of 4000 cells and the efficiency of the column drilling process is above 99.8 %. The first prototypes of small cell 3D diamond pixel detectors read out more charge than any planar pCVD diamond detector. The measured relative hit efficiency of the 3D pixel detectors reached 99.2 % compared to a planar silicon device.



(a) Hit efficiency map. The red box denotes the fiducial area.

(b) Hit efficiency vs. voltage.

Figure 4: Results of the FE-I4 readout.

Acknowledgements

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