New Test Beam Results of 3D and Pad Detectors Constructed with Poly-Crystalline CVD Diamond

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Abstract

Chemical Vapour Deposition (CVD) diamond is a possible material for particle detectors in a harsh radiation environment. This article presents beam test results of 3D pixel detectors fabricated with poly-crystalline CVD diamonds. The cells of the devices have a size of $50\,\mu\text{m} \times 50\,\mu\text{m}$ with columns $2.6\,\mu\text{m}$ in diameter. The cells were ganged in a 3×2 and 5×1 pattern to match the layouts of the pixel read-out chips currently used in the CMS and ATLAS experiments at the Large Hadron Collider, respectively. In beam tests, using tracks reconstructed with a high precision tracking telescope, both devices achieved tracking efficiencies greater than 97 %. The efficiency of both devices plateaus at a bias voltage of 30 V. The latest high rate beam test results of irradiated poly-crystalline CVD diamond pad detectors are also presented. In measurements with particle fluxes up to $20\,\text{MHz/cm}^2$ and irradiations up to $8 \cdot 10^{15}\,\text{n/cm}^2$ it was shown that the pulse height of irradiated poly-crystalline CVD diamonds does not depend on flux to the $O(2\,\%)$.

Keywords: Diamond Detectors, 3D Sensors, Particle Flux

1. Introduction

The radiation levels of the High-Luminosity Large Hadron Collider (HL-LHC) will become a big challenge for the future detectors. By 2028 an instantaneous luminosity of $7.5 \cdot 10^{34}\,\text{cm}^{-2}\,\text{s}^{-1}$ is and total dose of the $O(10\,\text{MGy})$ are expected [1]. In this environment the innermost tracking layer at a transverse distance of ~30 mm to the interaction point is expected to be exposed to a total fluence of $2 \cdot 10^{16}\,\text{n}_\text{eq}/\text{cm}^2$ [2]. The lifetime of the current planar silicon tracking detectors is expected to be about one year in the HL-LHC.

After a large fluence, all detector materials become trap limited with a mean drift distance below $75\,\mu\text{m}$. Due to its properties, such as the displacement energy of 42 eV/atom and the band gap of 5.5 eV, the RD42 collaboration is investigating CVD diamond as a possible detector material [3]. In various studies it was shown that compared to corresponding silicon detectors, diamond is at a minimum three times more radiation hard [4], collecting the charges at least two times faster [5] and conducting heat four times more efficiently [6].

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 [7], [8], [9].

The RD42 collaboration is investigating a novel detector de-

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sign in diamond, namely 3D detectors. This concept is a possible way to reduce the drift distance an electron-hole pair must undergo to reach an electrode below the trap limited mean drift distance (MDD) of an irradiated sensor without reducing the total number of the electron-hole pairs.

The particle flux of the HL-LHC will also reach a completely new regime. Hence high rate studies of pad detectors were performed at Paul Scherrer Institut (PSI) with nearly minimum ionising particles (MIPs) and tunable particle fluxes up to $O\left(20\,\mathrm{MHz/cm^2}\right)$.

2. 3D Pixel Detectors

By placing the 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 [10], [11]. All devices discussed in this article were constructed with polycrystalline CVD (pCVD) diamond.

2.1. Fabrication

In order to generate the electrodes in diamond, columns are fabricated using a 130 fs laser with a wavelength of 800 nm which is used to convert the diamond into a electrically resistive mixture of different carbon phases [12]. By using Spacial Light Modulation (SLM) a column yield of >99 %, a column diameter of 2.6 µm and a resistivity of the columns of the order of 0.1 ~ 1 Ω cm was be achieved. [13]. The largest fabricated device has about 4000 3D cells, where one cell consists out of four bias electrodes and one read-out electrode in the centre.

The detector is built by connecting to the bias and readout columns with surface metallisation and bump bonding the sensor to the readout electronics as shown in Figure 1. For the detectors described in here a cell size of 50 µm × 50 µm was chosen. Since the layout of the available readout chips (ROCs) has a different pixel pitch several cells had to be ganged together.

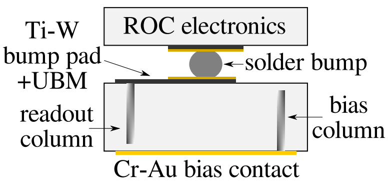
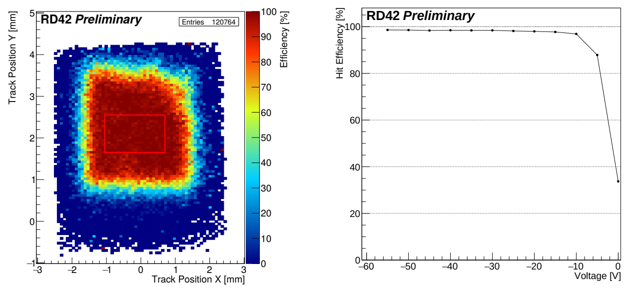


Figure 1: Bump bonding scheme.

2.2. PSI46digV2.1respin read-out

The first prototype of a 50 µm × 50 µm 3D pixel detector was connected to the PSI46digV2.1respin ROC [14] with a 3×2 cell ganging to match the pixel pitch of 150 µm × 100 µm. The 3D sensors were bump bonded to the ROC at the Nanofabrication Lab in Princeton with indium bumps by putting equal height indium columns on both ROC and the sensor and then pressing them together. The preliminary beam test results show that relative to a planar silicon device the efficiency in the fiducial area amounts to 99.3 % (Figure 2a). This efficiency estimation does not account for non-working 3D cells in this region which can happen due to broken or missing columns or due to metalisation issues. In order to acquire this information further data has to be analysed. Nevertheless, a small mismatch between a 3D and a planar device is expected due to regions inside of the detector where the electric field is low [15] and the columns themselves. Figure 2b shows that the device already plateaus at a voltage of 30 V. The preliminary analysis of the pulse height distribution yields a mean value of ~11 ke. The precise pulse height calibration of the ROC is currently being studied.



(a) 3×2 efficiency. The red box marks the fiducial area.

(b) Efficiency vs. voltage.

Figure 2: 3×2 results.

2.3. FE-I4b read-out

The second prototype was connected to the FE-I4b ROC [16] with a 5×1 cell ganging due to its 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 results yield an efficiency of 97.8 % in the contiguous fiducial area (Figure 3). The lower than 99 % efficiency is most likely due to issues with the bump bonding or

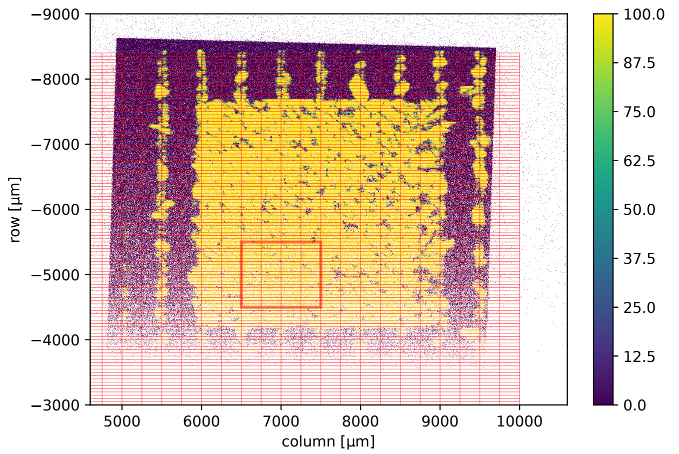


Figure 3: 5×1 efficiency. The red box denotes the fiducial area.

the metallisation. The preliminary pulse height in the fiducial region amounts to ∼15 ke which is consistent with the result of the first prototype considering the different momenta of the incident particles. The precise pulse height calibration for the FE-I4b ROC is in the process of being performed.

3. High Rate Studies

At the HL-LHC particle fluxes will reach the $O\left(\mathrm{GHz/cm^2}\right)$ hence it is very important to understand the effect of the incident particle flux on the signal of all prospective detectors. In order to conduct such a study it is necessary to be able to vary the particle flux over a large range. The πM1 beam line at the High Intensity Proton Accelerator (HIPA) at PSI [17] can provide beams with continuously tunable fluxes from the order of 1 kHz/cm^2 up to 20 MHz/cm^2. The πM1 beam is bunched with a spacing of 19.7 ns. For these studies a π^+ beam with a momentum of 260 MeV/c was chosen in order to reach the highest possible flux [18]. In total 17 pCVD diamonds were measured.

3.1. Setup

The planar diamond sensors were connected in a pad geometry and prepared as described in [19]. In order to resolve individual particles at high particle rates the sensors were connected to a fast, amplifier with low electronic noise and a rise time of approximately 5 ns. The resulting waveforms were digitised and recorded in a beam telescope setup which provides spatial information of the hits in the diamond detector. Due to the low momentum of the incident particles the spatial resolution of the telescope was of the $O(100\,\mu\mathrm{m})$.

3.2. Results

pCVD diamond has an interior crystal structure where the individual grains have slightly different properties. Therefore the size of the measured signal in pCVD depends also on the spatial position as can be seen in Figure 4. However this behaviour is constant and neither depends on time nor on rate.

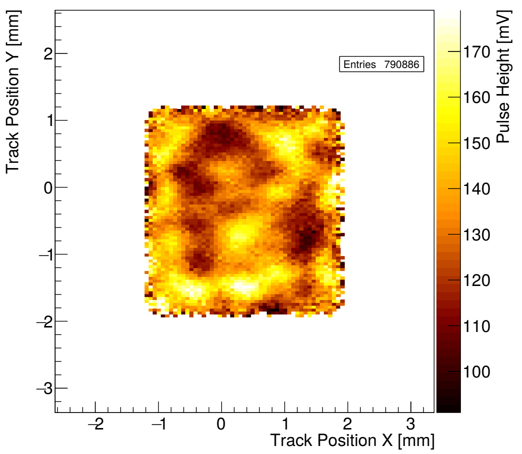


Figure 4: Pulse height map of a pCVD diamond as a function of spatial position.

The effect of particle rate on the beam induced current in diamond detectors was measured. In 80 % of the measured diamonds the current is proportional to the flux and the leakage current without a beam is of the $O(1\,\mathrm{nA})$. The other 20 % of the diamonds show shifting base lines or erratic currents [20]. These diamonds are considered problematic and were not analysed for this article.

In order to measure the signal behaviour as a function of incident particle flux and irradiation, several rate scans with both polarities of the bias voltage were performed. Figure 5 shows the final results for a pCVD diamond with various fluences

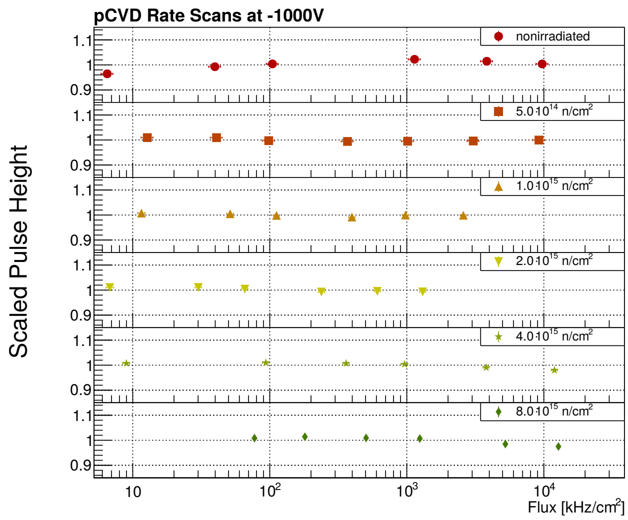


Figure 5: Pulse height versus incident particle flux for a pCVD diamond for various fluences at −1000 V.

up to a maximum particle flux of 20 MHz/cm^2. The sensors were irradiated at the irradiation facilities at the JSI TRIGA reactor in Ljubljana with fast reactor neutrons in steps up to $8 \cdot 10^{15}\,\mathrm{n/cm^2}$ [21]. The mean pulse height of the single scans is scaled to 1. The pulse height is flat with respect to the flux deviating less than 2 % from the mean.

We also observed a single diamond with a large rate dependence losing 90 % of the signal at the highest rate. After the surface was cleaned and processed with Reactive Ion Etching (RIE), the device was reprocessed. A new measurement showed a deviation of less than 2 % from the mean pulse height. This leads us to the conclusion that this rate effect is due to surface properties and is possible to repair.

4. Conclusion

There is progress in the development of radiation tolerant particle detectors based on pCVD diamonds. The working principle of 3D pixel detectors was proven for cell sizes of $50\,\mu\mathrm{m} \times 50\,\mu\mathrm{m}$ and column diameters of 2.6 µm. The largest device has a number of 4000 cells and the efficiency of the column drilling process is now above 99 %. The first prototypes of small cell 3D pixel detectors read out more charge than any planar pCVD diamond detector. The measured relative hit efficiency of the 3D pixel detectors reached 99.3 % compared to a silicon device.

It was found that irradiated pCVD diamond detectors work reliably and there is no signal variation greater than 2 % up to an incident particle flux of 20 MHz/cm^2. This was shown for an irradiation up to a fluence of $8 \cdot 10^{15}$ n/cm^2. The beam induced current of a pCVD diamond is proportional to the flux and the leakage current is of the O(1 nA). A small fraction of the diamonds shows a large rate dependence which is most likely to surface properties and is possible to correct.

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