PROCEEDINGS OF SCIENCE

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

The RD42 Collaboration

M. Reichmann*[24], A. Alexopoulos[3], M. Artuso[20], F. Bachmair[24], L. Bäni[24], M. Bartosik[3], H. Beck[23], V. Bellini[2], V. Belyaev[12], B. Bentele[19], A. Bes[27], J-M. Brom[7], M. Bruzzi[4], G. Chiodini[26], D. Chren[18], V. Cindro[9], G. Claus[7], J. Collot[27], J. Cumalat[19], A. Dabrowski[3], R. D'Alessandro[4], D. Dauvergne[27], W. de Boer[10], C. Dorfer[24], M. Dünser[3], G. Eigen[30], V. Eremin[6], G. Forcolin[22], J. Forneris[15], L. Gallin-Martel[27], M-L. Gallin-Martel[27], K. K. Gan[13], M. Gastal[3], M. Goffe[7], J. Goldstein[17], A. Golubev[8], A. Gorišek[9], E. Grigoriev[8], J. Grosse-Knetter[23], A. Grummer[21], M. Guthoff[3], B. Hiti[9], D. Hits[24], M. Hoeferkamp[21], T. Hofmann[3], J. Hosselet[7], F. Hügging[1], C. Hutton[17], J. Janssen[1], H. Kagan[13], K. Kanxheri[28], R. Kass[13], M. Kis[5], G. Kramberger[9], S. Kuleshov[8], A. Lacoste[27], S. Lagomarsino[4], A. Lo Giudice[15], I. Lopez Paz[22], E. Lukosi[25], C. Maazouzi[7], I. Mandić[9], C. Mathieu[7], M. Menichelli[28], M. Mikuž[9], A. Morozzi[28], J. Moss[29], R. Mountain[20], A. Oh[22], P. Olivero[15], D. Passeri[28], H. Pernegger[3], R. Perrino[26], F. Picollo[15], M. Pomorski[11], R. Potenza[2], A. Quadt[23], F. Rarbi[27], A. Re[15], S. Roe[3], D. A. Sanz Becerra[24], M. Scaringella[4], C. J. Schmidt[5], S. Schnetzer[14], E. Schioppa[3], S. Sciortino[4], A. Scorzoni[28], S. Seidel[21], L. Servoli[28], D. S. Smith[13], B. Sopko[18], V. Sopko[18], S. Spagnolo[26], S. Spanier[25], K. Stenson[19], R. Stone[14], B. Stugu[30], C. Sutera[2], M. Traeger[5], W. Trischuk[16], M. Truccato[15], C. Tuve[2], J. Velthuis[17], N. Venturi[3], S. Wagner[19], R. Wallny[24], J. C. Wang[20], N. Wermes[1], M. Yamouni[27], J. Zalieckas[30] and M. Zavrtanik[9]

[1] *Universität Bonn, Bonn, Germany*
[2] *INFN/University of Catania, Catania, Italy*
[3] *CERN, Geneva, Switzerland*
[4] *INFN/University of Florence, Florence, Italy*
[5] *GSI, Darmstadt, Germany*
[6] *Ioffe Institute, St. Petersburg, Russia*
[7] *IPHC, Strasbourg, France*
[8] *ITEP, Moscow, Russia*
[9] *Jožef Stefan Institute, Ljubljana, Slovenia*
[10] *Universität Karlsruhe, Karlsruhe, Germany*
[11] *CEA-LIST Technologies Avancees, Saclay, France*
[12] *MEPHI Institute, Moscow, Russia*
[13] *The Ohio State University, Columbus, OH, USA*
[14] *Rutgers University, Piscataway, NJ, USA*
[15] *University of Torino, Torino, Italy*
[16] *University of Toronto, Toronto, ON, Canada*
[17] *University of Bristol, Bristol, UK*

[18]Czech Technical University, Prague, Czech Republic
[19]University of Colorado, Boulder, CO, USA
[20]Syracuse University, Syracuse, NY, USA
[21]University of New Mexico, Albuquerque, NM, USA
[22]University of Manchester, Manchester, UK
[23]Universität Göttingen, Göttingen, Germany
[24]ETH Zürich, Zürich, Switzerland
[25]University of Tennessee, Knoxville, TN, USA
[26]INFN-Lecce, Lecce, Italy
[27]LPSC-Grenoble, Grenoble, France
[28]INFN-Perugia, Perugia, Italy
[29]California State University, Sacramento, CA, USA
[30]University of Bergen, Bergen, Norway
E-mail: michael.reichmann@cern.ch

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. As a possible candidate 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 $2 \cdot 10^{16}\,\mathrm{n_{eq}/cm^2}$ [1]. The expected lifetime of the current planar silicon tracking detectors would be about one year in such and environment.

Chemical Vapour Deposition (CVD) diamond is investigated by the RD42 collaboration as a possible detector material [2]. Its displacement energy of $42\,\mathrm{eV/atom}$ makes it intrinsically radiation tolerant and the band gap of 5.5 eV greatly simplifies the construction of the detectors as well as guarantees negligible leakage currents. Compared to analogous silicon detectors, it was shown that diamond is at a minimum three times more radiation tolerant [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].

After the doses expected in the HL-LHC, all detector materials become trap limited with a schubweg, the average drift distance before a free charge carrier gets trapped, below 75 µm. Therefore RD42 collaboration is studying a novel detector design in diamond, namely 3D detectors. This detector design places column-like electrodes inside the detector material. Therefore the drift distance an electron-hole pair must undergo to reach an electrode can be reduced below the schubweg of an irradiated sensor without reducing the amount of created electron-hole pairs.

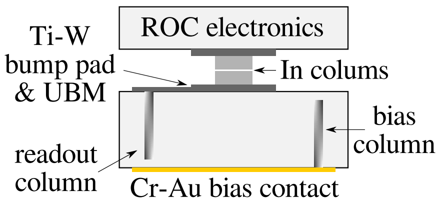
2. 3D Pixel Detectors

Details about the working principle can be found in [9].

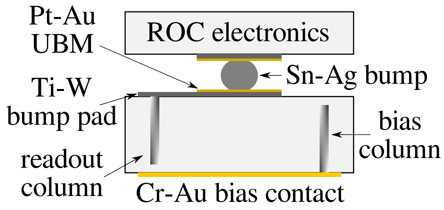
2.1 Fabrication

All devices discussed in this article were constructed with poly-crystalline Chemical Vapour Deposition (pCVD) diamond. The sensors are thin panes with a thickness of $\mathcal{O}(500\,\mathrm{\mu m})$ and a side length of $\mathcal{O}(500\,\mathrm{mm})$. In order to manufacture the electrodes in diamond, columns were fabricated through the thin side using a 130 fs laser with a wavelength of 800 nm which converts the diamond into a electrically resistive mixture of different carbon phases [10]. A Spatial Light Modulator (SLM) was used to correct spherical 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 $0.1 \sim 1\,\Omega\,\mathrm{cm}$ [11]. 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 at the operated voltages of up to $\sim$2 V/µm. The detector was constructed by ganging all bias columns together with a metallisation on the bottom surface and metallise the single readout columns on the top surface in order to bump bond the sensor to the readout electronics.

The detectors described herein were connected to two different readout chips (ROCs), which is why different bonding processes, as shown in Figures 1, had to be used. For both of these detectors a 3D cell size of 50 µm × 50 µm was chosen. Since the layout of the ROCs had a different pixel pitch several cells were ganged together by connecting several readout columns with the surface metallisation. The detector B6 was connected to the PSI46digV2.1respin ROC [12] with a 3 × 2 cell ganging to match the pixel pitch of 150 µm × 100 µm. It was 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 1a. The detector B5 was connected to the FE-I4B ROC [13] with a 5 × 1 cell ganging due to the pixel pitch of 250 µm × 50 µm. The bump bonding for this sensor was performed at IFAE-CNM in Barcelona by an adapted process with tin-silver bumps 1b.



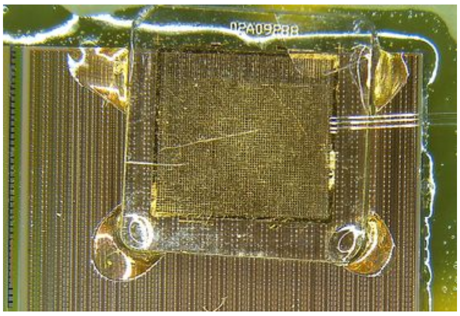
(a) CMS PSI46dig



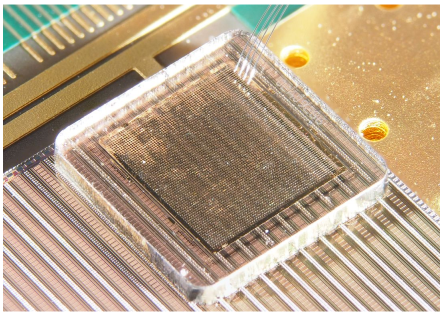
(b) ATLAS FE-I4B

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

Both devices have ∼4000 3D cells, where one cell consists of four bias electrodes and one readout electrode in the centre. Since the bias electrodes are shared between the cells, ∼7000 columns had to be drilled to build such a device. Photographs of the assembled 3D detectors on the ROCs are shown in Figure 2.



(a) B6 - 3 × 2



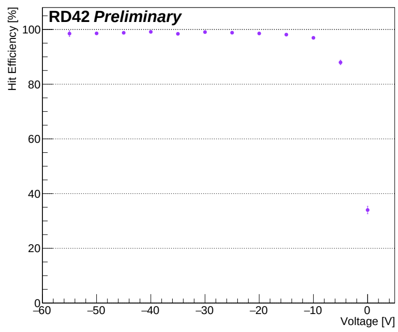
(b) B5 - 5 × 1

Figure 2: Assembled 3D pixel detectors.

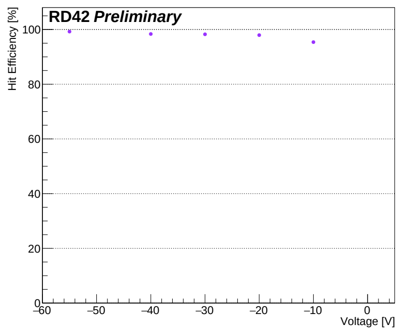
2.2 B6 Results

This detector was tested with pixel telescopes in beam lines at Paul Scherrer Institut (PSI) and the SPS facility at CERN in order to get both measurements at high rates as well as with high tracking resolution. 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 discrepancy between a 3D and a fully efficient planar device is partly expected 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. This demonstrates that the device already operates well at very low voltages compared to a planer diamond detector. The measurements at both facilities agree well, which shows that the detector is independent of the different particle energies and intensities which were used.



(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 $\sim$14 ke. The precise pulse height calibration of the ROC is currently being studied.

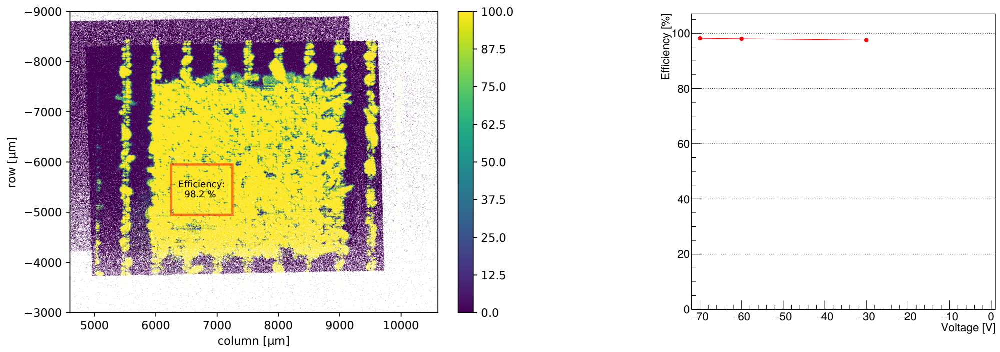
2.3 FE-I4B readout

This device was solely test at the CERN SPS beam line using a high resolution beam telescope, with a spatial resolution of 3 µm at the device under test so that the efficiency could be mapped to the spatial coordinates.

The first results are shown in Figure 4. The analysis yields an efficiency of 98.2 % in the contiguous fiducial area (Figure 4a). As shown in Figure 4b, 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 suggested by the inefficient patches in the efficiency map. The preliminary pulse height in the fiducial region was $\sim$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

We demonstrated a 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 $\times$ 50 µm and column diameters of 2.6 µm. The shown devices 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



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

(b) Hit efficiency vs. voltage.

Figure 4: Results of the FE-I4 readout.

measured relative hit efficiency of the 3D pixel detectors reached a maximum of 99.2 % compared to a planar silicon device.

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