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Diamond sensors for future high energy experiments

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ABSTRACT

With the planned upgrade of the LHC to High-Luminosity-LHC [1], the general purpose experiments ATLAS and CMS are planning to upgrade their innermost tracking layers with more radiation tolerant technologies. Chemical Vapor Deposition CVD diamond is one such technology. CVD diamond sensors are an established technology as beam condition monitors in the highest radiation areas of all LHC experiments. The RD42-collaboration at CERN is leading the effort to use CVD diamond as a material for tracking detectors operating in extreme radiation environments. An overview of the latest developments from RD42 is presented including the present status of diamond sensor production, a study of pulse height dependencies on incident particle flux and the development of 3D diamond sensors.

1. Introduction

With the planned upgrades of the Large Hadron Collider (LHC) to High Luminosity (HL-LHC) [1] and the next generation of particle physics experiments in development, new energy and luminosity regimes will be reached. The expected fluence for the inner most layer of the tracking detector at HL-LHC is $\Phi_{1\ \mathrm{MeVn_{eq}}} = 2 \times 10^{16}\ \mathrm{n_{eq}/cm^2}$ [2] and the flux is expected to be up to 1.5 GHz $/\mathrm{cm}^2$ [3, scaled to the expected instantaneous luminosity]. For these harsh radiation environments new technologies for tracking detectors are most likely required. With its large band-gap ($E_{gap} = 5.5$ eV at $T = 302$ K) and its high binding energy, diamond has ideal material properties to work as a particle detector in these environments. Chemical Vapor Deposition (CVD) diamonds have been shown to be at least three times more radiation tolerant [4], to have at least a two times faster charge collection [5], and to be four times more thermally conductive [6] than corresponding silicon detectors. Low leakage currents, low dielectric constant and the ability to work at room temperature are also appealing properties for tracking detectors.

The RD42-collaboration, based at CERN, is investigating the capability of diamond detectors in the field of high energy physics. The signal response of response of single-crystal CVD (scCVD) and polycrystalline CVD (pCVD) diamonds irradiated up to 1.8×10^{16} protons/cm^2 [7] has been measured, indicating that diamond-based detectors are good candidates for tracking detectors close to the interaction point. In order to increase the radiation hardness even further RD42 recently started to evaluate diamond detectors based on the new 3D geometry. As part of the mission, RD42 has been working with diamond manufacturers for two decades to improve the quality of artificially grown diamonds based on the (CVD) technique to make them suitable for use as charged particle sensors. For a long time only a single manufacturer [8] was capable of producing detector grade diamonds. In the last years two new producers, II-VI Incorporated [9] and IIa Technologies [10], have entered the market.

When comparing qualities of diamond sensors the figure of merit is the Charge Collection Distance (CCD), which is defined as the average distance an e/h-pair separates under the influence of an electric field [11]. In order to maximize the amount of collected charge and obtain the best possible signal, the CCD should be as high as possible. For a non-irradiated scCVD diamond full charge collection is expected, which means that the CCD is equal to the thickness of the diamond. For pCVD diamonds the CCD is expected to be lower than the thickness due to charge trapping.

The company II-VI Incorporated [9] has been producing laser windows based on pCVD diamonds for several years, and recently started to grow detector grade diamond material as well. In this time the quality of their pCVD diamonds has improved. They have delivered final finished parts (~ 100 parts of various sizes) to the particle physics experiments Compact Muon Solenoid (CMS) and A Toroidal LHC ApparatuS (ATLAS). The majority of their final finished diamond sensor parts now reach a CCD of 275–300 μm. In Fig. 1 the CCD of four preselected diamonds is shown as a function of bias voltage. All samples reach a CCD of above 300 μm at a bias voltage of 800 V, corresponding to an electric field of 1.5 V/μm.

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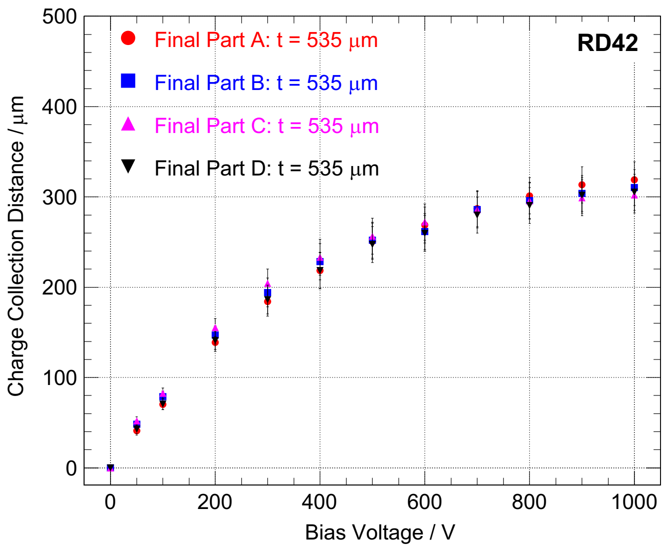

Fig. 1. The CCD as a function of bias voltage for four pCVD diamonds produced by II-VI Incorporated.

A second new company on the market is IIa Technologies [10]. They have delivered order of ten scCVD samples for evaluation, showing promising results.

RD42 is working with these companies to ensure that their diamonds have the necessary signal properties, uniformity and radiation tolerance. The appearance of additional manufacturers is encouraging. It has a positive effect on the quality of CVD diamonds and adds growth capacities.

2. Use of diamond detectors

In all experiments at the LHC there are detectors installed that use diamond as a sensor material. Several scCVD and pCVD diamond-based beam condition monitors for on-line background estimation and luminosity measurements are now in use in ATLAS [12,13], CMS [14,15] and LHCb [16].

The Pixel Luminosity Telescope (PLT) is designed to provide a bunch-by-bunch measurement of the luminosity for the CMS experiment. With the pixelated sensors particle tracking is possible. This allows us to distinguish collision products from beam background. During the LHC run in 2012 diamond pixel telescopes were employed in the pilot run of the PLT [15,17]. Four diamond telescopes, each telescope with three pixelated scCVD diamond detectors with an area of $4.5 \times 4.5\ \text{mm}^2$ and a pixel size of $150 \times 100\ \mu\text{m}^2$, were installed on the platform formerly housing a CASTOR detector [18] 14.5 m away from the collision point. In preparation for the final PLT installation, issues with these scCVD PLT diamonds (described in Section 3) created a situation where the timescale to complete the project was delayed. As a result the CMS collaboration decided to install a silicon based PLT and designed and added a full cooling system in order to meet the required installation deadline.

During the LHC shutdown in 2014, ATLAS installed the Diamond Beam Monitor DBM [19]. The purpose of the DBM is to provide a bunch-by-bunch luminosity and a bunch-by-bunch beam spot measurement. This is achieved by tracking individual particles using eight 3-plane pixel telescopes. Six of these telescopes use pCVD diamond sensors, each with a size of $18 \times 21\ \text{mm}^2$ and an active area of $3.4\ \text{cm}^2$. The DBM is included in the central data taking since the beginning of 2015. First results are expected in the near future.

3. Rate studies

The PLT pilot run [17] provided the first experience with scCVD diamond-based pixel sensors in the LHC-environment. A FLUKA [20,21] simulation estimated the total integrated fluence experienced by the PLT sensors during the 2012 LHC run to be 5×10^{13} neutral hadrons/cm^2 and 5×10^{13} charged hadrons/cm^2 [22].

An unexpected pulse height dependence on incident particle flux was observed already in the beginning of the run, after the diamond sensors received a relatively low fluence of 1×10^{13} hadrons/cm^2. When the particle flux was increased from $\sim$400 Hz/cm^2 to $\sim$16 MHz/cm^2, the pulse height was observed to decrease for these scCVD sensors [17]. This behavior has prompted a study in several high rate beam tests and first results are published [23].

Several diamonds were prepared for this study. The scCVD and pCVD diamonds were irradiated to a fluence of $(5.0 \pm 0.5) \times 10^{13}$ neutrons/cm^2. These sensors were compared with a non-irradiated scCVD sample and one of the scCVD diamonds irradiated in the PLT pilot run. All samples had a thickness of $\sim$500 μm. Two different sensor configurations as described later were tested in a pion beam with a momentum of 250 MeV/c provided by the High Intensity Proton Accelerator [24, beam line piM1] at Paul Scherrer Institut (PSI). The pion flux could be varied between 1 kHz/cm^2 and 10 MHz/cm^2.

In these beam test campaigns pad and pixel detectors were tested. The diamond pad sensors had a single $3.5 \times 3.5\ \text{mm}^2$ Cr/Au metalization on the front and backside plus an extra guard ring on one side. An ORTEC 142A preamplifier combined with an ORTEC 450 amplifier was used to amplify and shape the signals [25]. The waveforms were digitized with a DRS4 evaluation board [26] using a sampling rate of 700 MHz. The pixel detectors had a size of $4.5 \times 4.5\ \text{mm}^2$ and were produced with an electrode size of $75 \times 125\ \mu\text{m}^2$ and a pixel pitch of $100 \times 150\ \mu\text{m}^2$. The sensor was bump bonded to the CMS pixel Read Out Chip ROC PSI46v2 [27] with an internal threshold of 3000–3500 e. In total $\sim$1000 pixels were connected to the ROC. The collected charge was integrated on an internal capacitance and digitized with an ADC. With the different setups the impact of the internal threshold and effects due to the different electric field configurations were studied. While pad detectors have a uniform electric field within the bulk material, the electric field of pixel detectors is focused around the pixelated electrodes.

A beam telescope based on CMS pixel ROC PSI46v2 with silicon sensors was used to test these detectors. The ROC provided a fast trigger signal [27] if a hit was registered. The coincidence of the triggers from the two outermost planes was used for data acquisition decision. When running in the pad configuration the telescope was used to provide a scalable trigger with one silicon plane in front and one silicon plane in the back of the Device Under Test DUT. In the pixel configuration a total of six planes was used. The two outer planes were silicon reference detectors providing the trigger signal. The four inner detectors were diamond detectors. All silicon and diamond detectors, but the detector under study, were used for tracking. Pictures of both configurations are shown in Fig. 2.

PAD detectors. The shaped pad detector pulses have a peaking time of approximately 200 ns and return to the baseline in 500 ns. The pulse height of these signals was extracted from the waveform of the DRS4 board by summing the digitized waveform for 75 ns around the peak position. Since the trigger timing within the waveform was constant within a run the peak position was assumed to be fixed within a run. For each sample the flux scan started at the lowest flux of $\sim$22 kHz/cm^2 going up in flux. The pedestal was either measured in a separate pedestal run,

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