Diamond as a Particle Detector

D. Meier*
representing the *RD42 Collaboration*

Bristol University, CERN, CPP Marseille, Lawrence Livermore National Lab, LEPSI Strasbourg, Los Alamos National Lab, MPIK Heidelberg, Ohio State University, Universita di Pavia, Rutgers University, Sandia National Lab, University of Toronto, Institut für Hochenergiephysik Vienna

Abstract

This report surveys the detector properties of CVD-diamond samples and CVD-diamond strip detectors with respect to charge collection, spatial resolution and radiation damage. The collected charge on diamond samples and strip detectors to date is at best 4000 electrons. Diamond strip detectors with 50 μm readout pitch have been built and put into beam tests. Using a low noise readout with 2 μs shaping time, a resolution of 14 μm has been demonstrated. The diamond samples show no degration of charge collection after irradiation with electrons, photons and pions and small decrease after neutron irradiation.

1 Introduction

Silicon strip detectors are used at present with great success for high precision tracking of charged particles. However the radiation resistance of silicon puts limits to its application. In a high radiation environment problems occur with increasing leakage currents and decreasing charge collection efficiency.

The substrate material becomes p-doped and bias voltage has to be increased in order to deplete the bulk. Silicon strip detectors might be usable up to 10 MRad or 10^{14} n/cm^2. Detectors in future collider experiments at the Large Hadron Collider (LHC) will be exposed to extremly high radiation levels. At a distance of 10 cm from the beam axis, detectors are expected to receive a fluence of 1.6×10^{15} particles per cm^2 during 10 years of operation. The fluence decreases with distance from the beam axis and reaches at 20 cm distance 4.4×10^{14} per cm^2 and decade [1].

At present silicon pixel detectors are proposed in this region [2]. Another possibility is diamond, whose properties [Tab. 1] make it an ideal material for tracking detectors especially in such a high rate, high radiation environments of experiments at LHC [3]. Beside radiation hardness as reported in section 4, there are other advantages of diamond.

material		Si	diamond
proton number, Z	[.]	14	6
mass density	$[\text{g/cm}^3]$	2.33	3.5
lattice constant	[Å]	5.43	3.57
dielectric constant, ϵ	[As/V/m]	11.9	5.7
band gap	[eV]	1.12	5.47
resistivity, ρ	[MΩcm]	0.23	$10^7..10^9$
breakdown field	[V/μm]	30	1000
electron mobility	$[\mu\text{m}^2/\text{V/ps}]$	0.135	0.18
hole mobility	$[\mu\text{m}^2/\text{V/ps}]$	0.048	0.12
saturation velocity	[μm/ps]	0.1	0.27
thermal expansion coeff.	$[10^{-6}/\text{K}]$	2.5	0.8
thermal conductivity, λ	[W/cm/K]	1.4	10..20
energy $\mathcal{E}_{\text{pair}}$ to create eh-pair	[eV]	3.6	13
radiation length, X_0	[cm]	9.4	12.03
specific ionization loss $\mathcal{E}_{\text{loss}}$	[MeV/mm]	0.321	0.469
ave. no. of eh-pairs/mip	[e/0.1mm] [e/0.1%X_0]	8900 8400	3600 4500

Table 1: Properties of silicon and CVD-diamond at 293°K.

* *CERN, CH-1211, Geneva 23, Switzerland*

Its atomic structure results in very few free charge carriers and hence very low leakage current in presence of an external electric field. Lower leakage current decreases parallel noise in the readout electronics. Diamond has half the dielectric constant of silicon, which reduces the contribution to serial noise. The high carrier mobility allows collection of charges within LHC repetition cycle. Moreover due to the low proton number multiple scattering and photon conversion is low, which is important for particle tracking application.

2 Detector Principle and Charge Collection

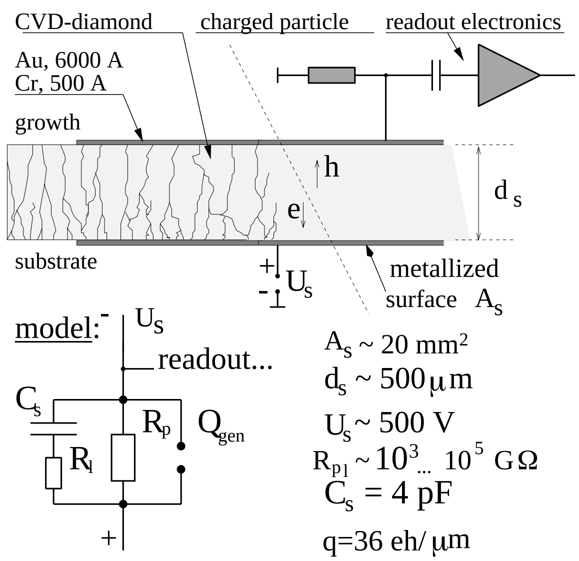

Figure 1: Principle of a diamond detector

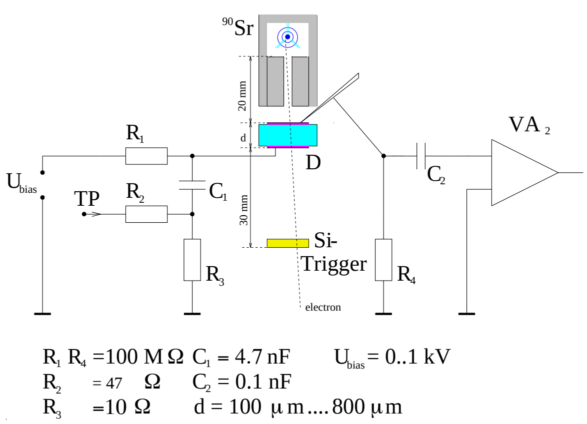

Figure 2: Setup for charge collection measurement in a diamond detector.

Polycrystalline CVD-diamond in detector quality can be produced in 4” wafers with thickness of up to 1 mm. Small test samples of 1 cm^2 were cut out of a wafer and metallized on both sides with ohmic contacts. Between both contacts a voltage U_s can be applied, which generates an electric field inside the bulk [Fig.1]. A charged particle traversing diamond looses energy $\mathcal{E}_{\mathrm{loss}}$ per path length and generates electron hole pairs. Taking the energy $\mathcal{E}_{\mathrm{pair}}$, which is necessary to create an *eh*-pair in diamond, a minimum ionizing particle *mip* generates $q = \mathcal{E}_{\mathrm{loss}}/\mathcal{E}_{\mathrm{pair}} = 36\ eh/\mu\mathrm{m}$, which yields an average number Q_{gen} of charge pairs in diamond of thickness d_s:

$$Q_{\mathrm{gen}} = q \cdot d_s \tag{1}$$

Charge carriers seperate in the electric field and induce charges in the contacts. A charge integrating circuit followed by a shaper gives a signal, whose amplitude is proportional to the number of collected charges Q_{col}, which is measured:

$$Q_{\mathrm{col}} = q \cdot d_c \tag{2}$$

The distance d_c is known as the charge collection distance. It is interpreted as the mean distance charge carriers with mean lifetime τ and mobility μ travel before being trapped. It is proportional to the applied electric field E_s:

$$d_c = \mu\tau E_s \tag{3}$$

The charge collection distance on diamond samples can be measured with a setup shown in Fig.2. Usually the sample is connected to a high voltage on its growth side. But turning the diamond and connecting high voltage to the substrate side is possible, too. A collimated, 37 MBq, ^{90}Sr β-source illuminates the sample. The substrate side of the diamond sample is AC coupled to one channel of a VA2 chip [4], a successor of the VIKING VLSI-chip [5]. One VA2 channel contains a charge integrating preamplifier and shaper. The shaping time is adjusted to 2 μs. The VA2 itself has an equivalent noise charge of 68 e+11 e/pF [6]. The setup without sample shows a system noise N_{system}=213 e. Signal readout is triggered by a silicon diode which is in line with the diamond and the ^{90}Sr source. In order to characterize its quality as particle detector the charge collection distance on samples is measured as a function of the applied voltage [Fig. 3]. The charge collection distance increases with the electric field and begins to plateau at a higher field.

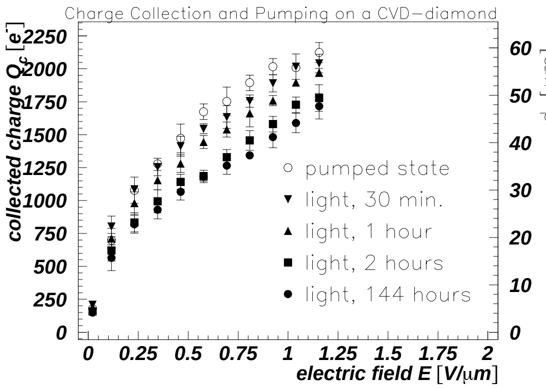

Figure 3: Charge collection distance d_c in CVD-diamond in different pumping states as a function of the applied electric field.

Moreover Fig. 3 shows, that the charge collection distance depends on the time of exposure to fluorescent light. On samples which were exposed to ^{90}Sr a high charge collection distance is observed. After illumination with fluorescent light the charge collection distance is lower. In a working-hypothesis exposure to ^{90}Sr passivates traps (pumping) and charge carriers can drift further. Exposure to fluorescent light removes the passivation (depumping) and charge carriers are trapped after a shorter distance. Starting from a pumped state the charge collection distance decreases during exposure to fluorescent light. On the shown sample the charge collection distance of the depumped state at 1 V/μm is smaller by a factor of 1.4 then the pumped value.

The distribution of collected charges in a diamond sample and a silicon diode were measured [Fig. 4]. The silicon diode has a thickness of 345 μm and pad size of 16 mm^2, the diamond has a thickness of 710 μm and metallization of 20 mm^2. The energy loss of a *mip* in each detector can be described as Landau distributed. Therefore the spectrum of collected charges is described as a convolution of a Landau and a Gaussian distribution, which is given as a fit to the measured data.

The most probable number of *eh*-pairs produced in the diode is 25900 e taking the standard value of 75 *eh*-pairs per μm silicon. The diode is fully depleted at 50 V. The noise measured at 50 V is 299 e, which gives a a most probable signal to noise ratio of 87-to-1. In comparison the diamond shows a most probable signal of 2500 e. The noise at 500 V is 247 e which gives a most probable signal to noise ratio of 10-to-1. The mean value of this diamond sample is at 3114 e, which corresponds to a charge collection distance of 87 μm. Moreover the measurement shows that the device noise on the diamond sample is smaller than in silicon. The device noise is given as the difference between the quadratic overall noise and the quadratic system noise. The device noise in diamond is 126 e, whereas the device noise in the silicon diode is 210 e. The higher noise in silicon is due to leakage current of 0.5 nA and a capacitance of 6 pF at 50 V, whereas the diamond sample shows a very small leakage current of about 100 pA and a capacitance of

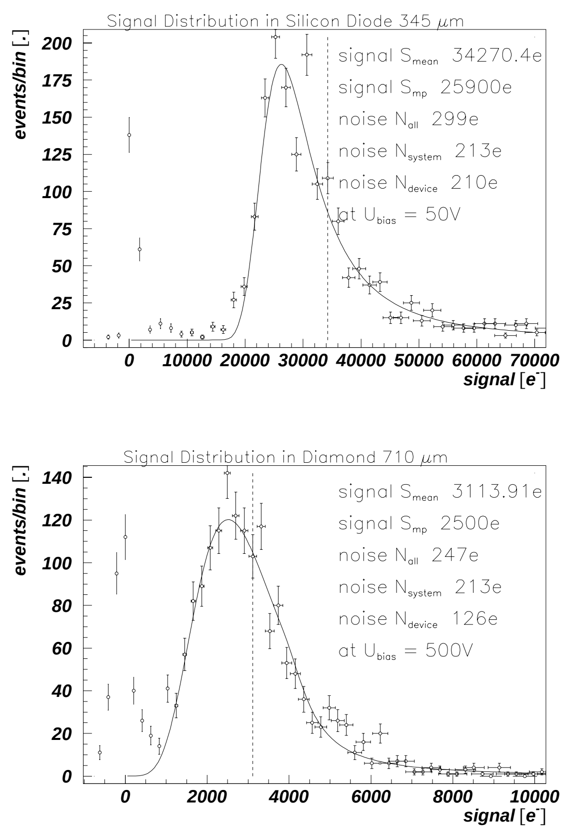

Figure 4: Signal distribution in a silicon diode (size 16 mm^2, $S_{\rm mp}/N_{\rm all}$=87) and diamond sample (size 20 mm^2, $S_{\rm mp}/N_{\rm all}$=10).

3 pF at 500 V and room temperature. The theoretically expected device noise can be calculated [5]. For the diamond the calculated device noise is 100 e and for the silicon diode 183 e.

3 Diamond Tracker

The first diamond tracker was tested in the fall of 1993 at CERN [7]. It had 100 μm readout pitch and a charge collection distance of 50 μm. The resulting detector had an average signal approaching 1400 e, a signal-to-noise of 6-to-1 and a position resolution of 25 μm.

A diamond tracker [Fig. 5] with 50 μm readout pitch was tested in a 100 GeV pion beam in 1995. 128 metal strips were DC coupled to a VA2 chip in order to measure charge collection and spatial resolution. The diamond strip detector was positioned between eight planes of silicon strip detectors [Fig. 6]. The silicon detectors predict particle trajectories with 1 μm precision.

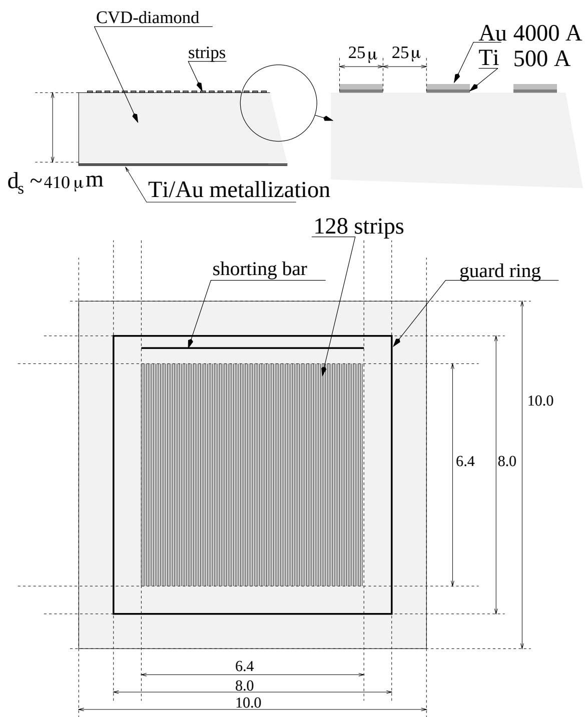

Figure 5: Cross section and top view of the latest diamond strip detector.

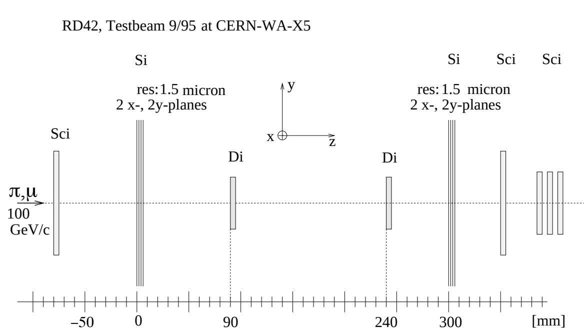

Figure 6: Sideview of the setup for diamond tracker tests, with scintillators Sci, silicon telescope Si and diamond tracker Di.

The pulse height distribution on all strips in the diamond tracker was measured. The measurement used only tracks with extrapolation errors smaller than 10 μm. Strips with noise above 200 e ENC noise were excluded. The pulse height includes the signal from two adjacent strips nearest to the predicted intersection in the diamond tracker. Fig. 7 shows the distribution of 140×10^3 beam events after 47 h pumping with a ^{90}Sr-source. The most probable collected charge is at 2300 $e \pm 10\%$ and the mean number of collected charge at 3600 $e\pm10\%$. The noise is about 85 $e \pm 10\%$ per channel and strip, which gives a most probable signal-to-noise ration for this tracker of about 27-to-1.

The spatial resolution was measured for the same detector with the same set of data [Fig. 8]. The difference between the predicted track position $x_{\rm track}$ and the measured hit position $x_{\rm hit}$ was calculated for each event. The hit position is given by a center of gravity method using the pulse heights $\rm PH_l$ and $\rm PH_r$ in two adjacent strips. The left strip defines the strip position $x_{\rm l}$. The hit position $x_{\rm hit}$ is then given by:

$$x_{\rm hit} = x_{\rm l} + \frac{\rm PH_l}{\rm PH_l + PH_r} \qquad (4)$$

and spatial resolution σ by

$$\sigma = \sqrt{{\rm VAR}\left\{x_{\rm hit} - x_{\rm track}\right\}}\ . \qquad (5)$$

The distribution has nearly Gaussian shape and its standard deviation gives the spatial resolution of about 14 μm.

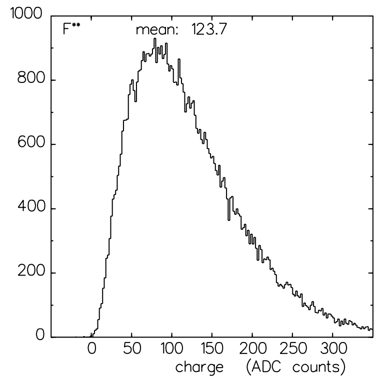

Figure 7: Pulse height distribution in a 'pumped' diamond Strip Detector. Calibration: 28 e/ADC$\pm$10% count.

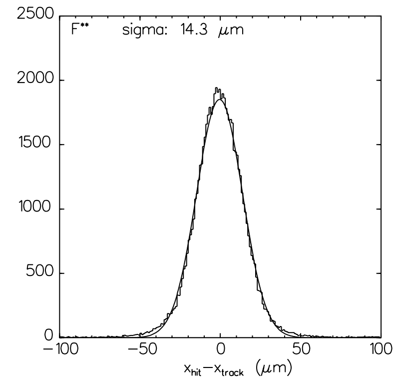

Figure 8: Distribution of track hit residuals in the pumped diamond strip detector.

4 Diamond Irradiation Studies

The charge collection before and after irradiation with photons, electrons, pions and neutrons has been studied.

Photon irradiation from a ^{60}Co γ-source was done with 1.2 MeV photons up to an absorbed dose of 100 kGy [Fig. 9]. The diamond was at room temperature and biased at 100 V. The charge collection distance is related to the value before irradiation. At low doses the charge collection increases which can be explained by passivation of traps. At higher doses charge collection saturates and is independent of dose. The diamond samples show no decrease of charge collection up to 100 kGy absorbed photon dose.

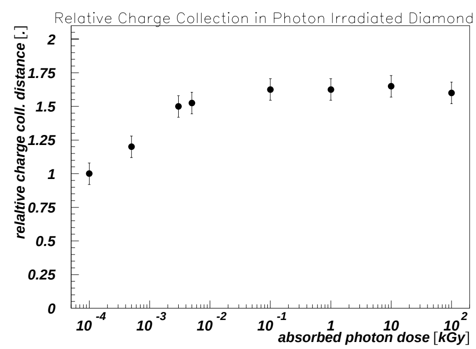

Figure 9: Relative charge collection in CVD-diamond as a function of absorbed dose from 1.2 MeV ^{60}Co-Source.

Electron irradiation at a Van de Graaf 2.2 MeV electron accelerator up to 1 MGy was carried out under the same conditions as with photons. Like in photon irradiation the signal increases with dose and traps passivate [Fig. 10]. At higher doses up to 1 MGy the signal saturates and is independent of dose.

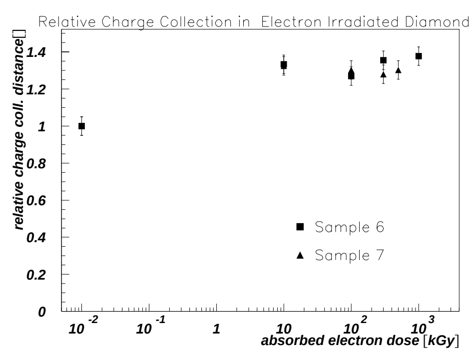

Figure 10: Relative charge collection in CVD-diamond as a function of absorbed dose from 2.2 MeV electrons.

Pions are the dominant damage source for detectors in LHC experiments. Therefore CVD diamond samples were irradiated with up to 8×10^{13} pions/cm^2 with an energy of 300 MeV [8]. The samples were at room temperature and biased at 100 V. Charge collection increased during characterization with ^{90}Sr electrons to its pumped value [Fig. 11]. After irradiation with 8×10^{13} π/cm^2 the charge collection distance was higher than before irradiation and no degration in charge collection has been observed.

A **neutron irradiation** was done on several diamond samples. The energy spectrum of the neutrons had two maxima, one below 10 keV and one at 1 MeV. The charge collection distance as a function of the applied field of one sample before and after irradiation is shown in Fig. 12. The sample received a measured fluence of $(3.17\pm 0.58)\times 10^{14}$ n/cm^2 with a mean energy of 1 MeV. The collection distance of the pumped state after irradiation decreases about 10%, whereas the depumped state on this sample decreases by about 20%.

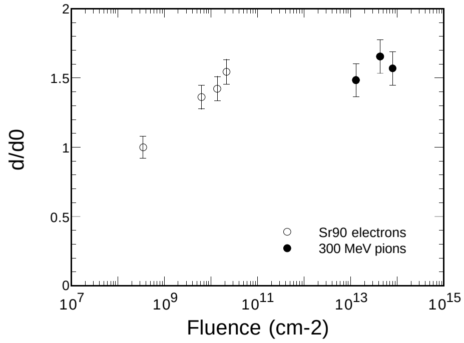

Figure 11: Ratio d/d_0 of charge collection in CVD-diamond after/before pion irradiation as a function of the pion fluence.

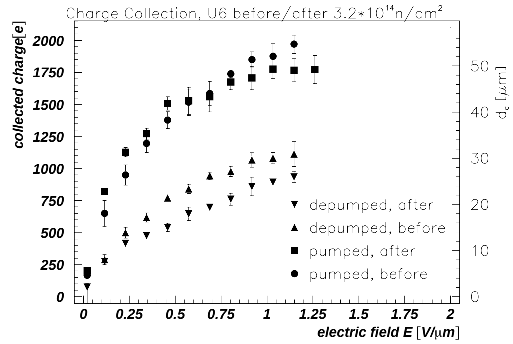

Figure 12: Charge collection in CVD-diamond before and after neutron irradiation of 3.2×10^{14} n/cm^2.

5 Summary and Future Directions

At present CVD-diamond samples with charge collection distance up to 110 μm equivalent to 4000 e in the pumped state are available. A silicon diode shows a most probable signal-to-noise which is about factor 9 higher compared to a diamond sample of similar size. The device noise in diamond is nearly half the noise of silicon.

In a pumped diamond tracker with 50 μm readout pitch equiped with charge integrator and shaper of 2 μs a most probable signal-to-noise of about 27-to-1 and spatial resolution of 14 μm is observed. Comparable silicon detectors with same readout electronics have signal-to-noise of $\approx$ 100-to-1.

It has been demonstrated that CVD-diamond samples are radiation hard to photons and electrons up to 100 kGy or 1 MGy, respectively. Moreover CVD-diamond samples show no degration after irradiation with pions up to 8×10^{13} π/cm^2. After neutron irradition of CVD-diamond samples up to 3.2×10^{14} n/cm^2 a decrease of 10% to 20% depending on the pumping state is observed.

Work on neutron, pion and also proton irradiation will be continued with better quality samples and higher fluences. Within the year it should be possible to obtain high quality CVD-diamonds with collection distances in excess of 200 μm. At this level, diamond based detectors would be suitable for LHC experiments. Moreover other sensor configurations like diamond pixel detectors are being built.

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