Recent Results from CVD-Diamond Heavy-Ion Detectors

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Abstract

Latest results from radiation hardness measurements as well as single-particle pulse shape parameters, pulse-height distributions and time spectra are presented. An intrinsic time resolution of 29 ps is achieved with ^{52}Cr ions of 650 MeV/amu and of 53 ps with ^{12}C ions of 1.5 GeV/amu, respectively. The resolution is by 20% worse when increasing the beam intensity from 10^6 ions/s to 10^8 ions/s.
Performing ^{58}Ni fragmentation, collected charge distributions are measured in the range $15 < Z < 28$. Whereas the S/N ratio improves about a factor of 2 the width of all spectra obtained is 70%. The same behaviour is found in ^{241}Am-α-distributions increasing the electric field applied to the detector. In order to visualize and to quantify the influence of the electric field as well as of the total particle fluence to the charge-collection efficiency micro-beam measurements are performed with ^{12}C ions of 5.9 MeV/amu stopped in the diamond bulk. Pulse-height spectra and charge-collection maps under different conditions are discussed.

1. Introduction

The radiation hardness of CVD diamond is the most important material property initiating the research and development of diamond detectors for the tracking of minimum ionizing particles (mip) in the LHC experiments ATLAS and CMS [1] as well as for a variety of heavy ion applications with high luminosity beams [2]. In the case of mip no increase in leakage current and unchanged collected charge is obtained for all kind of particles up to a fluence of about 10^{15} particles/cm^2 [1]. Above this fluence the behaviour changes slightly showing the best hardness for protons with 5×10^{15} p/cm^2 followed by the pions with 1.5×10^{15} π/cm^2 and the neutrons with 0.9×10^{15} n/cm^2. A decrease of the charge-collection efficiency (CCE) of about 20% accompanied by an improvement of the resolution of the detectors is observed after such irradiations. Particularly, the spatial resolution of the trackers tested is improved significantly by 18% [1].

However, the heavy ion fluence which starts damaging CVD diamond is still unknown. Lower limits are defined using both, ^{12}C ions stopped in the bulk material and traversing ^{238}U ions of 1 GeV/amu depositing only 5‰ of their kinetic energy ($\Delta E \approx 1$ GeV) in the detectors. Unchanged charge response and decreasing leakage current was still observed at a fluence of 5×10^{10} ^{238}U ions/cm^2 [2]. The micro beam (MB) ^{12}C spectra (s. section 5) confirm the mip results [1] up to the fluence of 10^{10} ^{12}C ions/cm^2. The radiation hardness tests are continued. Nevertheless, even these values are by three orders of magnitudes higher than for silicon, GaAs or plastic-scintillator detectors.

The incomplete charge collection of CVD-diamond detectors [1][2][3] is the special subject of this paper. It is attempted to find an explanation for the remarkable similar shape of pulse-height spectra measured for mip particles as well as for the heavy, highly-ionizing ions [1][2][3]. Systematic measurements of the charge distributions obtained with penetrating beams are related to MB data from ions stopped in the diamond bulk. MB measurements with proton beams are used for many years [4] to investigate the charge-collection efficiency of CVD diamond. The advantage of heavy-ion micro beams is the controlled adjustment of the ionisation density and the depth of the irradiated layer. The influence of external parameters (the impinging particle, the electric field applied) and internal parameters (the electron- and hole trap distributions, the size of the single crystals) to the charge-collection efficiency are visualized with an accuracy of 1 µm.

2. Characterisation Data and Beam-Test Results

Unpolished samples of different thickness from 80 µm up to 1200 µm are used. The detectors have either evaporated chromium-gold electrodes or titanium-gold electrodes produced by thick-film photolithography and they are glued on ceramic boards mounted in rf-sealed aluminum boxes. Each detector channel is connected to a DBA [5] (Diamond Broadband Amplifier, R=50 Ω) via a 50 Ω micro-strip line. No cooling is required.

In Figure 1 the spectra measured for the characterisation of heavy-ion diamond detectors are introduced. Figure 1a) shows ^{241}Am-α-signals obtained from a detector with a thickness of 100 µm and a strip capacitance of C_D = 8.6 pF at an electric field E_D = -7 V/µm. The signals are recorded with a high resolution broadband DSO (Digital Sampling Oscilloscope, 1.5 GHz, 100 ps/sample).

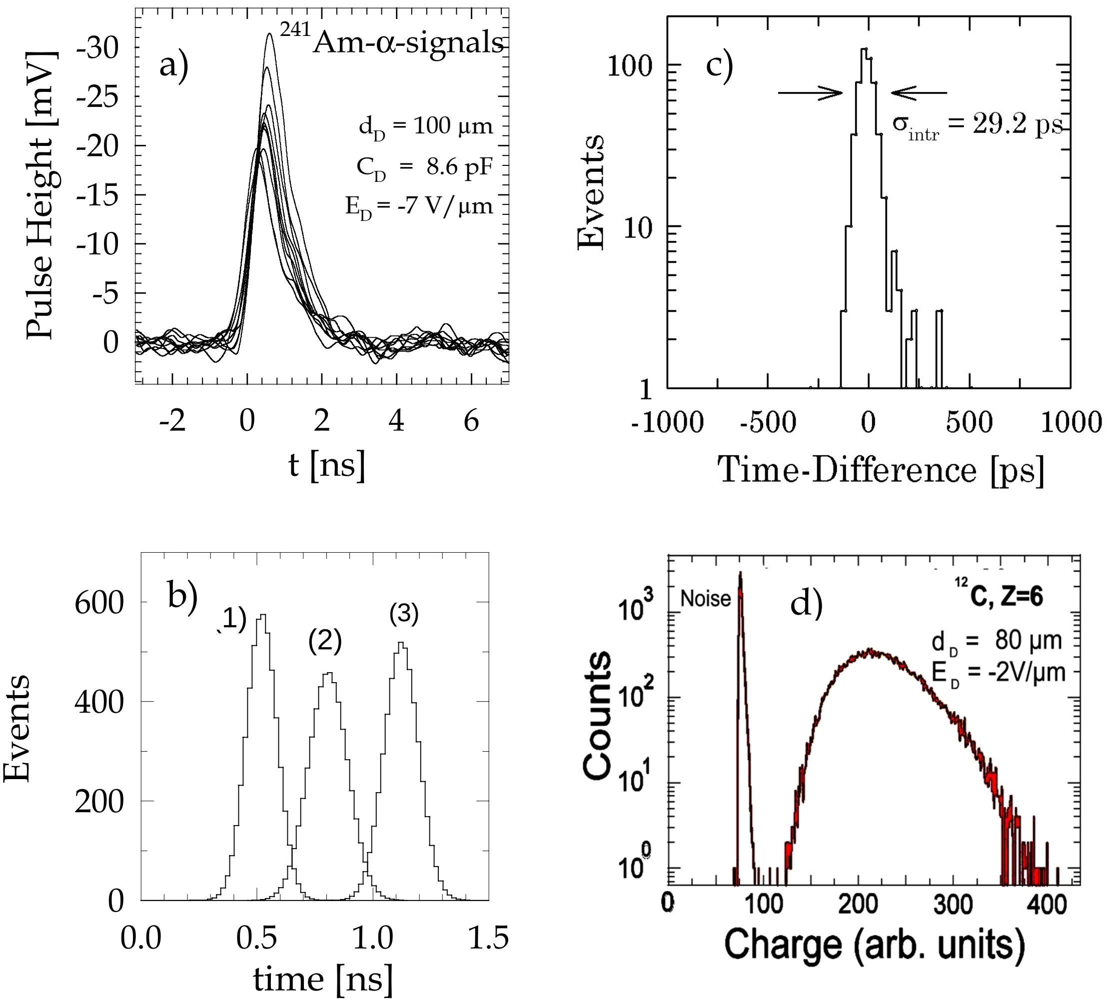

Figure 1: Characterisation Data

a) α-signals, b) single-pulse shape-parameter distributions,
c) time resolution, d) pulse-height resolution and S/N.

The quality of a heavy-ion diamond detector is characterized by the widths of the shape-parameter distributions of the single-particle pulses [2]. In Figure 1b) are analyzed the rise (1) - and the 1/e-decay time (2) distribution as well as the FWHM distribution (3) of about 1000 α-signals shown in 1a). The mean values of the distributions are dominated by the bandwidth of the measurement system. The systematic error including noise is 390 ± 100 ps. Due to the small rise-time variation diamond devices show an excellent time resolution. Figure 1c) shows a time spectrum measured in a beam test with ^{52}Cr ions of 650 MeV/amu. An identical detector was used in coincidence. An intrinsic time resolution $\sigma_{\text{intr}} = \sigma_{\text{measured}}/\sqrt{2} = 29.2$ ps is achieved.

The width of the 1/e-decay time distribution is the parameter best characterizing the pulse-height resolution of the detector. This value mirrors the spread of level lifetimes existing in the bulk region where the excess charge drifts to the electrodes. The FWHM of the signals (Figure 1b) (3)) defines the count rate capability of the device. It is a convolution of the lifetimes and of the RC_D constant of the electronics. Figure 1d) shows the charge distribution of ^{12}C ions of 11.5 MeV/amu measured with a sample of similar quality and of a thickness of 80 μm. The clear separation from the electronic noise allows high precision single particle counting of high rates. Nevertheless, the typical resolution of 70% obtained (see sections 3,4) prevents the use of todays CVD-diamond heavy-ion detectors for particle identification.

3. Collected Charge Distributions

The charge Q_C collected from an impinging charged particle in a CVD diamond detector is given by relation (1) [3]

$$Q_C = Q_G \cdot CCE = Q_G \cdot (\mu\tau) \cdot \frac{E_D}{d_D} \tag{1}$$

with Q_G the charge produced by the particle, CCE the charge-collection efficiency of the detector, $(\mu\tau)$ the mobility-weighted carrier lifetime, E_D the electric field applied to the detector and d_D the detector thickness.

Due to inhomogeneously distributed charge traps within the polycrystalline material an incomplete charge collection is usually observed [1][2][3]. A huge community [6] works on the research of the nature and of the properties of the various electron and hole traps in natural as well as in CVD diamond.

3.1 The Influence of the Ionisation Density and the Electric Field

Since traps are filled by the charge produced by the particle an improvement of the CCE and of the pulse-height resolution is expected for higher nuclear charge Z of the particle. In order to establish this early indication [7] ^{58}Ni fragmentation is measured at the FRS using a diamond detector with a thickness of 107 μm at an electric field E_D=-2.8 V/μm. Individual fragment distributions from the diamond detector are obtained by selecting events with the high-resolution MUSIC chamber used in coincidence [8]. The spectra are calibrated with a silicon detector and the results are shown in Figure 2. The MEAN- respectively the MP- (Most Probable) values of the collected charge distributions are plotted over the Z^2 of the corresponding fragment on the left picture. The solid line shows the theoretical values multiplied by 0.1, which is the CCE of this sample.

Despite the huge amount of charge loss the MEAN values increase with the expected slope, which is a not trivial fact in this case. The MP values show a deviation of –15%.

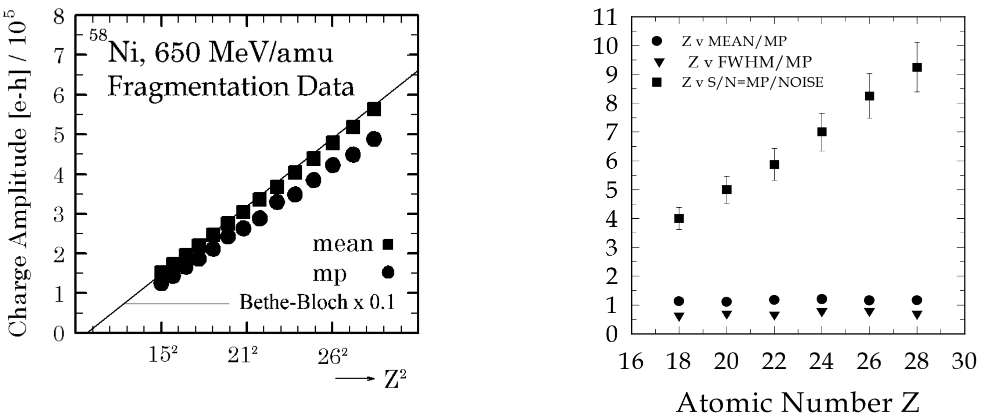

Figure 2: ^{58}Ni fragmentation data obtained with a 107 µm thick CVD-diamond detector at an electric field E_D= -2.8 V/µm,
the collected charge in the range 15 < Z < 28 (left),
the pulse-height resolution FWHM/MP, the homogeneity ratio MEAN/MP and the S/N ratio in the range 18 < Z <28 (right).

On the right picture the MEAN/MP, the S/N (Signal to Noise) and the FWHM/MP of the distributions analyzed are shown. Although the S/N ratio increases by a factor of 2.3 the pulse-height resolution remains within the error bars constant at 70%. Concluding, no significant dependence of the detector characteristics on the ionisation density is found within the range 18 < Z < 28 analyzed.

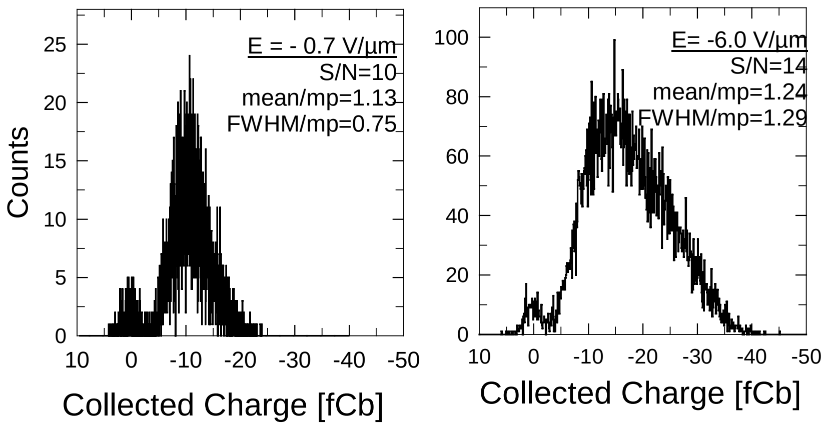

Figure 3: ^{241}Am-α-response of a 100 µm thick diamond detector at E_D = - 0.7 V/µm (left) and at E_D = - 6 V/µm (right).

A similar behaviour is observed during plateau measurements with ^{241}Am-α-particles. Figure 3 shows the α-distributions obtained from the detector of 100 μm thickness introduced in section 2. Spectra at two different electric fields are presented. The S/N ratio at E_D = - 6 V/μm is 50% higher than at E_D = - 0.7 V/μm. However, the resolution is worse.

3.2 The Influence of the Diamond Texture

Due to the columnar polycrystalline growth of CVD diamond the charge carrier lifetime as well as the electric field inside the diamond bulk depend on local parameters as there are the spatial distribution of the electron- and hole traps and the size of the single crystals. Using minimum ionizing particles and by a stepwise reduction of the diamond thickness a linear increase of the CCE from the substrate side to the growth side is measured. According to this "linear model" [3] the growth side efficiency is up to three times higher than the average. Hence, the charge response of detectors made of 'as grown' CVD-diamond to a certain traversing particle is not uniform.

In Figure 4 the ^{58}Ni fragmentation spectrum measured with a single-crystal silicon detector (right) is compared to that obtained from a polycrystalline CVD-diamond detector (left) in the same experiment [8]. The yields are arbitrary. Whereas the pulse-height resolution of the single-crystal silicon detector amounts to 2.4% no individual fragments are visible in the case of the diamond detector.

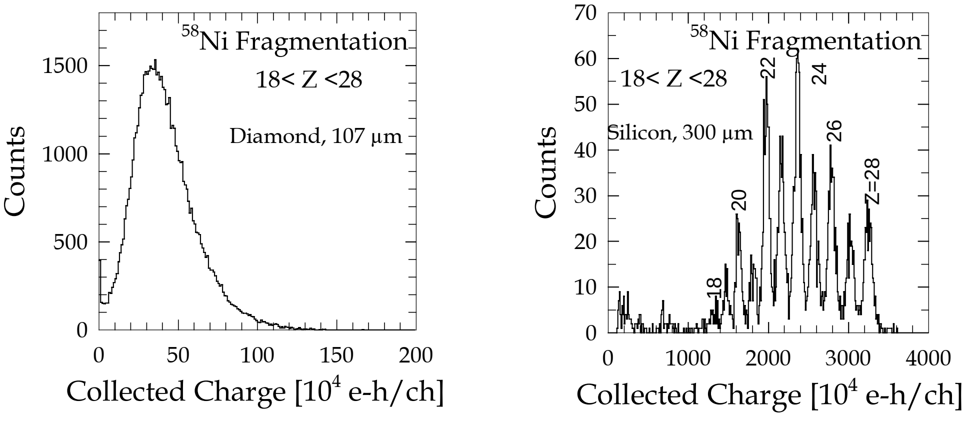

Figure 4: ^{58}Ni fragmentation spectra measured with a polycrystalline diamond detector (left) and with a single-crystal silicon detector (right).

4. Micro-Beam Measurements

For a deeper understanding of these results diamond samples are irradiated from the growth side and from a cleaved cross section with the heavy-ion microbeam of the UNILAC. The diamond amplitudes are recorded with the corresponding x- and y- coordinates event by event. Charge-collection maps with an accuracy of 1 µm are obtained. The surface topology of the irradiated regions is mapped by the measurement of the secondary electrons emitted from the hitted points.

The range of the used ^{12}C ions of 5.9 MeV/amu in diamond is 57 µm. Figure 5 shows data from a 120 µm thick detector irradiated from the side. Charge-collection maps of high efficiency regions are shown under different electric field conditions. The columnar growth of the single crystals becomes visible.

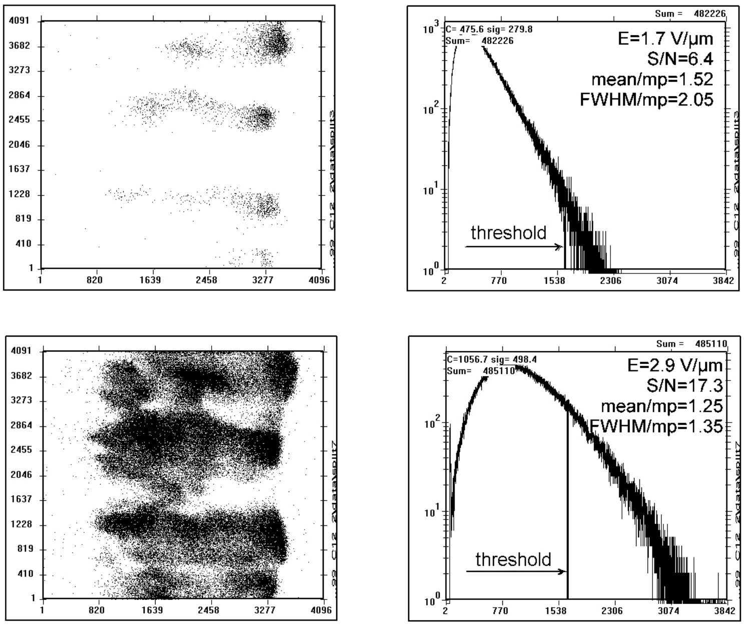

Figure 5: Charge-collection maps along the crystals growth (left) and the corresponding pulse-height distributions (right) at different electric fields. Same number of events is processed.

The corresponding collected charge distributions are plotted on the right. The expected improvement of the CCE with higher electric field (see relation (1)) is

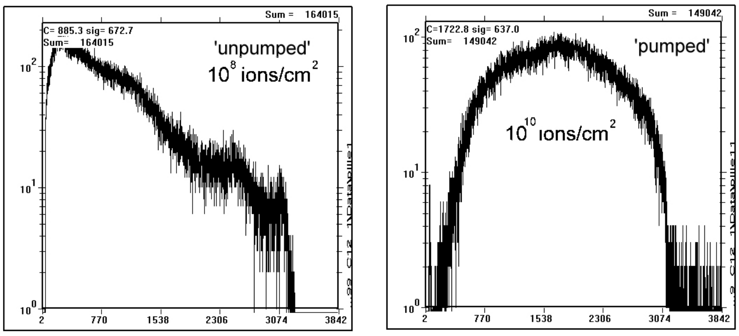

Figure 6: The 'pumping' effect. The 'unpumped' state is at a total fluence of 10^8 ions/cm^2 and the 'pumped' state at a fluence of 10^{10} ions/cm^2.

overlayed by the fact that the total fluence on the sample in this measurement was by 30% higher than at lower bias. The amount of events with a CCE above the indicated threshold (vertical lines) is increased by a factor of 50. The resolution of the single crystal regions selected is improved.

This hitherto in heavy ion measurements unobserved 'pumping' effect [1][3], is illustrated impressively in Figure 6. Collected-charge distributions from a scanned area of 300 x 320 μm^2 are shown, obtained from a diamond sample with a thickness of 390 μm after an irradiation with 10^8 ions/cm^2 (left) and with 10^{10} ions/cm^2 (right), respectively.

6. Conclusions and Outlook

A time resolution below 50 ps and a single-particle count-rate capability of 10^8 ions/s are universal properties of CVD diamond heavy-ion detectors [2][9]. However, an improved pulse-height resolution allowing a rough particle identification is still desirable. First micro-beam results considered in conjunction with fragmentation data show a much higher influence of the materials texture to the detector performance than of the charge density in the particles track.

Acknowledgments

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