Characterisation of Diamond Detectors

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In '97 the investigations of diamond detectors have been continued with the definition of the measurement procedures and the electronics suitable for the quality tests of CVD-diamond heavy-ion detectors.

Charge trapping due to chemical impurities and grain boundaries in the diamond bulk results in the incomplete charge collection observed in diamond detectors [1][2][3]. Different numbers of donator and acceptor traps in the polycrystalline material can occupy energy levels inside the band gap and to polarize the previous neutral material.

The average mean free path of the charge carriers in the bulk d_{cd} is used to characterize the quality of the CVD-diamond. The relation between the mobility weighted carrier lifetime and the charge collection distance d_{cd} is given by

$$d_{cd} = \mu \cdot E_D \cdot \tau \quad [1]$$

with $\mu = \mu_e + \mu_h$, the mobility of electrons and holes
E_D the applied electric field and
τ the carrier lifetime .

The characterisation of diamond samples is the measurement of the material properties described above. The charge collection distance can be evaluated from the mean value of the pulse-height distributions measured [1][2] and the carrier lifetime from the decay time of single pulses produced by charged particles. Information on possible polarisation of the bulk can be obtained from the I-U curve behaviour and pulse-height measurements with positive and negative bias.

To characterize the diamond samples the following steps ought to be performed:

1. Metallisation with cromium-gold electrodes
2. I-U characteristic measurements
3. Plateau measurements
4. Signal-shape analysis with ± U_{bias}
5. Pulse-height distribution measurements with ± U_{bias}
6. Counting-rate capability

1. Metallisation

Structured electrodes metallized with pixels of several millimeter pitch are advantageous because they allow investigations of the homogeneity of the electrical properties of the material. Cromium-gold electrodes can easily be removed after characterisation from the sample if other electrode shapes are needed for the final application.

2. I-U Characteristic Measurements

The measurement of the voltage-dependend dark current contains information about the chemical pureness of the material, the distribution of recombination centers and about the quality of the metallic contacts. Good CVD-diamond detectors have a symmetric I-U behaviour and can therefore be positively or negatively biased. Figure 1 shows a characteristic curve of a diamond detector measured with a programmable Keithley 6517 electrometer. The measurements have been performed in light-tight boxes flooded with nitrogen.

Due to the large band gap of 5.5 eV the dark current of CVD-diamond detectors at room temperature is in the order of picoamps and is caused mainly by excited atoms of chemical impurities. Deviations from a symmetric I-U curve indicate inhomogeneously distributed donator and acceptor traps in the bulk or blocking contacts [1]. Ohmic contacts are identified as a linear I-U behaviour above the break down field

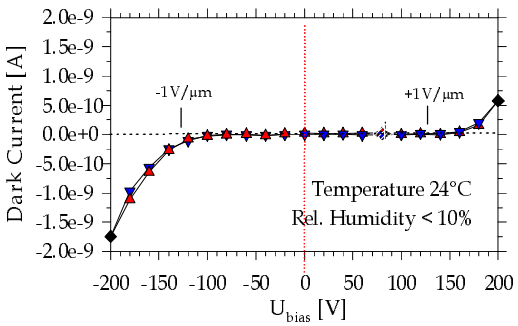

Fig. 1: I-U characteristic of a 120 µm thick diamond detector of an area of 4cm² measured with a Keithley 6517 electrometer

on both ends of a completely symmetric characteristic curve. Most of the samples tested show break-down fields from 2 V/µm up to 6 V/µm. However, a wide bias range implies on one hand higher chemical purity but not necessarily a good charge collection efficiency of the sample. Consequently, this preliminary observation indicates that the incomplete charge collection in diamond detectors must be on account of the polycrystalline CVD-diamond structure.

3. Plateau Measurements

The collected charge is expected to stay constant at saturated charge carriers velocities over a certain electric field [2]. The rise of the collected charge measured by increasing the bias relates to the ionisation density in the detector. Depending on the nuclear charge of the traversing particle an effective field strenght of at least ± 1 V/µm is required to achieve a constant amplitude [2]. Figure 2 shows that an electric field of -1.5 V/µm is required for Z=10.

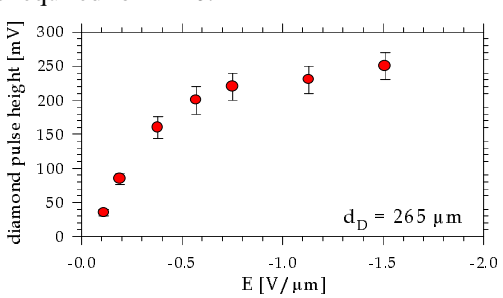

Fig. 2: Electric field dependence of the collected charge measured with ^{20}Ne projectiles of 300 MeV/amu kinetic energy

4. Signal Shape Analysis

Lead-ion signals can be measured without any amplification. Figure 3 shows pulses produced from single ^{208}Pb ions at 1 GeV/amu in a 265 µm thick diamond detector. The signals are the pure diamond response to the pass-through of the heavy ions and offer therefore the unique opportunity to extract direct information on the charge carrier mobility and the charge carrier lifetime in the diamond bulk. Whereas the rise time is defined by the bandwidth of the 1.0 GHz oscilloscope used, the

decay time is a convolution of both the mobility weighted carrier life time and the RC_D constant, given by the detector capacitance C_D and the 50 Ω impedance of the oscilloscope.

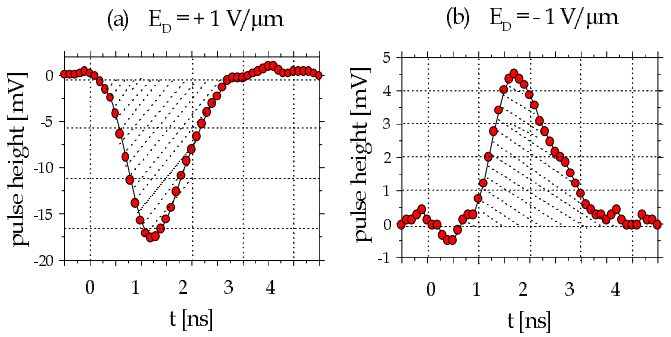

Fig. 3: Diamond detector signal from ^{208}Pb ions at 300 MeV/u

Preliminary data from different samples tested show lifetimes of several hundered picoseconds. The width of the decay time distribution of 1000 single shots analyzed per sample was in the order of ± 250 ps. The highest quality material available today has a collection distance of 250 µm and a lifetime of the charge carriers of 1 ns at an electric field of E_D = 1 V/µm [2].

5. Pulse-Height Distributions

The signals shown in Figure 3 correspond to an energy loss of 1.6 GeV in the 265 µm diamond detector. They are recorded with a digital storage sampling oscilloscope and sampled every 100 ps. The charge Q collected from thousend single ^{208}Pb ions is evaluated from the area of every single shot and is plotted in Figure 4. To compare our data with the results for minimum

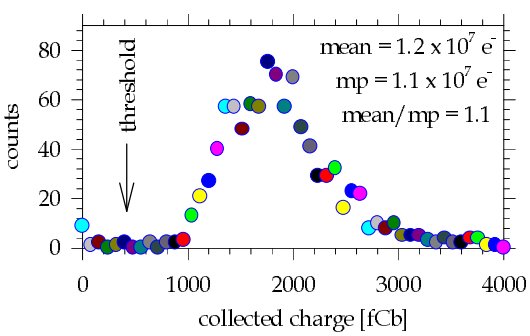

Fig. 4: Pulse-height distribution of ^{208}Pb ions at 1 GeV/amu measured with a 265 µm thick diamond without amplification

ionizing particles the same electric field of ±1V/µm was applied to the detector. The electric field needed to achieve saturated charge-carrier velocities for Z = 82 is by far not sufficient. Consequently, the collected charge is lower than expected.

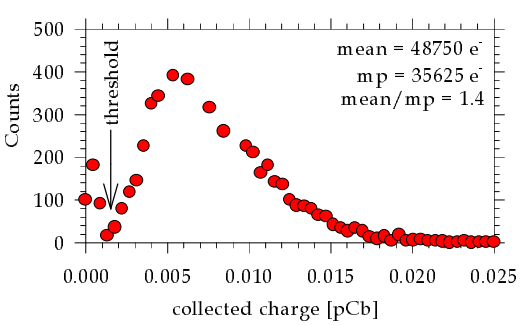

Fig. 5: ^{243}Am α spectrum measured with a 370 µm thick diamond detector at an applied electric field of E_D = -1.4 V/µm

The excellent time resolution of 38 ps measured with diamond detectors and uranium ions last year [3] have shown that diamond detectors are able to operate with broad-band amplifiers. A new low noise, 3 GHz broad-band amplifier has been developed and successfully tested with ^{12}C, ^{20}Ne and ^{58}Ni ions last year [4]. The ^{243}Am-spectrum plotted in Figure 5 shows the first 5.5 MeV α–spectrum taken with CVD-diamond detectors using 50 Ω, broad-band amplifiers. The gain choosen was 47 dB. The α-distribution is well separated from the electronic noise. In all spectra measured with heavier particles we observed a ratio mean/most probable value of 1.1 whereas the α-spectra show an asymmetric shape with a ratio of 1.4.

6. Counting-Rate Capability

Timing measurements with heavy ions require not necessarily detectors with long carrier life time. As long as the achieved signal amplitudes are well above the threshold (Fig.4), a shorter lifetime could be an advantage. For high frequency spill structure analysis for the SIS [4], signal widths of less than 1 ns are needed. In order to maintain the short pulse the detector capacitance has to be optimized by dividing the active area in strips or pixels. The capacitance of the diamond detector only defines finally the counting rate capability.

Figure 6 shows data taken with a 265 µm thick diamond detector with a capacitance of 10 pF in a test performed with ^{20}Ne projectiles at 300 MeV/amu kinetic energy. Inside the SIS ring the beam intensity was measured with beam-current transformers and outside the SIS with an ionisation chamber, placed directly in front of the diamond detector.

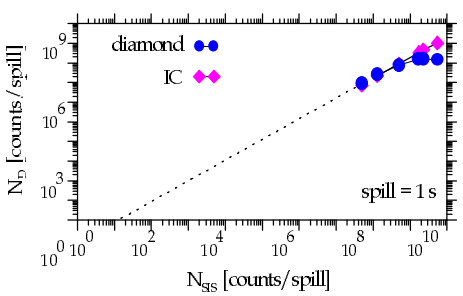

Fig. 6: Beam monitoring, diamond in a single particle mode versus ionisation chamber integrating over the spill duration

Due to decay time contributions of transmission lines and the scope the final width of the signal was 3 ns. This led to unresolved single pulses in the spill and to counting losses for the highest intensities. However, the data demonstrate the ability of diamond detectors to measure efficiently heavy ion rates from single particles up to 10^8 particles/s. This rate can be further increased by dividing a detector in strips or pixels.

The Z^2 dependence of the diamond pulse-height will be investigated systematically. Different fragments of a heavy projectile, identified by the magnetic system and the MUSIC detectors should be focused on diamond detectors placed on the S2 and S4 focal plane of the FRS spectrometer. Time-of-flight measurements with the new GSI broad-band amplifier will be performed as well.

References

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