Diamond detectors for hadron physics research

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1. Introduction

The term hadron physics will henceforth denote the basic research which comprises atomic, nuclear, and high-energy physics experiments. The fundamental interactions and forces, which define the structure of matter from quarks to galaxies, are studied using complementary probes, for instance, charged particles from protons to uranium, electrons, neutrons, and γ-rays. Over more than one decade, CVD-diamond sensors have been investigated for applications in these related research fields [1–5]. The radiation resistance of diamond [6] was initially the most interesting property; it was assumed that it is higher than the one of any other comparable detector material. However, the scientific communities are still somehow hesitant to approve diamonds on a large scale. The higher costs as compared for instance to novel ‘radiation hard’ silicon devices [7], has to be compensated by additional advantages and by the superior characteristics of the diamond detectors.

In this review we discuss the sensor categories in which electronic grade pcCVDD and scCVDD have currently the potential to compete with traditional sensors (Section 2). We present first results obtained from a DoI CVDD plate [8] prepared at the University of Augsburg, which belongs to a CVDD type promising to combine the timing properties of pcCVDD [2] with an improved crystal homogeneity. Section 3 is dedicated to the signal processing; the sample preparation and the characterization of surface and bulk structure are described in Sections 4.1 and 4.2, the behavior of the dark conductivity in Section 4.3, and the TCT results throughout obtained using 241Am-α-particles in Section 4.4. The performance of scCVDD sensors after intense proton, neutron, and electron irradiations is discussed in Section 4.5. The results are eventually summarized and concluded in Section 5.

2. Charged particle detection with diamond sensors

At ‘hadron’ accelerator facilities, the structure of matter is investigated performing collision experiments in the energy range of 1AMeV ≤ Ebeam ≤ 1ATeV of ions ranging from protons to uranium. The colliding particles (henceforth denominated projectile and target ions) decay after interaction into a number of reaction products defined by the energy dissipated in the colliding system; the amount of the charged products in one event varies from 2 up to more than 1000. At the highest dissipated energy the colliding ions disintegrate into their constituent
quarks and their bonding particles, the gluons, forming a new state of matter called ‘quark–gluon plasma’ [9] which is believed to describe the structure of the universe shortly after the Big Bang.

The investigation of new rare processes requires unprecedented high beam intensities (up to \( \sim 10^{12}/\text{beam pulse} \)). At the upcoming Facility for Antiprotons and Ion Research (FAIR) in Darmstadt as well as at the Large Hadron Collider LHC and its upgrade SuperLHC at CERN or at the upcoming International Linear Collider (ILC), the detector systems located in the vicinity of the beam interaction zones have to withstand integral rates of \( \geq 10^{16} \text{particles/cm}^2 \). In fixed-target experiments at GSI Darmstadt (Helmholtz Center for Heavy Ion Research), radiation hard, ultra-fast \textit{start detectors} of low material budget are applied to start time-of-flight (ToF) measurements in order to define the time-zero (T0) of the beam-target interactions of interest out of total collision rates which are eight orders of magnitude higher than the physics process which is investigated. The potential of pcCVDD as well as of scCVDD in such ion-ToF applications is superior to any other known detector material. The same is valid for single-particle beam and beam-loss monitoring at ion rates far beyond \( 10^6 \) particles/s [10] as well as the conditioning of ultra-relativistic beams of minimum-ionizing particles (MIP) [11] and beamstrahlung calorimetry at high luminosity linear colliders [12].

Energy or energy-loss measurement techniques are powerful tools for particle identification (PID) in nuclear physics experiments. Each detector signal corresponds to the specific energy \(-dE/dx\) dissipated per unit path length from an impinging ion in its bulk material; the ‘stopping power’ \(-dE/dx\) of each target/sensor material is characteristic for the nuclear charge \( Z \) and the velocity \( \beta \) of the impinging ion and can be calculated according Ref. [13]. The generated charge \( Q_{\text{g}} \) increases with the ratio \( Z_{\text{eff}}^2 \) (with \( Z_{\text{eff}} \) the atomic charge state of the ion) and with the density of the detector material; it does not depend directly on the energy \( E \) or the mass \( m_{\text{ion}} \) of the ion. It should be noticed for the following that, since ions have the same velocity when they have the same value of \( E/m_{\text{ion}} \), the hybrid unit \( E/A \) with \( A = m_{\text{ion}}/Z \) reflects \( \beta \). A is the atomic mass number of the ion in units of 1/12 of the mass of \( ^{12}\text{C} \).

At high relativistic velocities, all ions are usually fully ionized \((Z_{\text{eff}} \rightarrow Z)\) and the energy-loss of the ions differs by \( Z^2 \). High-resolution MULTiple Sampling Ionization Chambers (MUSICs) are implemented to cover the large solid angles of the reactions, whereas in low-energy measurements \( dE/dx \rightarrow E \) silicon telescopos are used. However, if small-area devices are acceptable, scCVDD detectors are a serious alternative to classical sensors [14]. Note that this PID method do not apply for ultra-relativistic physics experiments, where all particles involved are minimum-ionizing and of \( Z = 1 \). The energy-loss signals of those are almost equal and therefore indistinguishable for a single sensor.

The ion mass is defined by particle tracking in magnetic fields combined with velocity measurements either by ion-ToF for moderate particle velocities, or by RICH (ring-imaging Čerenkov hodoscopes) techniques in the relativistic ion case. For heavy-ion tracking and ToF systems at FAIR pcCVDD sensors are a reasonable alternative to silicon detectors [15]. However, the requirements of vertex devices (MIP detection) are hardly met by this type of diamond. In contrast to CERN experiments, the sensor thickness of at least 300 to 500 \( \mu \)m needed is not acceptable in measurements performed at projectile energies of \( E_{\text{max}} \sim 30\text{AGeV} \) (ions) or \( E_{\text{max}} \sim 90\text{GEV} \) (protons and antiprotons). Monolithic pixel devices of a total material budget of only 200 \( \mu \)m silicon are projected for the Compressed Baryonic Matter (CBM) experiment, in order to minimize energy straggling and secondary reactions. Even worse is the application of pcCVDD for start detectors of relativistic proton measurements, which is an urgently needed detector type for both the present GSI and the future FAIR experiments. Spectroscopic grade scCVDD of extremely high breakdown field is required (Section 4.1) in addition to optimized broadband assemblies of improved signal-to-noise (S/N) ratio (Section 3).

### 3. Diamond signal processing

We refer henceforth to a ‘diamond detector’ assuming an \((100)\)-oriented intrinsic diamond crystal of thickness, \( d_{\text{p}} \), metallized with sandwich electrodes (the sensor) and connected to an amplifier. In the equilibrium state, the sensor is biased with \( V_{0} = d_{\text{p}}/E_{\text{p}} \), where \( E_{\text{p}} \) is a positive or negative electric field applied in the \((100)\) direction of the crystal. The simplified equivalent schematics of the two alternative readout schemes are shown in Fig. 1: the low-impedance broadband (BB) signal processing applied for time measurements and the high-impedance charge-sensitive (CS) readout of limited bandwidth used for charge measurements.

The left hand part of this schematics belongs to both circuits consisting of the diamond sensor (framed) described by its capacitance \( C_{0} \) and a current generator, the bias circuit represented by \( V_{0} \) and a bias resistor, \( R_{b} \), as well as various electronic components depicted by the thermal noise current generator \( I_{\text{amb}} \). The inherent noise of diamond sensors is negligible (intrinsic carrier density \( N_{\text{in}} \approx 10^{12}/\text{cm}^2 \)), and (for simplicity) we neglected also the parasitic capacitances \( C_{p} \), which otherwise play a crucial role for the detector performance. In the right hand part of the figure are depicted a timing amplifier (i.e., a current amplifier) represented by its input impedance \( R_{i} \) and a coupling capacitance \( C_{c} \) (solid lines scheme) as well as, alternatively, a spectroscopy preamplifier (dashed lines scheme) represented by its feedback circuit \( C_{f} \leftrightarrow R_{i} \). A detailed description of the diamond signal creation, propagation, and processing can be found in [16].

For heavy-ion timing and TCT with \( ^{241}\text{Am-α} \)-sources in the laboratory, we developed a diamond broadband amplifier (DBA [17]), which is an inverting, AC coupled current amplifier of a bandwidth BW from 1 MHz to 2.3 GHz, an \( R_{i} = 50 \Omega \), input capacitance \( C_{i} = 5 \text{pF} \), and a low bias resistor \( R_{b} = 10 \text{kΩ} \) enabling high rate operation. Energy and energy-loss measurements are performed with CSTA2 spectroscopy preamplifiers originally developed for heavy-ion silicon sensors at the Technical University of Darmstadt. For the alpha measurements, the CSTA2 parameters are modified to \( C_{1} = 1 \text{pF}, R_{f} = 1 \text{GΩ}, R_{b} = 1 \text{kΩ} \). The preamplifier signals are amplified and shaped by commercial shaping amplifiers (Canberra or ORTEC) and digitized with 13bit peak-sensing SILENA ADCs.

In an ideal detector, the particle induced transient current \( I_{\text{tr}}(t) \) is described by the simplified Eq. (1)

\[
I_{\text{tr}}(t, E) = \frac{Q_{c}(E)}{d_{\text{p}}} e^{-(t/\tau_{c})-(t/RC)} = \frac{Q_{c}(E)}{\tau_{c}} e^{-t/RC}
\]

where \( Q_{c} \) and \( Q_{c}(E) \) are the ion-generated and the collected charge at field \( E \), respectively, \( d_{\text{p}} \) is the detector thickness, \( v(E) \) the carrier

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**Fig. 1.** Simplified equivalent schematics of a diamond sensor (framed) connected to the two kinds of preamplifiers used alternatively for hadron physics detectors: A BB amplifier (short-dashed lines) represented by its input impedance \( R_{i} \) and a coupling capacitance \( C_{c} \) as well as a CS preamplifier (long-dashed lines) represented by its feedback circuit \( C_{f} \leftrightarrow R_{i} \). The left hand part of the schematics, consisting of a bias circuit \( (V_{0}, R_{b}) \) and a noise current generator \( i_{\text{amb}} \) which depicts the thermal noise of the electronic components, belongs to both circuits.
Fig. 2. Estimated amplitudes on 50 Ω input impedance of a DBA amplifier expected from relativistic ions of kinetic energy $E=1$ AGeV in CVD diamond sensors of different quality and thickness. The equivalent noise amplitude (rms) of the DBA amplifier is indicated by the solid line at $\sigma_{\text{DBA}}$, and the noise deviations by the dashed line at $3\sigma_{\text{DBA}}$. The plot demonstrates impressively the large dynamic range of signals involved in hadron physics experiments.
are preferable. On the other hand, charge blocking and release in and from a Schottky barrier may be the reason of an occasionally observed hard breakdown at high rates of ions stopped in the vicinity of the contacts [25].

The growth of evaporated chromium and aluminum on smooth diamond surfaces has been investigated in more detail under high-vacuum conditions by in-situ infrared spectroscopy [26]. A remarkable structural phase transition from a discontinuous phase to the crystalline bulk phase has been observed in ultra-thin Cr at a critical film thickness of \(d_{\text{crit}} = 2.5 \, \text{nm} \) [27]. This value and the IR spectral properties corroborate the old theoretical finding of preferred fcc nanocluster formation of Cr for \(d < d_{\text{crit}} \) [28], which is an interpretation also supported by the better lattice match of diamond and fcc Cr. Photo-emission-spectroscopy with synchrotron radiation is planned to study the behavior of diamond-carbide-systems [29]. It is known from measurements using silicon-silicide-structures that the height of the barrier does not depend on the metals band structure. It has been suggested that chemical bonds of the interface surface are important [30].

4.2. CVD-diamond surface and bulk structure

The characteristics of the diamond samples exemplarily selected for discussion are listed in Table 2.

For traversing particles, polished surfaces are only required for micro-patterned electrodes. In all other cases, 'as grown' samples are preferable since the surfaces are rough but not damaged. As grown pcCVDD shows a roughness of approximately 10% of the film thickness. AFM pictures illustrating typical defects of differently polished surfaces are shown in Fig. 3(A). The left hand side image demonstrates the atomically flat surfaces of \(0.5 \, \text{nm} \) (rms) achieved on both sides of the ion-beam polished (IBP) sample sc6BP. Abrasively treated samples show rather different morphology and roughness of opposite sides: sample sc6A reveals \(6 \, \text{nm} \) and \(8 \, \text{nm} \) for side 1 (S1) and side 2 (S2), respectively. In the Dol case, an rms roughness of \(0.9 \, \text{nm} \) and \(2.4 \, \text{nm} \), and a maximum depth of scratches of \(7 \, \text{nm} \) and \(11 \, \text{nm} \), respectively, have been achieved by sc8BP polishing.

Fig. 3B shows white-beam X-ray topographs of the scCVDD samples sc8BP (a) and sc6A (b), respectively. Defect-free regions appear as homogeneous bright areas and dislocations or strain as dark figures. The image of the RWP plate reveals more stress and a higher density of structural defects. The dark regions surrounding a bright spot at the bottom border of the indicated sc6A electrode, point to bundles of threading dislocations found to originate from defects of the HIPHT diamond substrate used for growth [25,26,31].

Since threading dislocations may be crucial for the detector operation, birefringence imaging is systematically performed prior to the sensor preparation. Fig. 3C shows full-size pictures of the scCVDD and the Dol sample (a, b, and d), and a part of the larger pcCVDD plate (c), respectively. Structural defects or strain appear in cross-polarized light microscopy bright within homogeneous dark areas of optically isotropic diamond. The sector electrodes applied for electrical characterization are drawn on top of the images.

Little stress but one threading dislocation in each of the scCVDD sample is indicated (to right of sc6A and of sc8BP). The polycrystalline diamond of \(0.5 \, \text{µm} \) thickness (c) is produced by polishing a thicker plate on both sides, reducing somewhat the density of dislocations compared to an 'as grown' film. However, the picture illustrates the pcCVDD structure consisting of single-crystal grains separated by grain boundaries. The initial thickness of the Dol film was \(300 \, \text{µm} \), and the final thickness of \(230 \, \text{µm} \) was achieved by removing \(30 \, \text{µm} \) diamond from the substrate side and some polishing of the uneven growth side. The corresponding image (d) is a consequence of the homogeneous and high nucleation density of diamond on iridium [8], which is still dominant after \(30 \, \text{µm} \) film growth. It would be interesting to investigate whether the removal of more layers from the nucleation side is a way to take advantage of the better lattice match between diamond and iridium.

4.3. Dark conductivity

The IE characteristics of the diamonds are measured in a metallically shielded dark nitrogen atmosphere using Keithley 6517A electrometers. This setup suppresses electrical pick-up, photo excitation and surface humidity. Since an early test has confirmed the measured leakage currents originating from the diamond bulk we do not apply systematically guard ring electrodes. Fig. 4 shows typical IE characteristics of some scCVDD samples (a), diverse 'as grown' pcCVDD films (b), and of the Dol549 plate (c).

Compared to pcCVDD samples (central plot), the dark conductivity of scCVDD is two orders of magnitude lower (left hand plot). However, the behavior of the leakage current versus \(E_D \) is similar. It has been shown [32] that the dark conductivity of pcCVDD is governed by transport in the grain boundaries, characterized as thermally activated hopping in antibonding \(\pi^* \) and \(s^* \) states [33]. Recent work on spectroscopic grade diamond revealed that isolated bundles of threading dislocations are dominating the breakdown behavior of single crystals [25]. Homogeneous low conductivity (dark currents \(<0.1 \, \text{pA} \)) was measured in all sectors of sample sc8BP up to

Table 1

Intrinsic time resolution of scCVDD.

<table>
<thead>
<tr>
<th>Test</th>
<th>(p = 1.25 , \text{GeV} )</th>
<th>(p = 3.5 , \text{GeV} )</th>
<th>(p = 6 , \text{MeV} )</th>
<th>(^{12}\text{C}, 0.4-0.8 , \text{MeV} )</th>
<th>(^{27}\text{Al}, 2 , \text{AeV} )</th>
<th>(^{58}\text{Ni}, 1.9 , \text{AeV} )</th>
<th>(^{185}\text{Ta}, 1.4 , \text{AeV} )</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\text{FEE} )</td>
<td>sc6A</td>
<td>sc6A</td>
<td>sc6A</td>
<td>sc6A</td>
<td>sc6A</td>
<td>sc6A</td>
<td>sc6A</td>
</tr>
<tr>
<td>(\text{CVDD} )</td>
<td>sc6A</td>
<td>sc6A</td>
<td>sc6A</td>
<td>sc6A</td>
<td>sc6A</td>
<td>sc6A</td>
<td>sc6A</td>
</tr>
<tr>
<td>(\sigma ) [ps]</td>
<td>sc6A</td>
<td>sc6A</td>
<td>sc6A</td>
<td>sc6A</td>
<td>sc6A</td>
<td>sc6A</td>
<td>sc6A</td>
</tr>
<tr>
<td>(\text{eff. %} )</td>
<td>sc6A</td>
<td>sc6A</td>
<td>sc6A</td>
<td>sc6A</td>
<td>sc6A</td>
<td>sc6A</td>
<td>sc6A</td>
</tr>
</tbody>
</table>

Table 2

Properties of the samples discussed in this article.

<table>
<thead>
<tr>
<th>Sample</th>
<th>(d_{\text{Si}} )</th>
<th>Surface finishing</th>
<th>N, B [ppb]</th>
<th>Electrodes: (d_{\text{Si}} )</th>
<th>Annealing</th>
<th>Area/mm(^2)</th>
<th>Ce/pF</th>
</tr>
</thead>
<tbody>
<tr>
<td>pcPF350</td>
<td>350</td>
<td>As grown</td>
<td>(\leq 50; \leq 1)</td>
<td>Cr/Au; 100/200</td>
<td>Ar, (500 , ^\circ \text{C} )</td>
<td>Single dot, 50.3</td>
<td>7.3</td>
</tr>
<tr>
<td>sc6A</td>
<td>100</td>
<td>Resin-wheel</td>
<td>(&lt; 5; \leq 5)</td>
<td>Al; 100</td>
<td>No</td>
<td>4 \times 0.5, 1.5</td>
<td>4 \times 0.8</td>
</tr>
<tr>
<td>sc8BP</td>
<td>100</td>
<td>Ison-beam</td>
<td>(&lt; 5; \leq 5)</td>
<td>Al; 100</td>
<td>No</td>
<td>4 \times 0.5, 1.5</td>
<td>4 \times 0.8</td>
</tr>
<tr>
<td>sc6BP</td>
<td>100</td>
<td>Resin-wheel</td>
<td>(&lt; 5; \leq 5)</td>
<td>Al; 100</td>
<td>No</td>
<td>4 \times 0.5, 1.5</td>
<td>4 \times 0.8</td>
</tr>
<tr>
<td>Dol549</td>
<td>230</td>
<td>Scaife</td>
<td>Nominally without N</td>
<td>Ti/Pt/Au; 40/50/100</td>
<td>Ar, (500 , ^\circ \text{C} )</td>
<td>Single dot, 6.1</td>
<td>1.3</td>
</tr>
</tbody>
</table>
Fig. 3. a. AFM images of the ion-beam polished (IBP) plate sc8B (left picture), the resin-wheel polished (RWP) film sc6A (S1, S2 central pictures), and the scaffle polished (SP) Dol sample (S1, S2 right pictures), respectively. Whereas IBP plates show atomically smooth surfaces on opposite sides, abrasive treatments lead to quite different morphology and roughness which may influence the properties of the contact-diamond interface. b. ‘White-beam’ X-ray topographs of sc8BP (a) and sc6A (b), respectively. Defect-free regions are indicated by bright areas, whereas dislocations and crystal stress by dark figures. The circles indicate the shape of the electrodes applied afterwards for electrical characterization. The defect density of the RWP sample sc6A is higher. c. Birefringence images of the samples sc8BP (a), sc6A (b), pCPF350 (c), and Dol549 (d). Structural defects and strain appear bright within homogeneous dark areas of optically isotropic diamond. Little stress and isolated dislocations are visible in both homoepitaxial samples, whereas a high defect density is obvious in both heteroepitaxial plates.
E_D = ±3 V/μm (Fig. 5, left). The erratic dark current expected [34] from the threading dislocation in q4 (Fig. 3C(a)) was not observed, or, the image is misleading. Another suggestion is that it appears in conjunction with defective surfaces, which is the case of the mechanically treated film sc6A. In contrast to sc8BP, a strong increase of the dark current has been measured in sector q3 of sample sc6A (Fig. 5, right) at relatively low-field E_D ∼ ±1.2 V/μm. In addition, polarization (q4) and memory effects (q3 and q4) appear. The different behavior of the currents obtained from q1 and q4 (revealing similar extended defects), may indicate either coplanar roughness inhomogeneities, or a dependence of the dark conductivity on the inclination angle between dislocations and the (100) E-field direction.

The measured IE curves are in good agreement with the space charge limited conductivity mechanism (SCLC) [25,35]. Two distinct ranges are measured for pcCVDD and scCVDD samples: the ‘safe detector bias range’, where the measured dark current shows an Ohmic or blocking behavior on the sensitivity limit of the measurement system, and the ‘soft breakdown’ regime, where the curves are described by a single power law I ∼ E^α with an exponent α = 2.2 for ‘defect-free’ films and 5–7 for lower quality samples [25]. In addition, blue-light electroluminescence was observed from defective scCVDD plates (Fig. 6, left), which was correlated with extended structural defects, as it is confirmed from the corresponding X-ray topograph (Fig. 6, central). The Gaussian peaking at 2.84 eV (σ = 0.16 eV) which is shown on the right graph of the figure is the spectrum of the light emitted. The power-low exponents of α ≫ 2 in conjunction with the broad width of the emitted light distributions indicate that charge recombined rather at a band than at discrete levels. It is suggested that such a band in the forbidden gap is formed by dislocations or other extended structural defects (for instance stress or bundles of dislocations). Defect-free samples does not show light emission, even at much higher electric fields [25].

Up to present, the attempt to understand the dark conductivity of Dol diamond the same way as of the other CVD types failed. Based on the applied growth conditions (Table 2) we assumed diamond of rather high purity. However, the N and B concentrations are not measured so far. The very low dark current obtained is in contradiction to the birefringence image. Following the idea that charge transport in dislocations controls the dark conductivity of CVD, a much higher dark current was expected. An assumption that the dislocations of Dol samples do not release charge is unlikely. Conceivable is that the dark current vanishes due to the compensation of shallow traps by deep defect levels (compare Section 4.6). In that case, a significant loss of the particle induced charge and a very short charge-transition time are expected. The positive aspect is the predicted high breakdown field of Dol sensors (Fig. 4C).

4.4. Transient current signals

The TC technique (TCT) is based on the fact that the transition time t_tr of the ion-generated charge from the point of pair separation to the electrode is given by the width of the TC signals. The short range of 241Am-α-particles in diamond \( R_{\alpha} = (12 \pm 5) \mu m \) renders possible to control the drift of electrons and holes by the bias polarity of the electrode impinged by the particles; the longer drift distance corresponds (almost) to the detector thickness being \( d_D \gg R \) and the

Fig. 4. Typical IE characteristics of scCVDD (A), pcCVDD (B) and Dol (C) samples. Besides the current levels, which deviate by two orders of magnitude, the electric field dependence of the dark conductivity of scCVDD and pcCVDD is similar. (C) The extremely high resistivity obtained from the Dol sample is an experimental result, which needs further detailed investigations (see text).

Fig. 5. Dark current behavior in sectors Q1–Q4 of the ion-beam polished sample sc8BP (left) and the resin-wheel treated sample sc6A (right), respectively. The erratic current expected from threading dislocations is observed only in conjunction with the defective surfaces of the resin-wheel polished sample sc6A.
Drift velocities are given by $v_{\text{drift}} = \frac{d_D}{\text{FWHM}}$. The signal shape illustrates the internal electric field profile for the single-carrier drift in the small-signal case, as well as possible trap and space charge concentrations in the sensors [36,37].

However, TCT applies precisely only for crystal detectors in which the majority of the charge carriers reach the sensor electrodes. Fig. 7 shows the development of $\alpha$-induced current pulses at increasing $E_D$ in diamonds of different quality and thickness: a defect-free scCVDD sensor of 400 μm thickness (Fig. 7A), as well as the pcPF350 (Fig. 7C) and the DoI549 (Fig. 7D) sensors, respectively. In all measurements, the DBA amplifier was reading out the signals through the biasing electrode irradiated by the $\alpha$-source installed at growth side; hole-drift signals are the positive pulses. The pcCVDD and the DoI sensors have been tested in the primed state [19]. ‘High-frequency ringing’ of the scCVDD signals is caused by some unavoidable impedance mismatching.

As expected, the first conspicuous distinction is the extremely different transition time of the charge carriers, which eventually defines the single-particle rate capability of the different CVDD types. In the case of the scCVDD pulses, the slopeless flattop of the signals demonstrates negligible space charge and comparable drift velocity of electrons and holes [18] moving in a constant field $E_D(100)$ (Fig. 7A). Indeed, the measured drift velocities at a safe detector operation bias amounted to $v_h \sim 110$ μm/ns for holes and $v_e \sim 90$ μm/ns for electrons, whereas the...
extrapolated low-field mobilities and saturation velocities obtained by fitting the experimental data achieve values \( \mu_{\text{sat}} = 1300–3100 \text{ cm}^2/\text{V} \cdot \text{s}; \)
\( \nu_{\text{sat}} = 190 \mu\text{m} / \text{ns} \) and \( \nu_{\text{sat}} = 2400 \text{ cm}^2/\text{V} \cdot \text{s}; \) \( \nu_{\text{sat}} = 140 \mu\text{m} / \text{ns} \)
for electrons and holes, respectively [38]. These results are in good agreement
with other measurements using the same technique at comparable high
bias values as required for particle detector operation [39]. Note that complete
velocity saturation has not been observed despite the very high bias applied.
In Fig. 7(B) are signals compared, which have been recorded from scCVDD
of a thickness of 50 \( \mu\text{m} \) (dashed lines) and of 100 \( \mu\text{m} \)
(dashed–dot lines), respectively. The linear dependence of the signals
FWHM on \( 1/d_0 \) is obvious in this case of complete charge-collection.

The groups of signals (incrementing symbols) have been obtained from the
sectors \( q_1 \)–\( q_4 \) of samples sc8BP (electrons) and sc6A (holes), respectively,
demonstrating spatial homogeneity of the detector response. The inverted
electron pulse has been overlaid on the corresponding 6A94 hole signal
dotted line) in order to test polarization. The different behavior of the
dark current by inverting the bias (see Fig. 5) does not affect significantly
the electric field profile.

In contrast to 'as grown' samples, which show rapid charge
quenching indicated by inhomogeneous triangular signal shapes [40],
this 'detector grade' pcPF350 show two distinguished regions for both
electrons and holes drift. The signals develop an obvious 'cusp', which
shifts with increasing bias. This may indicate a decrease of the
effective sample thickness [18], for instance by accumulation of
electrons and holes drift. The signals develop an obvious
charging inverting the bias (see Fig. 5) does not affect significantly
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the electric field profile.

The evidence of this exponential is crucial for the design of
diamond sensors. The message is that a CCE equal to unity is
impossible; furthermore that for \( w_s(E) \) equal to the detector
thickness, the collected charge amounts only to 63.2% of the generated
charge, whereas a \( w_s(E) > 100 \cdot d_0 \) is required for the collection of
about 99% of \( Q_G \).

Fig. 8 (left) illustrates the general trend of the CCE(E) character-
istics of scCVDD and pcCVDD as well as of 'early' DoI material: the three tested diamond types are represented by sample sc12B
diamonds), pcPF350 (circles), and DoI549 (triangles), respectively.
Note that the 'error bars' indicate the widths of the measured \( Q_C \) distributions (Fig. 8, right graph), whereas the uncertainties of the
CCE mean values are small.

The characterization of the CCE and of the energy resolution \( \Delta E / E \)
is usually performed under vacuum conditions using CS detector
readout. Since these measurements have not been performed so far
with the DoI sensor, we present systematic data measured in air with
DBA amplifiers; the data are corrected by taken into account the energy-loss of the \( \alpha \)-particles in the 5 mm air distance between
source and diamond surface (i.e., \( \Delta E_{\text{air}} = 0.54 \text{ MeV or } \Delta Q_C^{2} = 6.7 \text{ fC} \).
Almost full saturation of the collected charge to a CCE~0.95 is obtained for sc12B at very low fields $E_D \leq 0.2 \text{ V/\mu m}$ for holes drift and slightly higher $E_D$ for electrons drift. The CCE of the pcPF350 sensor amounts to 0.2 for holes and to 0.25 for electrons, respectively. The successive increase of the mean value and the width by increasing the bias demonstrates improving charge-collection but also a deteriorating energy resolution of the sensors. This trend is also confirmed by the TCT results shown in Fig. 7. The Dol sample shows a rather symmetric characteristic with slightly better efficiency for holes drift (CCE~0.12), and significantly less spread of the collected charge distributions compared to pcCVDD (Fig. 8, right graph). These results are in agreement with heavy-ion data published in [42].

As expected for fully depleted high-quality sensors, the energy resolution of scCVDD detectors improves with increasing bias. Therefore, also devices implemented for ion spectroscopy profit from a high breakdown field and a fast collection of charge [14]. Note that a reasonably good $\Delta E/E$ is always required for background reductions, even in experiments in which the sensor task is solely the timing. To our opinion, scCVDD is the only known detector material combining energy and time resolution in such an excellent manner. For $^{241}$Am-α's and light ions, spectroscopic grade diamond shows a $\Delta E/E$~0.003, which is comparable to the resolution of silicon sensors measured under same conditions [43], and a $\Delta E/E$~0.02 for ions of A~40 which is superior to the silicon ones. As discussed in [14], in contrast to the high-mobility diamond sensors, silicon detectors deteriorate at SCLC transport showing pulse-height defects (plasma effect).

4.6. A radiation hardness study of scCVDD diamond plates

The detector characteristics of scCVDD samples measured in the virgin state was compared to the properties obtained after heavy irradiations with 26 MeV protons and 20 MeV neutrons [6,25], as well as with electrons of 10 MeV [12]. The integral particle fluences were $\Phi \geq 10^{16}$ (p,n)/cm$^2$ for the hadron-irradiated films, whereas in the electron case a fluence of an equivalent dose of 10 MGy was applied. For details see Refs. [6,25] and [12], respectively. The conclusion of all data is that a stable operation of the sensors with MIP distributions separated from the electronic noise is confirmed within the hadron-fluence range tested, whereas the sensors have been still operational after absorbing relativistic electrons of a dose equivalent of ~7 MGy.

However, radiation-induced defects of the detector signals were observed in all cases. In the following we will discuss in more detail the defects induced by protons and neutrons. Note that the described study has been performed with thick diamond sensors ($d_D$~400–500 μm) while expecting that thinner samples ($d_D$~50–100 μm) show better radiation resistance [25]. OAS in the UV–VIS range shows [25] that the main surviving defects are neutral mono-vacancies $V_0$, identified in all measured spectra by a characteristic zero-phonon line at 1.638 eV. TCT has been applied to measure effective deep-trapping lifetimes $\tau_{e,h}$ and a linear scaling of $1/\tau_{e,h}$ with fluence has been obtained as well as almost identical defect production rates for both neutron and proton irradiations. The neutral state of the defects was confirmed by the absence of space charge and no degradation of the carriers drift velocity, both visible in the TC signals. Due to migration and recombination of the neutral mono-vacancies, a permanent recovery of the CCE was achieved after high-temperature annealing (~800 °C). It was also possible to prime sensors irradiated by up to $F \sim 10^{14}$ particles/cm$^2$ with $^{90}$Sr electrons to almost the initial CCE value.

In contrast to damaged silicon sensors, the dark conductivity of irradiated diamond detectors is decreased. The same observation was found for irradiated pcCVDD devices [1]. In the scCVDD case, this is most likely due to a compensation of shallow traps by neutral vacancies. However, these results confirm the assumption that, in order to understand the dark conductivity of CVD, more parameters than nitrogen concentrations and crystal dislocations (found to control the dark current in high-purity virgin samples) have to be considered. In addition, the behavior of the simultaneously irradiated detector electrodes and the possible consequences for the diamond-contact interface has to be systematically investigated.

5. Summary and conclusions

In this article, we have discussed the potential of electronic grade CVDD materials for detector applications in hadron physics research. The characteristics of diamond sensors consisting of scCVDD and pcCVDD plates have been compared to recent results obtained from ‘early’ Dol sensors grown on the multi–layer substrate ‘Ir/YSZ/Si001. In addition, the important role of the front-end electronics has been addressed in conjunction to the large dynamic range of signals to be processed in hadron physics experiments. It was shown that the best diamond quality is not necessarily the best choice for heavy-ion beam monitoring or timing measurements but an indispensable requirement for ion spectroscopy and for time measurements of relativistic ions lighter than carbon.

The central material properties justifying diamond detectors as being superior to comparable classical sensors are the high breakdown fields observed in conjunction with the high drift velocities of both charge carriers. It is evident that these characteristics support high rate single-particle counting and ion-ToF applications. In addition, they are the reason for the excellent energy resolution of diamond sensors applied for spectroscopy of highly ionizing ions where the detectors operate in the SCLC regime. The preliminary radiation hardness study with protons and neutrons revealed a linear decrease of the collected charge to about 15% of the initial value which corresponds to a MIP signal still separated from the electronic noise of the spectroscopy amplifiers. Similar values have been measured recently for silicon sensors. The advantages of heavily irradiated diamond detectors with respect to this issue are: the decreasing dark conductivity and the still excellent timing properties, most likely sustained due to the predominant creation of neutral vacancies ($V_0$).

The comparison of the heteroepitaxially grown diamond sensors revealed a lower CCE for the tested Dol sensor, which is in accordance to the higher dislocation density observed in birefringence images. Nevertheless, the high breakdown stability and the strong induced current amplitudes obtained in conjunction with a homogeneous distribution of the structural defects are favourable. We expect a similar heavy-ion time resolution as of the pcCVDD sensors as well as improved position and energy resolutions. In addition that further material removal from the nucleation side will lead to significantly improved charge-collection properties.

Summarizing the results of all tested diamond materials, we conclude that the combination of radiation resistance, high rate capability, and time resolution leads to extraordinary heavy-ion timing detectors superior to plastic scintillation counters, proportional chambers, or channel plates used usually for these purposes. High-quality scCVDD sensors are competitive to silicon detectors in heavy-ion spectroscopy and in any position sensitive measurement that requires charge-sharing between strips. On the other hand, the higher material budget required and the deteriorated charge-collection properties after heavy irradiation thwart at present the emergence of a serious competition to silicon devices in MIP tracking applications. Despite all hesitations, the most of the scientific groups collaborating at FAIR have included pcCVDD as well as scCVDD sensors in their Technical Proposals for the Design, Construction, Commissioning and Operation of FAIR experiments [44].

Acknowledgments

This work is partially supported by the European Community through the Integrated Infrastructure Initiatives HadronPhysics (FP6 Proj. RII3-CT-2004-506078) and HadronPhysics2 (FP7 Proj. RII3-CT-227431) and partially by the FP7 Marie Curie project MC-PAD. We would
like to thank Element Six and Diamond Detectors Ltd. for the excellent diamond materials provided and the participants and users of the NoRHDia and the CARAT Collaborations for fruitful cooperation and lively discussions about advanced diamond detectors. We express our gratitude to the Target Laboratory of GSI for enthusiastic efforts and patience during the metallization studies and the GSI accelerator people as well as Jürgen Härtwig, Muriel Salomé and the technicians of the ID21 beamline of the ESRF for the support during the beam tests. The corresponding author is particularly grateful to Christophor Kozhuharov for the discussions and comments to this manuscript.

References

[24] Diamond Detectors Ltd., Poole, Dorset, UK.