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Charge transport properties of single crystal CVD-diamond particle detectors

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Abstract

The charge transport properties of virgin and heavily irradiated intrinsic Single-Crystal CVD-Diamond Detectors (SC-CVD-DD) are discussed by means of the Transient-Current Technique (TCT), which proved to be a sensitive tool to detect the first changes of the detector's performance. Charge-carrier mobilities $\mu_e = 1300–3100\ cm^2/V\ s$, $\mu_h = 2400\ cm^2/V\ s$ and effective deep-trapping lifetimes $\tau_{eff\text{-}h} = 300–900$ ns, $\tau_{eff\text{-}e} = 160–360$ ns were measured in the non-irradiated state, decreasing slightly after irradiation by a fluency $F > 10^{13}\ p_{26MeV}\ cm^{-2}$. The carriers drift velocity remained almost unchanged after irradiation, indicating the creation of mainly neutral defects. After exposure to fluency above $10^{16}\ p\ cm^{-2}$ however, TC signals were not detectable with the available broadband electronics. A significant improvement was observed after annealing at 1000 °C, and almost complete restoration was obtained by priming with ^{90}Sr-electrons. Optical absorption (OA) spectra confirmed the degradation of the detector performance after exposure to increasing particle fluencies, showing deviations from the intrinsic 'edge absorption' shape around 5.3 eV that was observed before irradiation.

Keywords: Particle detector; Radiation hardness; Single crystal CVD diamond

1. Introduction

Large communities in nuclear and particle physics research (LHC, FAIR, ESRF, ILS) are preparing next generation experiments in which detectors will operate either directly in intense beams, or near the interaction point of projectiles with target atoms. Radiation hard, low-mass vertex detectors are required which have a few micrometers spatial resolution and high rate capability [1]. Over the last years, the ongoing intense R&D on CVD diamond has enabled the replacement of classical detectors in several beam-diagnosis and Heavy-Ion (HI) timing applications with Poly-Crystalline (PC) CVD-DD [2,3]. However, in order to replace silicon vertex devices, SC-CVD-DD are needed because of their ~three times better Charge-Collection Efficiency (CCE). The key issue is the stability of detector operation with accumulated radiation dose. Whereas a lot of articles have been published (recently Ref. [4]) by the RD42 Collaboration concerning the behaviour of PC-CVD-DD under minimum-ionizing particles (MIP), electron, γ and neutron irradiation, no experimental data about the performance of heavily irradiated SC-CVD-DD have been reported.

Virgin SC sensors supplied by [5] have been systematically tested by the authors and the characterization data are published in [6–8]. In this report, the properties of virgin and heavily irradiated detectors are compared and we describe the changes in their response where physics experiments with high-intensity beams are expected to face. This is by no means a detailed radiation hardness study, in which increasing, well-defined fluencies of certain particle species are applied on the same virgin samples. However, useful data are presented regarding the TC signal behaviour (Sections 2 and 6), OA spectra (Section 4), and $I–V$ characteristics (Section 5), after heavy irradiation. The annealing and priming results (Sections 6 and 7) illuminate the nature of the radiation induced defects as well as their migration

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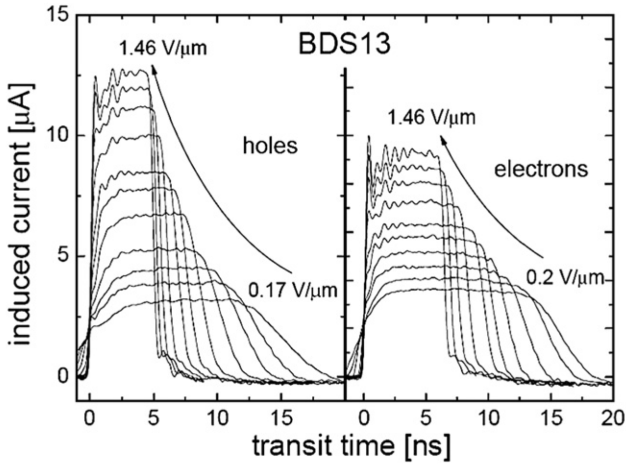

Fig. 1. Development of α-induced TC signals in detector BDS13 by increasing the external applied electric field.

dynamics. The detailed description of sample preparation and the α-ToF test setup used have been published in [7,8].

2. Charge transport properties of non-irradiated SC-CVD-DDs

A ^{241}Am-α-particle of $E_\alpha \sim 5.5$ MeV produces 4.3×10^5 e–h pairs in a range of 12 µm in diamond, which is short compared to the thicknesses 300 µm–500 µm of the tested samples. A weak α-source (~10 Hz rate on DD) provided measurements in the non-space-charge limited regime [9]. The FWHMs of the measured signal current pulses correspond to the transit times of the charge-cloud centres. These widths have been corrected taking into account the contributions of detector capacitances and the bandwidths of the 2.3 GHz preamplifier [2] and the 3 GHz DSO used. A Δ_{FWHM} of 200 ps for both the rise and decay times of the signals was also taken into account.

The TC measurements were performed with detectors metallized with a sandwich arrangement of Cr–Au electrodes. Fig. 1 shows the typical development of electron and hole drift signals in a high-quality intrinsic detector (BDS13) at increasing external electric field E. A constant-current flow is observed until the charge cloud arrives at the opposite electrode. The current signals are described by the Schockley–Ramo theorem [10]:

$$i_{\mathrm{tr}}(E) = \frac{Q_0}{d} \cdot \mathrm{v}(E(x)) \cdot \exp(-t/\tau_{\mathrm{eff-h,e}}) \qquad (1)$$

where Q_0 is the generated charge, d the sample thickness, $v(E(x))$ the local charge-carrier drift velocity, and $\tau_{\mathrm{eff\text{-}h,e}}$ the effective trapping time. The current amplitude is given by $Q_0 v(E(x))/d$, which decreases exponentially due to charge trapping in the presence of electrically active defects. Any space-charge N_{eff} gives rise to an internal electric field which affects the local drift velocity $v_{\mathrm{e,h}}(E(x))$ due to its superposition with the external applied field. The flat-top signals in Fig. 1 however, demonstrate a uniform field E and the absence of trapping centres and space charge, resulting in a constant drift velocity over the whole detector thickness with corresponding constant-current pulses. This constant value of $v(E) = d/t_{\mathrm{tr}}(E)$ is calculated by taking the transit time $t_{\mathrm{tr}}(E)$ to be equal to the FWHM of the signal current pulse. Fitting the $v(E)$ data as proposed in [11], low field mobilities $\mu_0^{\mathrm{h}} = 2400$ cm^2/V s, $\mu_0^{\mathrm{e}} = 1300$–$3100$ cm^2/V s and saturation velocities $v_{\mathrm{sat}}^{\mathrm{h}} = 1.4 \times 10^7$ cm/s, $v_{\mathrm{sat}}^{\mathrm{e}} = 1.9 \times 10^7$ cm/s were obtained. The corresponding $v(E)$ and collected charge $Q_{\mathrm{coll}}(E)$ distributions have been published in [6–8,12].

3. Influence of radiation damage on detector operation

Charged particles impinging into solids produce displacement damage if the host atoms after the collision have a kinetic energy greater than the displacement energy E_{d} of the material. Displacement damage, which scales with the mass ratio $m_{\mathrm{projectile}}/m_{\mathrm{projectile}} + m_{\mathrm{target}}$, is obviously higher for HI than for MIP, and is almost negligible for electrons. However, the displaced lattice atoms are single-vacancies or self-interstitial pairs, which can recombine quickly (self-annealing) or for stable defects at room temperature [13]. Excess damage is expected if nitrogen (or other) impurities are present as these create complex aggregates and when damage cascades can occur when kinetic energy of knock-on carbon atom is much higher than E_{d}. Diamond has the highest reported value of displacement energy $E_{\mathrm{d}} = 40$–80 eV (≈20 eV for other materials including silicon), and this, together with its wide band gap of 5.45 eV results in diamond being the most radiation hard detector material.

To study the properties of damaged SC-DD, samples were irradiated with a very large dose of 26 MeV protons at the Karlsruhe cyclotron: sample BDS14 with $F_{\mathrm{BDS14}} = 6.39 \times 10^{13}$ p cm^{-2}; EBS3 with $F_{\mathrm{EBS3}} = 6.11 \times 10^{14}$ p cm^{-2}; and BDS13 with $F_{\mathrm{BDS13}} = 1.2 \times 10^{16}$ p cm^{-2}. This additional irradiation was needed because no damage was observed after various HI-beam tests made at earlier moderate intensities. All irradiations were carried out in ambient atmosphere.

4. Optical absorption spectra

Fig. 2 shows the UV–VIS spectra taken at room temperature for samples EBS3 and BDS13 before (dashed lines) and after HI- and proton irradiation (solid lines). A featureless 'edge absorption' was found for 'fresh' samples, indicating their perfect type IIa diamond-like quality. Weak deviation of this shape was observed for EBS3 at $F_{\mathrm{EBS3}} > 6.11 \times 10^{14}$ p cm^{-2}, but new features appeared, superimposed on the continuum absorption curve, only for the most heavily irradiated sample with $F_{\mathrm{BDS13}} > 1.2 \times 10^{16}$ p cm^{-2}: these were the two well-known structures at around 2 eV (GR1 band, V0 vacancy [14]) and 4 eV (UV band, 5RL vibronic band, clusters and aggregates of vacancies and interstitials). The inset of Fig. 2 shows the measured GR1 zero phonon line.

5. *I–V* hysteresis

In contrast to irradiated silicon detectors, a suppression of leakage current was observed for all samples. The measured value of dark current after irradiation up to $E \sim \pm 2$ V/µm is just at the detection limit $I < 1 \times 10^{-14}$ A/mm^2. This may be explained by an increase in the Schottky barrier contact potential if intrinsic

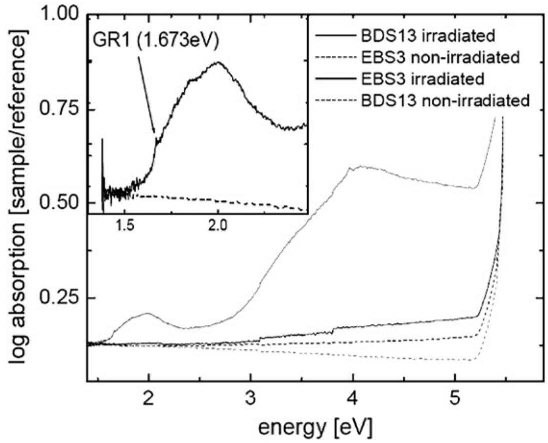

Fig. 2. UV–VIS absorption spectra of two SC-CVD samples measured at RT before (dashed line) and after (solid line) irradiation with 26 MeV protons.

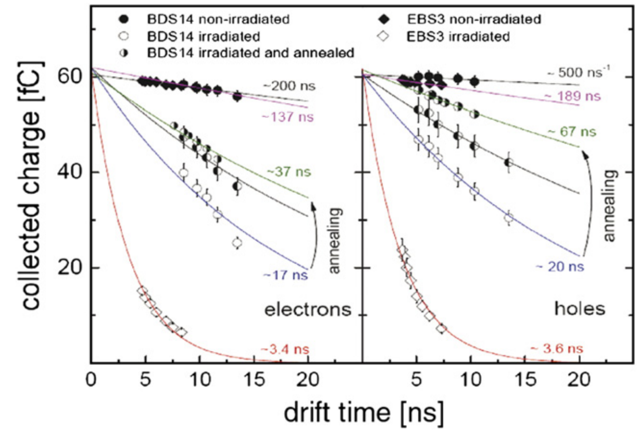

Fig. 4. Estimation of effective trapping time τ_{eff} for samples EBS3 and BDS14 at non-irradiated (filled symbols) and irradiated (open symbols).

excess deep defects passivate uncompensated shallow states that were present before irradiation. This effect was also observed for HPHT-IIa- and PC-CVD-DD under fast neutron irradiation [15].

6. TCT on irradiated SC-CVD-DD

Averaged BDS14 and EBS3 signals measured at E ~ 1 V/μm after irradiation are overlaid in Fig. 3 with those obtained from the virgin samples. In the case of the most heavily irradiated sample BDS13, no TC signal was detectable with the electronics used. Care was taken to avoid polarization in the irradiated samples by limiting the exposure to α-particles below 30 s for each measurement. The previous flat top of the signals shows exponential decay due to trapping of both electrons and holes. However, the transit time t_{tr} remains unchanged, presumably due to the creation of mainly neutral vacancies during the irradiation. Immobile vacancies and interstitials generated by radiation are annealed in relatively low temperatures [13]. Migrating defects may form different complexes such as vacancy pairs or aggregates with any nitrogen or other impurities present in the diamond bulk.

The inverse effective trapping time $1/\tau_{\mathrm{eff\text{-}e,h}}$ is proportional to the number of defects and related to the collected charge by

$$Q_{\mathrm{coll}} = Q_{\mathrm{gen}} \cdot \exp\left(-\frac{t}{\tau_{\mathrm{eff-e,h}}}\right) \tag{2}$$

The restoration of the CCE e.g. after annealing or priming (Section 7) is of interest for detector operation. Fig. 4 shows the $Q_{\mathrm{coll}}(t,E)$ distributions of BDS14 and EBS3 fitted with Eq. (2), before and after irradiation. BDS14 was annealed twice at 1000 °C (1 h and 2 h, respectively), after which τ_{eff} recovered by ~70% for holes and ~55% for electrons. As a smaller recovery in electron than in hole trap-annealing was observed, we conclude that higher activation energy of primary defects or/and different order kinetics due to possible formation of complex defects is observed when annealing the electron trap defects.

7. Trap passivation — priming effect

Due to the low probability of re-emission of charge carriers at room temperature, created deep acceptor and donor traps in

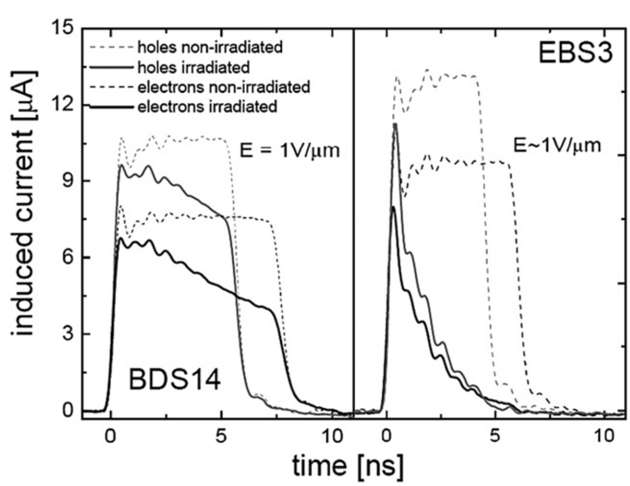

Fig. 3. Transient current signals of two SC-CVD-DD induced by holes (grey) and electrons drift (black) before (dashed lines) and after irradiation (solid lines).

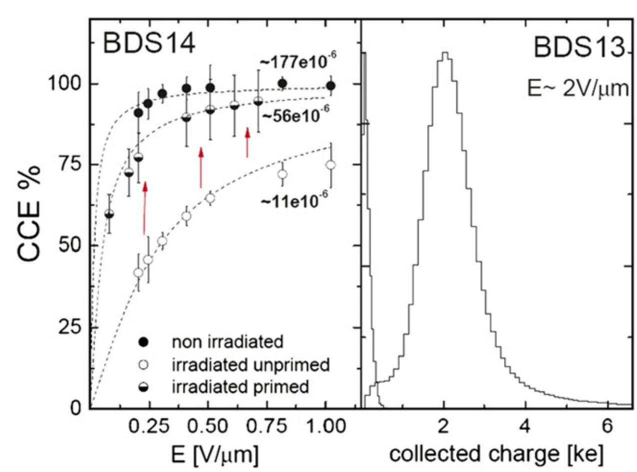

Fig. 5. (Left) Effect of priming on BDS14 detector. (Right) Spectrum of ^{90}Sr-electrons of $E_{\beta} > 1$ MeV measured at primed state of BDS13 sample.

diamond can be passivated by trapped charge. Polarization may occur when short-range ionizing particles hit a detector containing defects, with the build up of an electric field that reduces (or increases) any externally applied field. Intrinsic SC-CVD-DDs do not show this phenomenon, which is however well-known for PC-CVD-DD [16,17]. After heavy irradiation a progressive decrease of the α-amplitudes was nevertheless observed during ~40 min of operation. On the contrary, a homogenous bulk priming with traversing particles (high energy electrons) resulted in a neutral N_{eff} and an increase in $\tau_{\mathrm{eff\text{-}e,h}}$.

CCEs of sample BDS14 after irradiation were measured in the unprimed and primed conditions using ^{90}Sr-electrons and using an energy threshold $E_{\beta}>1$ MeV (Fig. 5, left). A detailed description of the measurement setup is given in [7]. The data points were fitted using the Hecht equation and the combined $(\mu\tau)_{\mathrm{e,h}}$ product was used for comparison. After ~15 h of priming at room temperature, for $E>0.8$ V/μm the CCE was almost restored to its pre-irradiated value. Due to the priming effect, in the case of the most heavily irradiated detector BDS13, minimum-ionizing electrons with $E_{\beta}>1$ MeV were detected with ~96% efficiency and mean signal value 2200e at $E=2$ V/μm (Fig. 5, right) using charge-sensitive electronics.

8. Summary and conclusions

To compare the transport properties of virgin and irradiated intrinsic SC-CVD-DD, three samples previously used in HI-beam tests at moderate intensities were irradiated in the ambient atmosphere with 26 MeV protons with doses up to 10^{16} p cm^{-2}. In their virgin state, mobilities $\mu_{\mathrm{e}}=1300$–3100 cm^2/V s, $\mu_{\mathrm{h}}=2400$ cm^2/V s and effective trapping times $\tau_{\mathrm{eff\text{-}h}}=200$–$500$ ns, $\tau_{\mathrm{eff\text{-}e}}=130$–$200$ ns were measured. After heavy irradiation, the drift velocities remained almost unchanged. In contrast to silicon detectors, leakage current decreased dramatically, thus maintaining its low contribution to the signal-to-noise ratio of the measurements. After fluencies $>10^{16}$ p cm^{-2} the TC α-signals disappeared, but using spectroscopy electronics MIP were still detectable after priming with >95% efficiency and mean value of 2200e at 2 V/μm. These preliminary data are promising, but more systematic radiation hardness studies are needed to confirm the observations and to provide precise data for comparison with silicon and PC-CVD-D detectors.

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References

[1] CBM, P. Senger et al 2005 (from I3HP web-page).
[2] Moritz, et al., Diamond Relat. Mater. 10 (2001) 1770.
[3] EBe, et al., Proc. XL Int. Winter Meeting on Nuclear Physics, Como, 2001.
[4] RD42 annual report 2006 available at http://www.cern.ch.
[5] Element Six, Ascot, UK.
[6] E. Berdermann, et al., Proc. XLIII Int. Winter Meeting on Nuclear Physics, Universita degli Studi di Milano, Ricerca scientifica ed Educazione Permanente, Bormio, Italy, 2005, p. 371.
[7] M. Pomorski, et al., Phys. Status Solidi, A Appl. Res. 202 (11) (2005).
[8] M. Pomorski, et al., Phys. Stat. Sol. (a) 203 (12) (2006) 3152.
[9] J. Isberg, et al., Phys. Status Solidi, A Appl. Res. 202 (11) (2005) 2194.
[10] S. Ramo, Proc. IRE 27 (1939) 584;
W. Shockley, J. Appl. Phys. 9 (1938) 635.
[11] C. Jacoboni, et al., Solid-State Electron. 20 (1977) 776.
[12] E. Berdermann, et al., 1st Industrial Conference Diamond at Work, Barcelona, 2005.
[13] Brendan Campbell, Wahid Choudhury, Alison Mainwood, Mark Newton, Gordon Davies, Nucl. Instrum. Methods A 476 (2002) 680.
[14] K. Iakoubovskii, et al., Physica B 340–342 (2003) 67.
[15] L. Allers, A.S. Howard, J.F. Hassard, Alison Mainwood, Diamond Relat. Mater. 6 (1997) 353.
[16] Dirk Meier, PhD Thesis, University of Heidelberg, 1999.
[17] Oh. Alexander, et al., Diamond Relat. Mater. 7 (1998) 1553.