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Thin single crystal diamond detectors for alpha particle detection

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ABSTRACT

Charged particle detectors based on thin single crystal diamond films ($3.0 \times 3.0 \times 0.09$ mm^3) grown by chemical vapour deposition (CVD) technique are developed at Ruđer Bošković Institute and low field mobility, transit time and saturation velocity, measured by using a ^{210}Po alpha source in vacuum at room temperature, are presented. The comparison of the charge transport properties obtained by time of flight (ToF) technique between detectors based on the same diamond samples, but with different metallization of the electrodes (Au and Al, 100 nm thick), and commercially purchased diamond detectors is performed.
The fabricated diamond sensors showed a spectroscopic resolution of up to 1%, mobility up to 1808 ± 16 and 1914 ± 71 cm^2/V s for electrons and holes respectively and carrier transit time below 2 ns for an applied electric field of 17.8×10^3 V/cm. Results also show variations of the charge transport properties according to the electrode metallization used and the different modality at which the detectors are irradiated.

1. Introduction

The capability of single-crystal CVD (scCVD) diamond detectors to detect different types of radiation from the visible and ultraviolet wavelengths [1–3] up to the X- and γ-rays [4,5] and charged particles as well [6–8] has been widely demonstrated over the past few decades. The interest in using diamond as a radiation detector stems from its unique properties such as the high band gap (5.47 eV) [9] which leads to a low dark current and a high breakdown field (>1×10^3 V/μm), the resilience to radiation damage due to the strong bonds of the crystal structure [10,11] and the room temperature thermal conductivity that is the highest of any other material [12].

A better understanding of the detection performance of the diamond detector can be achieved by performing a study of its main electronic properties, namely the low field mobility and the transit time of the charge carriers. The former describes the rate at which the carrier drift velocity increases with the applied electric field and mainly varies according to the experimental conditions adopted and the sample quality. In a typical experiment alpha-particles are used to induce currents. Values of low field mobility at room temperature of ~2300 cm^2/V s and ~1700 cm^2/V s, for holes and electrons respectively [13], have been reported. On the other hand, in experiments with laser-induced currents, mobility for holes was found to be in the range of 2000–2250 cm^2/V s and for electrons in the range of 2200–2750 cm^2/V s [14]. Other studies have shown hole and electron mobility up to 3800 cm^2/V s and 4500 cm^2/V s respectively [15].

The electronic properties of a diamond sample can be studied by the time of flight (ToF) technique (also known as TCT or transient current technique) in which the duration of the current pulse induced on a read-out electrode by the drift of free charge carriers under the influence of an externally applied field is measured. For the ToF technique we assume that the effective charge carrier lifetime is much longer than the drift time t_{dr}, so the current pulse width equals the time the charge carriers need to traverse the detector. In addition, it has to be recalled that the ToF measurements may depend on the charge density injected especially in the case of high charge densities.

Considering a 5.4 MeV alpha particle, the charge carriers are generated in the first 16 μm below the diamond surface and, depending on the direction of the electric field applied, only one type of charge carrier will cross the whole detector thickness and mainly contribute to the signal.

In first approximation, by knowing the drift time t_{dr} and the thickness d of the diamond sample, the drift velocity of the carrier v_{dr} can be easily calculated as $v_{dr} = d/t_{dr}$. On the other hand, by calculating the drift velocity as a function of the electric field applied, it is then possible to extract the low field mobility μ_0 and saturation velocity (maximum drift velocity) of the carrier v_{sat} as [13]:

$$v_{dr} = \frac{\mu_0 E}{1 + \frac{\mu_0 E}{v_{sat}}} \quad (1)$$

Electronic properties of thick (usually 300–500 μm) scCVD diamonds have been studied using the ToF technique and discussed by many authors [16–19]. On this topic, however, little can be found

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in literature about thin samples with thickness below 100 μm. Moreover, there are few papers which present a comparative study between the electronic properties of diamond devices and different types of electrodes [20–22].

For these reasons we report on the electronic properties (low field mobility, transit time and saturation velocity) and spectroscopic resolution of charge particle detectors based on 90 μm thin (scCVD) diamond samples metallized with gold (Au) and aluminium (Al) electrodes. The results, derived from measurements taken at room temperature by the ToF technique, are also compared with those obtained from commercially available scCVD diamond detectors.

2. Material and methods

The material considered for this work consisted of:

- 2 × scCVD (electronic grade) diamond samples 3.0 × 3.0 × 0.09 mm^3 purchased from Element Six and labelled as Dmd#1 and Dmd#2.[3] The corresponding detectors were fabricated in house with Au or Al/Au electrodes in a sandwich configuration with squared shape and area of 4 mm^2.
- 2 × scCVD diamond detectors 4.6 × 4.6 × 0.5 mm^3 purchased from CIVIDEC with both surfaces fully covered by 300 nm Al electrodes. These detectors, labelled B10044 and B10045 were used for comparison purposes only.

Prior to deposition of Au electrodes, Dmd#1 and Dmd#2 were at first thoroughly cleaned in acetone, hysopropanol and de-ionized water. Deposition of 100 nm Au electrodes was performed by using a shadow mask and a SC7620 'Mini' Sputter operating at a working pressure of 10^{-3} Torr.

Once the measurements on the sample Dmd#1 were completed, Au contacts were removed from the diamond sample using a solution of *aqua regia*. New Al/Au electrodes with a thickness of 100/30 nm were then deposited onto Dmd#1 by thermal evaporation at the working pressure of 10^{-5} Torr. First a 100 nm Al layer was deposited followed by 30 nm of Au layer which served to prevent oxidisation of the Al itself.

After deposition of electrodes, samples were installed and fixed by vinyl-acetate non-conductive glue onto an in-house built printed circuit board (PCB) based on standard Fr-4 whose schematic is shown in Fig. 1. In order to minimize the influence of the properties of the PCB on the detector performances, dimensions of its copper pads, used to transfer the signals from the detectors to the preamplifier via SMA connector, were minimized. The noise generated by the PCB itself was in fact reduced by decreasing its capacitance and increasing as much as possible the resistance of the housing.

The sample electrodes were then connected to a gold wire of 25 μm in diameter (mounted on a K&S 4123 wedge bonder) by silver loaded conductive epoxy. The second end of the wire was next connected to the PCB copper pads by fast drying silver paint.

After successful fabrication of the diamond detectors, a set of measurements was then performed with the aim to:

- investigate the spectroscopic and charge transport properties of the diamond detectors Dmd#1 and Dmd#2 fabricated with Au electrodes;
- compare the properties of spectroscopic resolution of Dmd#1 and Dmd#2 with those obtained from the diamond detectors B10044 and B10045;
- compare the charge transport properties of the diamond sensor Dmd#1 fabricated first with Au and then with Al/Au electrodes.

[3] Samples provided by Dr. Elèni Berdermann (GSI, Darmstadt, Germany).

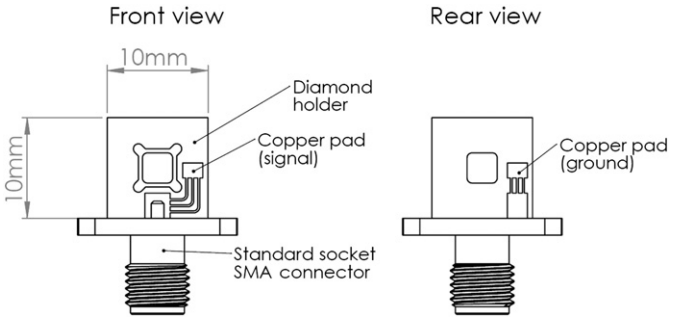

Fig. 1. Schematic of the detector PCB on which the diamond samples Dmd#1 and Dmd#2 were mounted. The diamond detector signals were fed to the preamplifier by a standard socket SMA connector.

3. Experimental setup

Spectroscopic and charge transport properties of the diamond detectors were investigated by irradiating the samples with a 5.4 MeV alpha-particles from ^{210}Po source whose activity was about 0.02 μCi when the experiments started. The devices were mounted, along the alpha source, inside a newly developed vacuum chamber (details can be found in a forthcoming paper [23]). Measurements were recorded at the pressure of ~10^{-2} Torr. Irradiations of the devices were performed in two different modes: by placing the biased or the grounded electrode in front of the alpha source. Henceforth these irradiation modes will be called "forward" or "backward", respectively. The diamond sensors were positioned carefully in front of the alpha source by means of a translation stage purchased from OWIS®.

The induced charge carriers i.e. the generated signal was measured either with a charge sensitive preamplifier (CANBERRA 2004) for spectroscopic characterization or with a current sensitive (DBA IV) preamplifier for a ToF characterization by using respectively RG-58 and RG-316 50 Ω impedance cables whose lengths (40 cm) are as short as possible to minimize the loss of signal.

For spectroscopic measurements (Fig. 2 (left)), the signal is further fed into the amplifier (CANBERRA AFT Research Amplifier 2025) and then displayed and acquired by an oscilloscope (Tektronix DPO4054) with a sampling time of 400 ps. For ToF measurements (Fig. 2 (right)), the DBA IV output is directly connected to the oscilloscope for signal visualization and acquisition. In both configurations, a NIM crate HV based supply C.A.E.N. N1470, connected to PC via USB/RS488 link, is used to supply the proper bias voltage to the diamond detectors.

Measurements on Dmd#1 and Dmd#2 detectors were performed in both bias polarities and in the voltage range of 8–160 V which corresponds to a maximum applied electric field of 17.8 kV/cm. Due to the geometry of the electrodes, the devices B10044 and B10045 were biased up to 300 V only which corresponds to an electric field of 6 kV/cm.

4. Data processing

Data processing of the detector signals was performed according to the type of preamplifier used during the experiments. For each voltage applied, a set of $N = 1000$ events was recorded from the oscilloscope and then stored in a file. The alpha particle rate measured by the detectors was below 10 s^{-1} as theoretically expected due to the geometry of the experimental setup.

4.1. Data processing with the charge sensitive preamplifier

The signal generated in the detector is directly integrated online by the charge sensitive preamplifier (CANBERRA 2004) and processed by the AFT Research Amplifier (CANBERRA 2025). The latter gives in output a semi-Gaussian pulse shape and a waveform of the resulting signal is stored in the PC via the digital oscilloscope Textronix