Fabrication and characterization of efficiency and radiation tolerance of 3D diamond detectors*

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3D diamond detectors combine the intrinsic properties of radiation tolerance of diamond with the advantages of the 3D architecture: a shorter inter-electrode distance and, consequently, lower trapping probability and operating voltage bias. 3D diamond electrodes can be fabricated by laser irradiation [1]. Femtosecond laser irradiation is required, because with longer laser widths, at least in the nanosecond range, a more defective modified material is obtained [2]. We have previously reported [1] on 3D monocrystalline Chemical Vapour Deposited (scCVD) diamond detectors, which exhibited a full collection to beta Minimum Ionizing Particles (MIP) at a voltage bias of a few volts, i.e., one order of magnitude lower than the bias level required for a two 2D sensor prepared with the same material. Since scCVD diamond are presently only obtained in very small areas, usually less than 1 cm^2, we decided to investigate the performances of 3D detectors fabricated on polycrystalline (pCVD) diamond, before and after neutron irradiation up to the highest fluence ever reported for diamond. From our results 3D diamond detectors seem the most radiation-hard detectors available at present. Heteroepitaxial growth of Diamond On Iridium (DOI) seems a very promising technique to obtain a high quality material, more homogeneous in its electronic properties than the pCVD one and not limited in surface area. A 3D sensor implemented on DOI material has also been tested and reported in this work.

Sample preparation ant tests

3D radiation sensors have been implemented on four pCVD samples (5×5×0.5 mm^3) by laser irradiation. Bulk electrodes were fabricated with an 800 nm Ti:Sa 30 fs laser with an energy density of 12 J/cm^2. The columns were started from one of the 5×5 mm2 faces and terminated about 80 μm away from the opposite one. They were connected by graphitic combs written on the surfaces with a Nd:YAG ns laser (schematics in Fig. 1). Two 3D sensors and a 2D reference sensor have been fabricated in each of the four sample as shown in Figure 1. The 3D electrodes are patterned by repeating two elementary cells of sizes 100×160 μm^2 (3D$_{100\times160}$ sensors) or 70×114 μm^2 (3D$_{70\times114}$ sensors). The CCE has been measured by means of a ^{90}Sr beta source, producing 18000 electron-hole pairs per MIP in the sample. The saturation collected charge was evaluated as 8700±300, 7200±300, and 7100±200 for the 3D$_{70x114}$, the 3D$_{100x160}$ and the 2D sensor, respectively.

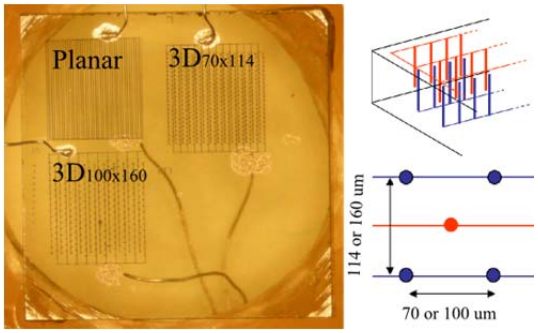

Figure 1: One pCVD sample with the 2D reference sensors and the two 3D sensors. On the right: the unit cell.

The 90% of these values were reached at 45 V, 60 V and 450 V, respectively. Hence, we assessed also for pCVD diamond, that the required bias voltage is an order of magnitude lower for the 3D than for the 2D sensors. The maximum signal for the 3D$_{100x160}$ and the 2D sensor have about the same value, but the 3D$_{70x114}$ sensors yield a collection efficiency about 20% higher. The CCE vs. voltage bias has been fitted by use of the following expression for the mean free path of the carriers:

$$\frac{1}{\lambda} = \frac{1}{\lambda_g} + \frac{1}{v\tau} \qquad (1)$$

where τ is the lifetime of the carriers, limited by the intra-grain defects, *v* is the drift velocity, which depends on the applied electric field (the bias voltage), λ_g is a mean path limited by the grain boundaries. The parameter values resulting from the fit of the 2D sensors data are τ = 4.3 ns and λ_g =160 μm. We assumed the same value of τ for the 3D sensors and evaluated numerical the CCE, by means of a three-dimensional finite element simulation of the electric field. The resulting values for λ_g were 29 and 25 μm for 3D$_{100x160}$ and 3D$_{70x114}$, respectively. The above values correlate well with the structure of the grains of the samples, which exhibit a truncated cone shape along the

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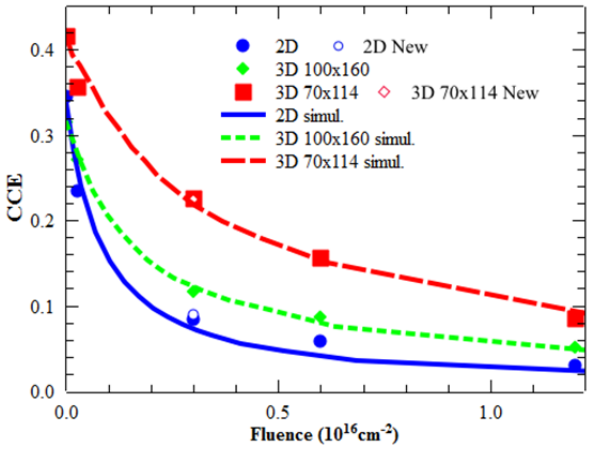

Figure 2: CCE vs, neutron irradiation fluence, 1 MeV equivalent.

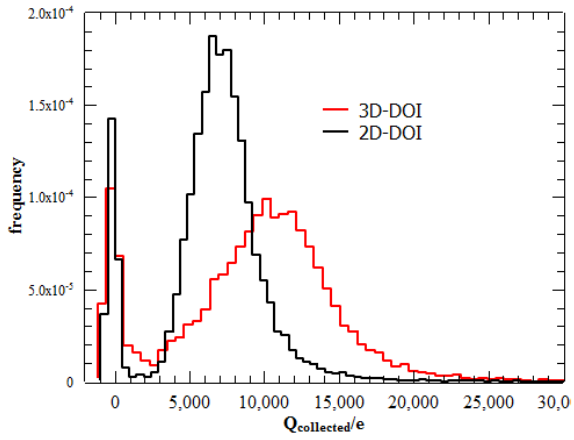

Figure 3: Pulse height spectrum of DOI 2D (at 600 V) and 3D (at 140 V) sensors.

diamond thickness, as evidenced by a morphological analysis carried out by optical profilometry. In the case of the 2D sensors the carriers drift almost parallel to the grain boundaries while in the case of 3D sensors they are strongly limited by the polycrystalline material in their path between the columnar electrodes.

Radiation Tolerance of the 3D sensors

We irradiated the four diamond samples at the experimental nuclear reactor of the Jožef Stefan Institute of Ljubljana, with fast neutron (neutrons of energy greater than 100 keV) at fluences ranging from 2.2×10^{14} cm^{-2} to 10^{16} cm^{-2}. Figure 2 shows the variation of the CCE with the equivalent fluence of 1 MeV neutrons, for the 2D and the 3D sensors. In order to prove that the all-carbon electrodes are not degraded by the neutron irradiation, we have also fabricated a new 2D sensor and new 3D $3D_{70x114}$ sensor, on the sample irradiated at 3×10^{15} cm^{-2} 1MeV-eq. neutrons. These new sensors exhibited the same response as the older ones after irradiation (see Fig. 2). The results from the planar sensors allow the immediate evaluation of the hardness factor *K* of the material, defined by the following relation:

$$\frac{1}{CCE} = \frac{1}{CCE_0} + KL\phi \qquad (2)$$

where ϕ is the fluence and L = 500 μm the thickness of the material. The result, K= (4.7±0.2) 10^{-18} μm^{-1} cm^2, is in good agreement with that previously reported in [3]. The data represented in Fig. 2 have been fitted by use of a modification of expression (1):

$$\frac{1}{\lambda} = \frac{1}{\lambda_g} + \frac{1}{v}\left(\frac{1}{\tau} + k\phi\right) \qquad (3)$$

A k value of about 1.5 10^{-6} cm^2 Hz can be used to fit consistently the three curves. The factor 3 in efficiency gained by the irradiated 3D detectors with the smaller pitch can be explained by the assumption that neutron damage results in the introduction of new intra-bandgap levels reducing the bulk mean lifetime of the charge carriers in the conduction and in the valence band, leaving unaffected the grain boundaries-limited mean free path λ_g.

Diamond On Iridium 3D sensors

A 3D sensor of the type $3D_{70\times114}$ has been implemented on a DOI plate together with a reference planar 2D sensor. The sample is about 500 μm thick, hence the overall generated charge from a MIP beta source is 18000 electrons. The collected charge was 7600 *e* corresponding to a CCE=42% for the 2D sensor at a bias voltage of 600 V. The 3D sensor yielded a mean value of 11000 *e*, corresponding to a CCE of 61%, at a bias voltage of 140 V. The relative gain from 2D to 3D is quite high. Figure 3 shows the pulse high spectrum for the two sensors at maximum collection. The DOI sample exhibits relevant pumping effect and polarization. The above results correspond to the pumped state (>100 Gy beta-irradiation). The 2D signal before pumping was 4000 *e* (21 % CCE). The study of the radiation tolerance of these sensors is under way.

References

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