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Laser induced nano-graphite electrical contacts on synthetic polycrystalline CVD diamond for nuclear radiation detection ☆

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ABSTRACT

We created a radiation detection device from a plate of high quality polycrystalline CVD diamond, fabricating nano-graphite electrical contacts on both diamond surfaces, by front and back irradiation with a 193 nm ArF excimer laser. We measured the electrode electrical resistance and evaluated a graphite resistivity of about $10^{-5}\ \Omega \cdot$ m. The ohmic nature of the contact graphite/diamond is established measuring the current–voltage characteristic that it is described by a linear behavior up to 90 V, by a Space Charge Limited (SCL) regime above 100 V and below 300 V, and by a Trap Filled Space Charge Limited (TFSCL) regime above 300 V. Finally, we investigated the device response in counting mode to a ^{60}Co γ-rays source and to a 120 GeV proton beam proving its capability to work as a fast nuclear radiation detector.

1. Introduction

Due to its exceptional electrical, thermal and optical properties, diamond is a very attractive material for radiation detection. Diamond can detect any kind of radiation that is more energetic than its band-gap of 5.47 eV, e.g., deep UV photons, X-rays, gamma rays, charged particles and neutrons. Because of its radiation hardness it needs no frequent replacements, it can operate at room temperature with no need for cooling, it has a resistivity several orders of magnitude greater than silicon, an extremely low leakage current and no need for p-type or n-type junctions as required for fabrication of silicon radiation detectors.

In this work, we studied a device based on detector grade polycrystalline CVD diamond plate with graphite electrical contacts fabricated on both faces of the diamond surfaces (called "Sandwich" configuration). The device was prepared by front and back irradiation of the diamond bulk by a 193 nm ArF excimer laser. In literature, several techniques to produce graphitic layers on diamond surface were suggested and realized such as by ion implantation [1].

The purpose of this work is to prove that electrodes made by laser graphitisation are Ohmic electrical contacts and that diamond device is capable to detect nuclear radiation in counting mode. Usually, Ohmic contacts for diamond detectors are made by metal deposition on diamond surface and followed by thermal annealing, in such a way to create a carbide layer [2].

2. Diamond graphitisation

In this work we used an ArF excimer laser beam (193 nm), which is absorbed by diamond surface and a graphitised layer can be created [3]. The absorbed laser energy is converted to lattice thermal energy making transition diamond to graphite energetically favorite [4]. At the same time laser light power density and laser pulses are kept lower than diamond ablation thresholds [5,6]. In literature, graphitisation process with ArF laser light on CVD diamond is reported [6]. The authors showed that a graphitic layer was created, and not another allotropic carbon structure, making use of micro-Raman scattering spectroscopy. In reference [7] we also use this technique on thermal grade polycrystalline CVD diamond to confirm the graphitic nature of the fabricated layers by ArF excimer laser.

2.1. Experimental procedure

We made a nuclear radiation detection device based on high quality Chemical Vapor Deposition (CVD) diamond acquired from Diamond Detectors Ldt. The sample was an undoped synthetic detector grade polycrystalline diamond with a thickness of 300 μm after chemical polishing and laser cut to a size of 0.5 × 0.5 cm^2. Chemical polishing was given by 15 min boiling diamond sample in a chromic acid powder dissolved in H_2SO_4 followed by 5 min boiling in piranha solution (50:50 H_2SO_4 and H_2O_2). The next step was the immersion of the sample in a boiling solution: 4:1:1 deionized (DI) water + HCl + H_2O_2 for 1 min. Finally the sample was blow dried in ultra dry N_2 gas for 7 min ≈40 W plasma in 50 cubic in chamber. In each case when we changed the boiling solution, prior to immerging the sample, we

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made a DI water rinse by ultrasonic bath. After chemical polishing diamond device was prepared by front and back irradiation of the diamond surfaces with a 193 nm ArF excimer laser (Lambda Physik LPX305i). The laser emitted 20 ns long light pulse with an energy of about 160 mJ/pulse at 10 Hz repetition rate. The laser beam with a transverse size of about 20 × 10 mm^2 was directed onto a homogenizer single matrix. The homogenized beam was then directly projected via a thin and plain convex lens onto the sample. The sample was placed on a holder fixed to an x-y handling stage automatically controlled by a 2D step motors (see Fig. 1). The focused image was a square of 3 mm^2 and the local laser fluence was about 5 J/cm^2 at the sample surface. The irradiation intensity was uniformly distributed within the radiation spot. The device was treated in air and at room temperature, because laser radiation produces a thin graphite layer which remains unoxidized on the sample surface [8]. In this way graphite electrodes with an area of about 3 × 3 mm^2 were made on both sides of diamond by using the automatic handling to scan the surfaces with a velocity of about 0.3 mm/s (see Fig. 2). The graphitic layers have a strong mechanical resistance. In fact, we couldn't remove graphite pieces by any mechanical instrument, such as cutters or knives.

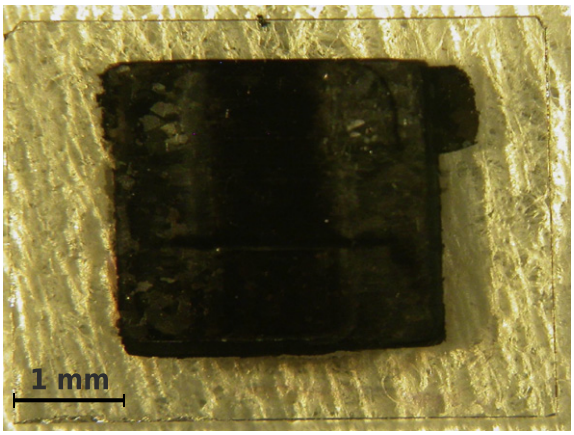

Fig. 2. Optical microscopy image of the polycrystalline CVD diamond detector grade plate of (5 × 5 × 0.3) mm^3 size after laser treatment. The black pad at the center of the device is the photo-generated graphite electrical contact created on diamond sample surfaces.

3. Results and discussion

3.1. Electrode electric resistance and thickness

We performed electric resistance measurements on graphite electrodes by a common digital multimeter KDM-350 CFT. We collected 100 measurements, along the horizontal and vertical directions, and we obtained a mean value for all cases of about 40 Ω. Consequently, we can assume that the irradiated area was uniform, despite three graphitic vertical bands, related to the laser scanning, are visible in Fig. 2. In order to evaluate the sheet resistance R_S for graphite layers, we applied the Van Der Pauw method [9] given by the equation:

$$e^{-\pi R_{vertical}/R_S} + e^{-\pi R_{horizontal}/R_S} = 1. \quad (1)$$

Assuming the condition $R_{vertical} = R_{horizontal} = R = 40\Omega$, we can calculate the sheet resistance R_S:

$$R_S = \frac{\pi R}{ln2} = \frac{\rho}{t}, \quad (2)$$

where the third member of Eq. (2) is given by the definition of sheet resistance, i.e. t is the sheet thickness of the graphite pad and ρ is the graphite electrical resistivity. We assume that t is about 60 nm for a laser fluence of about 3 J/cm^2 in reference [5] and estimate ρ from Eq. (2) that is about $10 \times 10^{-6}\ \Omega \cdot$ m quite consistent with graphite resistivity along the perpendicular direction of c-axis $9.8 \times 10^{-6}\ \Omega \cdot$ m [10].

3.2. Current–voltage characteristic of the device

We biased the device by fixing the sample between two gold arms soldered to a coaxial SMA connector. A small anodized aluminum box was used as a Faraday shield to avoid any type of electrical noise during dark current–voltage (IV) measurements. We employed the instrument 6487 Keithley picoammeter/voltage source with voltages ranging from 0 to 400 V. The plot of Fig. 3 shows the measured IV characteristic in log-log scale, where it is possible to see three different conduction mechanisms characterized by three different power law relations between current and voltage $I \propto V^k$ (see Table 1).

For voltages up to about 90 V the relation between I and V is approximately linear with a measured power index $k = 1.13 \pm 0.02$ (Table 1). This behavior can be explained assuming that the graphite/diamond interface behaves like a metal/semiconductor interface with an electrode work function smaller than the semiconductor work function. The diamond acts like a semiconductor with a band gap of about 5.47 eV and very high bulk electrical resistance. From the theory of Schottky contacts this gives a barrier free electrode interface and we obtain an Ohmic contact [11]. In this case electrons are injected from the external circuit by one electrode and collected by the other one. For small applied voltages, a space charge region

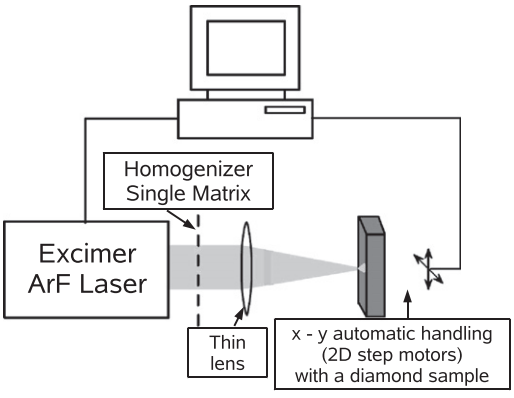

Fig. 1. Schematic of the experimental setup used to fabricate on a diamond plate sample a nano-graphite layer with high spatial precision by an excimer laser.

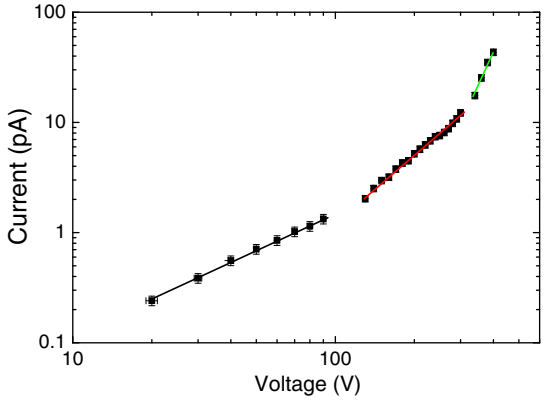

Fig. 3. Current–voltage characteristic of the graphitised device in log-log scale. The superimposed fits correspond to power law curves $I \propto V^k$ where the power law indexes k, for the three different voltage regimes, are reported in Table 1.