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Electrical and Raman-imaging characterization of laser-made electrodes for 3D diamond detectors

S. Lagomarsino [a,b,*], M. Bellini [c,d], C. Corsi [c], S. Fanetti [c], F. Gorelli [c,d], I. Liontos [c,e], G. Parrini [a,b], M. Santoro [c,d], S. Sciortino [a,b]

[a] National Institute of Nuclear Physics (INFN), Via B. Rossi 1–3, 50019 Sesto Fiorentino (FI), Italy
[b] Department of Physics and Astronomy, University of Florence, Via G. Sansone 1, 50019 Sesto Fiorentino (FI), Italy
[c] European Laboratory for Non-Linear Spectroscopy, Via Nello Carrara 1, 50019 Sesto Fiorentino (FI), Italy
[d] Istituto Nazionale di Ottica (INO-CNR), Largo Enrico Fermi 6, 50125 Firenze (FI), Italy
[e] Center for Plasma Physics and Lasers (CPPL), 1 E. Daskalaki Str., 74100 Rethymno (Crete), Greece

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ABSTRACT

Pulsed laser writing of graphitic electrodes in diamond is a promising technique for innovative particle detectors. Although of great relevance in 3D fabrication, the processes involved in sub-bandgap bulk irradiation are still not well understood. In this work, Raman imaging is exploited to correlate resistivity and graphitic content in 5–10 μm-thick electrodes, obtained both in the domains of femtoseconds and of nanoseconds of pulse duration. A wide interval of resistivities (60–900 mΩcm), according to the irradiation technique employed, are correlated with an sp^2 content of the modified material ranging over a factor 2.5. The stress distribution (maximum of about 10 GPa) and the presence of nanostructured sp^3 material around the graphitic columns have also been studied by Raman spectroscopy, and a rationale for the conductive behavior of the material is presented in terms of the thermodynamics of the process.

1. Introduction

Diamond detectors have long been envisaged as a promising solution for the challenges of radiation-harsh environments [1], and are now assuming an important role in R&D activities for the upgrade of the innermost tracking layers at the Large Hadron Collider (LHC) at CERN [2,3].

Qualities which make diamond a good candidate are the high saturation velocity of the charge carriers (double as high as for silicon), the low dielectric constant (5.6 vs. 11.9 for silicon), the extremely low leakage currents (at most 10^{-3} times those of silicon at the same bias voltages and temperatures), the high operative temperatures (tested [4] up to 80 °C) and, most importantly, a very high knock-on energy (about 50 eV, vs. 15 eV for silicon [5]), which contributes to an extremely favorable tolerance to radiation damage.

The advantages of diamond on silicon become even more effective in the 3D concept, developed in the last decades for silicon detectors [6,7]. In this architecture the charge collection is accomplished by narrow columnar electrodes which, being normal to the sensor larger surfaces, are nearly parallel to the path of the particles crossing the sensor itself. In this way both the response speed and the radiation tolerance take a further advance due to the shortening of the carrier paths, which depends on the distance between electrodes, which is much lower than the material thickness.

Although micro-fabrication of buried structures in diamond could also be possible with techniques employing MeV ion irradiation [8,9], pulsed laser graphitization is a technique which offers a much easier way to fabricate conductive channels orthogonal to the diamond surface [10]. This is, at present, the technique used for fabrication of 3D electrodes [11–13]. Nevertheless, despite the progresses in their implementation, graphitic structures in the diamond bulk exhibit a resistivity [14] two orders of magnitude higher than that reported for amorphous graphite, and the production of mechanical cracks in the diamond structure is still an issue. Moreover, although Raman analysis evidenced the presence of a graphitic phase in the buried conductive channels [14], there is a lack of quantitative studies correlating the Raman signature with the peculiar conductive behavior of this material.

In this work, we fabricated conductive structures both on the surface and in the bulk of diamond by means of pulsed laser irradiation with pulse widths in the nanosecond and the femtosecond domains, and we performed their quantitative characterization by means of micro-Raman imaging, with a resolution of ~2 μm. We extracted information about the local phase composition of the obtained structures in terms of sp^2 and sp^3-bonded carbon concentrations, evidencing a strong correlation between their conductivity and their graphitic content. Information about the local stress conditions was also obtained, from

* Corresponding author at: Department of Physics and Astronomy, University of Florence, Via G. Sansone 1, 50019 Sesto Fiorentino (FI), Italy.
E-mail address: lagomarsino@fi.infn.it (S. Lagomarsino).

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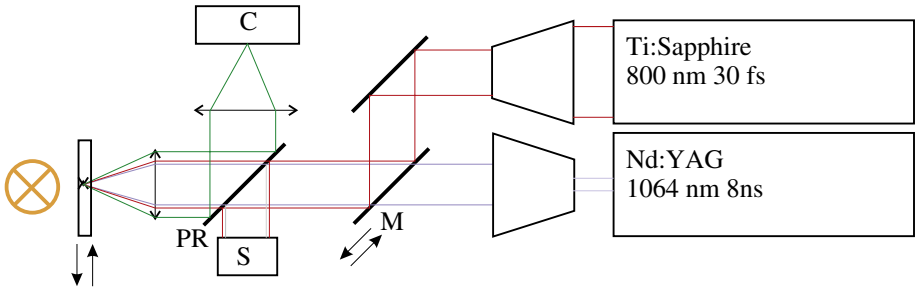

Fig. 1. Experimental setup used to fabricate graphitic structures in diamond. The sample is moved with respect to the laser beam by an *xyz* interfaced system. Mirror M allows to switch from one source to another. The images of the sample (illuminated in transparency) and the laser spot are collected by camera C. The power at target is monitored by power-meter S.

which a rationale for the different phase compositions of structures fabricated under different local conditions is given, involving the thermodynamics of the process.

2. Materials and methods

We used polycrystalline and monocrystalline detector-grade diamond samples by Element Six. This kind of material is usually defined [15] as a type IIa diamond exhibiting a minimum charge collection distance of about 200 μm. The pulsed laser sources employed were:

a) a Nd:YAG Q-switched source with an 8 ns pulse width, 1064 nm wavelength, pulse energies in the range 10–60 μJ and repetition rates from 1 to 10 kHz.
b) a Ti:sapphire femtosecond laser source of 30 fs pulse width, 800 nm wavelength, pulse energies between 3 and 18 μJ and repetition rate of 1 kHz.

Both beams have been focused either on the diamond surface or in the diamond bulk with microscope objectives optimized for the wavelengths of interest. The waist in the two cases had about the same diameter, in the range 8–10 μm. The same objectives were also used to acquire optical micrographs of the sample during the irradiation, with the aid of a suitably arranged microscope system (see Fig. 1).

The sample position was controlled by a three-axis displacement stage driven by computerized step motors with micrometric resolution.

The experimental setup has been arranged in a way that it is possible to switch from a laser source to the other without moving the sample and allowing, if necessary, an easy integration of the two techniques in processing the same device.

The graphitic structures we implemented are: A) superficial conductive tracks obtained by keeping the front surface of the diamond in the focal plane of the objective and translating it at constant velocity (*xy*-directions). B) Buried conductive wires obtained by focusing the laser beam on the back diamond surface and moving the focus at constant velocity perpendicularly to the surface, across the bulk for 100–500 μm (*z*-direction).

Fig. 2A shows a 3D structure made of staggered wires, fabricated with the fs-laser source, connected with two interdigitated superficial graphitic combs engraved with the nanosecond laser irradiation. We fabricated structures of up to 310 columns in 2-dimensional arrays

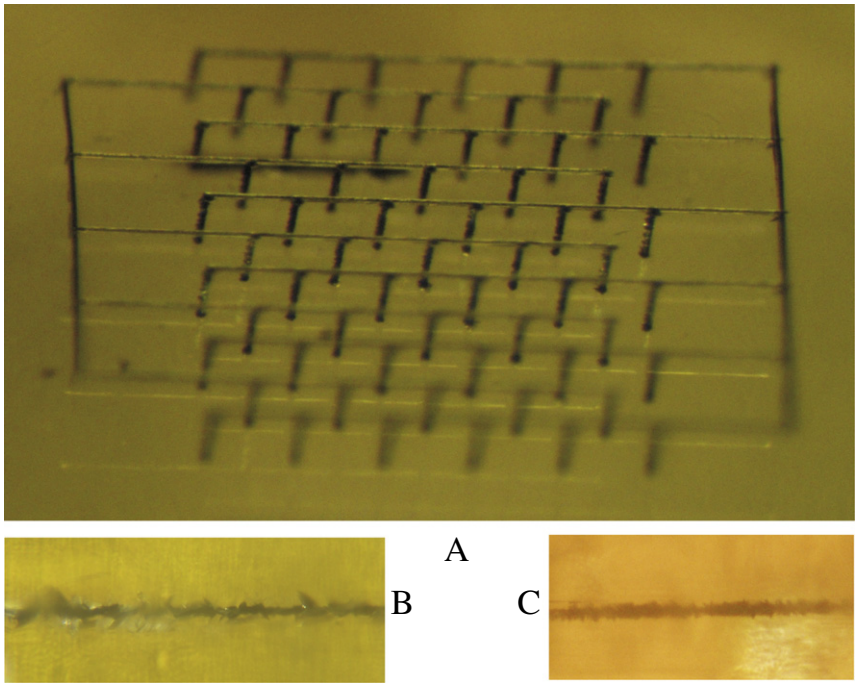

Fig. 2. A: 1 × 1 mm^2 3D structure consisting of 36 + 25 = 61 staggered vertical wires 500 μm long, connected to interdigitated graphitic combs on the same surface of diamond. The distance between the comb teeth is 100 μm. The wires appear to be shorter than they are because of the refraction. B: image of a wire fabricated with the nanosecond laser source. C: image of a wire fabricated with the femtosecond laser source. The image of the wire in C appears to be sharper because of the refraction on the cracks created in B by the nanosecond source.