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Direct fabrication and IV characterization of sub-surface conductive channels in diamond with MeV ion implantation

P. Olivero[1], G. Amato[2], F. Bellotti[2], S. Borini[2], A. Lo Giudice[1], F. Picollo[1], and E. Vittone[1,a]

[1] Experimental Physics Department, Centre of Excellence “Nanostructured Interfaces and Surfaces”, University of Torino, and INFN sez. Torino Via P. Giuria 1, 10125 Torino, Italy
[2] Quantum Research Laboratory, Istituto Nazionale di Ricerca Metrologica, Strada delle Cacce 91, 10135 Torino, Italy

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Abstract. In the present work we report about the investigation of the conduction mechanism of sp^2 carbon micro-channels in single crystal diamond. The structures are fabricated with a technique which employs a MeV focused ion-beam to damage diamond in conjunction with variable thickness masks. This process changes significantly the structural properties of the target material, because the ion nuclear energy loss induces carbon conversion from sp^3 to sp^2 state mainly at the end of range of the ions (few micrometers). Furthermore, placing a mask with increasing thickness on the sample it is possible to modulate the channels depth at their endpoints, allowing their electrical connection with the surface. A single-crystal HPHT diamond sample was implanted with 1.8 MeV He^+ ions at room temperature, the implantation fluence was set in the range $2.1 \times 10^{16}-6.3 \times 10^{17}$ ions cm^{-2}, determining the formation of micro-channels with a graded level of damage extending down to a depth of about 3 μm. After deposition of metallic contacts at the channels' endpoints, the electrical characterization was performed measuring the I-V curves at variable temperatures in the 80−690 K range. The Variable Range Hopping model was used to fit the experimental data in the ohmic regime, allowing the estimation of characteristic parameters such as the density of localized states at the Fermi level. A value of 5.5×10^{17} states cm^{-3} eV^{-1} was obtained, in satisfactory agreement with values previously reported in literature. The power-law dependence between current and voltage is consistent with the space charge limited mechanism at moderate electric fields.

1 Introduction

In the 70s, the pioneering work of Vavilov et al. [1] triggered a series of studies on the effect of ion induced damage on the electrical conduction properties of diamond. Since the early years, Hauser et al. demonstrated that the electrical properties of ion implanted diamond layers were similar to those of amorphous carbon produced by sputtering graphite [2,3]. In the following decades, extensive work has been conducted on this topic, elucidating the characteristic conduction mechanisms in structurally damaged diamond. Such processes can be divided into two characteristic regimes: when the damage density exceeds a critical level (usually referred as “graphitization threshold” [4]), after high temperature thermal annealing the damaged structure exhibits ohmic conductivity. Examples of such behavior in buried conductive channels created with MeV ion deep implantations can be found in [5] and [6]. On the other hand, when the damage density does not reach a critical value and/or the sample is not annealed at high temperature, the conduction mechanism in the resulting amorphized layers can be described with more articulated models based on variable range hopping, as discovered by Hauser et al. [2,3] and investigated in further details by Prins [7,8]. While in the former case the nature of the conductivity is unambiguously attributed to metallic charge transport in a graphite-like medium, in the latter case more articulate models must be adopted, as reported in detailed works by Kalish et al. [9–11] and other groups [12–14], where a number of characteristic energies for hopping transitions were extracted from the temperature dependence of the resistivity. While the adoption of different models to the description of temperature-dependent current-voltage characteristics of amorphized diamond is still under investigation, it is worth stressing that a very limited amount of works were focused on the fabrication of sub-surface conductive layers in diamond by means of high energy MeV ions. Examples of such works can be found in [5,6] for graphitization at high damage levels, and in [15] for sub-graphitization damage levels.

In the present work we report about the direct fabrication of sub-surface damaged microchannels in single crystal diamond with MeV ion implantation, which was performed through variable-thickness masks in order to

[a] e-mail: ettore.vittone@unito.it