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Kelvin probe characterization of buried graphitic microchannels in single-crystal diamond

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In this work, we present an investigation by Kelvin Probe Microscopy (KPM) of buried graphitic microchannels fabricated in single-crystal diamond by direct MeV ion microbeam writing. Metal deposition of variable-thickness masks was adopted to implant channels with emerging endpoints and high temperature annealing was performed in order to induce the graphitization of the highly-damaged buried region. When an electrical current was flowing through the biased buried channel, the structure was clearly evidenced by KPM maps of the electrical potential of the surface region overlying the channel at increasing distances from the grounded electrode. The KPM profiling shows regions of opposite contrast located at different distances from the endpoints of the channel. This effect is attributed to the different electrical conduction properties of the surface and of the buried graphitic layer. The model adopted to interpret these KPM maps and profiles proved to be suitable for the electronic characterization of buried conductive channels, providing a non-invasive method to measure the local resistivity with a micrometer resolution. The results demonstrate the potential of the technique as a powerful diagnostic tool to monitor the functionality of all-carbon graphite/diamond devices to be fabricated by MeV ion beam lithography. © *2015 AIP Publishing LLC*. [http://dx.doi.org/10.1063/1.4905425]

I. INTRODUCTION

The existence at ambient conditions of different allotropic forms of carbon with radically different structural and electrical properties (most importantly, diamond and graphite) is an important feature allowing the fabrication of all-carbon devices for various technological applications. In this context, the employment of focused MeV ion beams in diamond is a versatile tool to create different structural forms of carbon by the progressive conversion of the sp^3-bonded diamond lattice to a sp^2-bonded amorphous/graphitic phase.[1] This effect is related to the ion-induced formation of structural defects (vacancies, interstitials, and more extended complexes) in the crystal lattice, with a strongly non-uniform depth profile that determines the creation of highly damaged layers at a depth of the order of micrometer within the crystal bulk, depending on the ion energy (see, for example, Fig. 1). Ion beam implantation in diamond was extensively applied for the fabrication of a broad range of devices: waveguides,[2,3] photonic structures,[4–6] and micromechanical resonators.[7,8] In particular, the possibility of creating graphitic and electrically conductive regions allowed the fabrication of infrared radiation emitters,[9] field emitters,[10] bolometers,[11] biosensors,[12] and ionizing radiation detectors.[13,14]

The charge conduction mechanisms in amorphized/graphitized diamond have been investigated in previous works.[15–17] In the case of buried conducting layers and channels, the analyses were based on current-voltages characterizations carried out by probing 2 or 4 terminals emerging at the surface through conductive columns fabricated by laser induced graphitization,[18] high-voltage-induced thermal breakdown,[19] or by modulating ion penetration depths by multiple energy ion implantation[20] or variable-thickness metallic masks.[21]

However, to our best knowledge, because of the inaccessibility of the buried conductive regions, no local microscopic analyses of their electrical properties have been so far performed. They could be effectively explored by scanning probe microscopy techniques such as Electric Force Microscopy (EFM)[22] and Kelvin Probe Microscope (KPM),[23,24] but these techniques are mainly used to investigate the surface electrical properties of semiconductors and

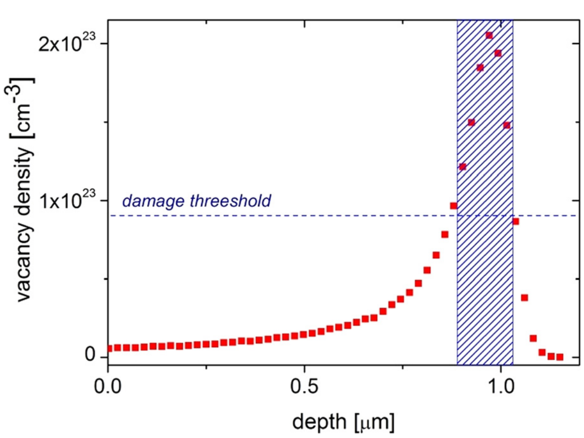

FIG. 1. Vacancy density profile induced by 1.2 MeV He^+ ions at a fluence of 1×10^{17} cm^{-2} in diamond covered by a 1-μm-thick copper layer as calculated by SRIM2013.00 Monte Carlo simulations. The dashed region in the graph represents the highly damaged buried region where the thermal annealing induces the graphitization, due to the vacancy densities exceeding a critical threshold.

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