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An analytical model for the mechanical deformation of locally graphitized diamond

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ABSTRACT

We propose an analytical model to describe the mechanical deformation of single-crystal diamond following the local sub-superficial graphitization obtained by laser beams or MeV ion microbeam implantation. In this case, a local mass–density variation is generated at specific depths within the irradiated micrometric regions, which in turn leads to swelling effects and the development of corresponding mechanical stresses. Our model describes the constrained expansion of the locally damaged material and correctly predicts the surface deformation, as verified by comparing analytical results with experimental profilometry data and Finite Element simulations. The model can be adopted to easily evaluate the stress and strain fields in locally graphitized diamond in the design of microfabrication processes involving the use of focused ion/laser beams, for example to predict the potential formation of cracks, or to evaluate the influence of stress on the properties of opto-mechanical devices.
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1. Introduction

A relevant number of works has concentrated in the recent years on the application of MeV-ion-induced graphitization to fabricate and functionalize microstructures and devices in single-crystal diamond, including bio-sensors [1], ionizing radiation detectors [2,3], bolometers [4], nano-electromechanical systems (NEMS) [5,6], photonic structures [7–10] and optical waveguides [11,12]. Laser-induced graphitization has also been employed to fabricate metallo-dielectric structures [13] and ionizing radiation detectors [14] in diamond. This versatility is due to the fact that both MeV-ion and laser focused beams can locally deliver high power densities in specific regions within the diamond bulk with micrometric spatial resolution in all directions, thus creating confined regions where the diamond lattice structure is critically damaged. In these regions, annealing leads to the graphitization of the damaged structure, whilst the remaining surrounding material is largely restored to pristine diamond, so that well-defined structures can be created by selectively etching the graphitized regions [3,5–12] or taking advantage of the optical/electrical properties of the graphitized regions [1,2,4,13,14]. At significantly lower damage densities (i.e. well below the graphitization threshold), ion implantation was employed to tailor the optical properties of diamond either by modifying its refractive index [15–18] to directly write/fine-tune waveguiding structures [19] and photonic structures [20], or to induce spectral shifts in the emission of luminescent centres [21]. In all of these cases, accurate knowledge is required of the modification of the diamond lattice structure as a function of implantation/irradiation parameters and in-situ/post-processing annealing conditions, in order to exactly localize the graphitized/modified layer and predict its structural effects on the surrounding material.

As far as ion implantation is concerned, the critical damage level (D_C) above which diamond is subject to permanent amorphization and subsequent graphitization upon thermal annealing is referred to as the "graphitization threshold" [22], and its dependence on implantation parameters has been ascertained (e.g. depth and/or local strain and self-annealing) [23–27]. An observable effect of ion implantation and laser irradiation in diamond is surface swelling, due to the density variation in the sub-superficial damaged regions and the corresponding constrained volume expansion [28–30]. It is therefore possible to analyze this effect

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