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Characterization of the recovery of mechanical properties of ion-implanted diamond after thermal annealing

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ABSTRACT

Due to their outstanding mechanical properties, diamond and diamond-like materials find significant technological applications ranging from well-established industrial fields (cutting tools, coatings, etc.) to more advanced mechanical devices as micro- and nano-electromechanical systems. The use of energetic ions is a powerful and versatile tool to fabricate three-dimensional micro-mechanical structures. In this context, it is of paramount importance to have an accurate knowledge of the effects of ion-induced structural damage on the mechanical properties of this material, primarily to predict potential undesired side-effects of the ion implantation process, and possibly to tailor the desired mechanical properties of the fabricated devices. We present an Atomic Force Microscopy (AFM) characterization of free-standing cantilevers in single-crystal diamond obtained by a FIB-assisted lift-off technique, which allows the determination of the Young's modulus of the diamond crystal after the MeV ion irradiation process concurrent to the fabrication of the microstructures, and subsequent thermal annealing. The AFM measurements were performed with the beam-bending technique and show that the thermal annealing process allows for an effective recovery of the mechanical properties of the pristine crystal.

1. Introduction

MeV ion implantation has been widely exploited in recent years for the micro-fabrication of single-crystal diamond, through the implementation of the so-called "lift-off technique" [1–4]. This technique can be effectively adopted to fabricate micro-mechanical structures in single-crystal diamond, with applications ranging from high-frequency MEMS devices [5–11] to opto-mechanical resonators [12], thus taking advantage of the extreme mechanical properties of diamond [13]. Recently, the latter topic attracted significant interest due to the outstanding properties of nitrogen-vacancy centers in diamond [13], whose spin-dependent optical transition can effectively couple with local mechanical stresses [14–16]. To this end, various different techniques have been employed to fabricate opto-mechanical resonators in diamond [17–20].

In the case of the lift-off technique, the fabrication process is based on the local conversion of diamond to a sacrificial graphitic layer through MeV-ion-induced damage and subsequent thermal annealing [4]. The fabrication technique is very versatile, because the local induced damage density can be controlled by varying implantation parameters (namely ion energy, species and fluence). Nonetheless, a residual damage density (and related mechanical stress) is induced in the non-sacrificial regions as a side-effect of the fabrication technique [21]. Similarly, with other fabrication techniques [17–20], a residual damage can be induced in the fabricated opto-mechanical microstructures, particularly if ion implantation is adopted to induce the formation of nitrogen-vacancy centers [22].

For these reasons, it is necessary to accurately estimate deformation and stress levels to reliably design and fabricate MEMS structures. Moreover, the variation of elastic properties of damaged diamond as a function of induced damage density and post-processing (annealing) parameters remains to be clarified. In particular the Young's modulus of ion-implanted diamond can potentially vary between that of pristine diamond (>1 TPa, in the presence of no damage) and that of amorphous carbon (~10 GPa, for full amorphization), i.e. over two orders of magnitude. Clearly, this large variation in elastic properties is likely to strongly affect modeling results in the fabrication of mechanical and opto-mechanical resonators. Attempts have been made to experimentally derive the variation of elastic properties of diamond as a function of induced damage, but only indirect estimations with limited accuracy have been obtained [23]. This lack of experimental data is partly due

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