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Original

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1 **AFM characterization of free-standing diamond microcantilevers for the investigation of the**
2 **damage-induced variation of Young's modulus**

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15
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17 microscopy

18
19 **Abstract**

20 Due to their outstanding mechanical properties, diamond and diamond-like materials find
21 significant technological applications ranging from well-established industrial fields (cutting tools,
22 coatings, etc.) to more advanced mechanical devices as micro- and nano-electromechanical systems.
23 The use of energetic ions is a powerful and versatile tool to fabricate three-dimensional
24 micro-mechanical structures. In this context, it is of paramount importance to have an accurate
25 knowledge of the effects of ion-induced structural damage on the mechanical properties of this

26 material, firstly to predict potential undesired side-effects of the ion implantation process, and
27 possibly to tailor the desired mechanical properties of the fabricated devices. We present an Atomic
28 Force Microscopy (AFM) characterization of free-standing cantilevers in single-crystal diamond
29 obtained by a FIB-assisted lift-off technique, which allows a determination of the Young's modulus
30 of the diamond crystal after the MeV ion irradiation process concurrent to the fabrication of the
31 microstructures. The AFM measurements were performed with the beam-bending technique,
32 showing that the thermal annealing process adopted during the microfabrication process allows for
33 an effective recovery of the mechanical properties of the pristine crystal.

34

35 **1. Introduction**

36 MeV ion implantation has been widely exploited in recent years for the micro-fabrication of
37 single-crystal diamond, through the implementation of the so-called "lift-off technique" [1-4]. This
38 technique can be effectively adopted to fabricate micro-mechanical structures in single-crystal
39 diamond, with applications ranging from high-frequency MEMS devices [5-11] to opto-mechanical
40 resonators [12], thus taking advantage of the extreme mechanical properties of diamond [13].
41 Recently, the latter topic attracted significant interest due to the outstanding properties of
42 nitrogen-vacancy centers in diamond [14], whose spin-dependent optical transition can effectively
43 couple with local mechanical stresses [15-17]. To this end, various different techniques have been
44 employed to fabricate opto-mechanical resonators in diamond [18-21].

45 In the case of the lift-off technique, the fabrication process is based on the local conversion of
46 diamond to a sacrificial graphitic layer through MeV-ion-induced damage [4]. The fabrication
47 technique is very versatile, because the local induced damage density can be controlled by varying
48 implantation parameters (namely, ion energy, species and fluence). Nonetheless, a residual damage
49 density (and related mechanical stress) is induced in the non-sacrificial regions as a side-effect of
50 the fabrication technique [22]. Similarly, also with other fabrication techniques [18-21], a residual

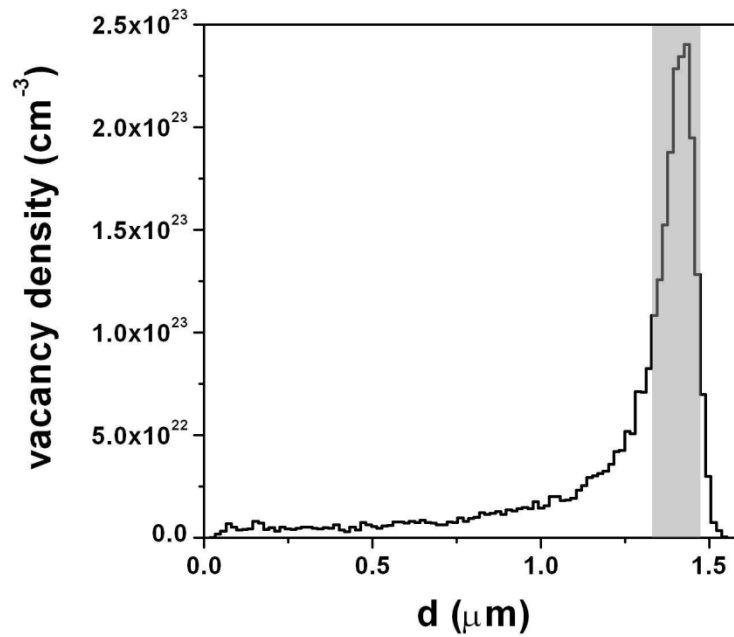
51 damage can be induced in the fabricated opto-mechanical microstructures, particularly if ion
52 implantation is adopted to induce the formation of nitrogen-vacancy centers [23]
53 For these reasons, it is necessary to accurately estimate deformation and stress levels to reliably
54 design and fabricate MEMS structures. Moreover, the variation of elastic properties of damaged
55 diamond as a function of induced damage density and post-processing (annealing) parameters
56 remains to be clarified. In particular the Young's modulus of ion-implanted diamond can potentially
57 vary between that of pristine diamond (>1 TPa, in the presence of no damage) to that of amorphous
58 carbon (~ 10 GPa, for full amorphization), i.e. over two orders of magnitude. Clearly, this large
59 variation in elastic properties is likely to strongly affect modelling results in the fabrication of
60 mechanical and opto-mechanical resonators. Attempts have been made to experimentally derive the
61 variation of elastic properties of diamond as a function of induced damage, but only indirect
62 estimations with limited accuracy have been obtained [24]. This lack of experimental data is partly
63 due to its high Young's modulus, which makes it difficult to perform indentation experiments.
64 Here, we perform a study of the elastic properties of ion-implanted diamond by means of Atomic
65 Force Microscope (AFM) measurements on free-standing cantilever structures microfabricated in
66 single-crystal diamond with FIB-assisted lift-off technique [3, 4].

67

68 **2. Micro-fabrication**

69 An artificial diamond sample grown by High Pressure High Temperature (HPHT) by ElementSix
70 (UK) was employed in this work. The sample is $2.6 \times 2.6 \times 0.5$ mm³ in size and is classified as type
71 Ib, on the basis of a nominal concentration of substitutional nitrogen ~ 500 ppm. The sample is cut
72 along the [100] crystal direction and is optically polished on one of the two opposite large faces.
73 The sample was implanted at room temperature across one of the polished surfaces with 800 keV
74 He⁺ ions at the AN2000 accelerator of the INFN National Laboratories of Legnaro with a focused
75 ion beam, in order to deliver a fluence of 1×10^{17} cm⁻². The microbeam spot was ~ 10 μ m in

76 diameter, and was raster-scanned to implant a rectangular area of $\sim 500 \times 200 \mu\text{m}^2$. The high density
77 of damage induced by ion implantation promotes the conversion of the diamond lattice into an
78 amorphous phase within a layer which is located at $\sim 1.4 \mu\text{m}$ below the sample surface, as shown in
79 Fig. 1.



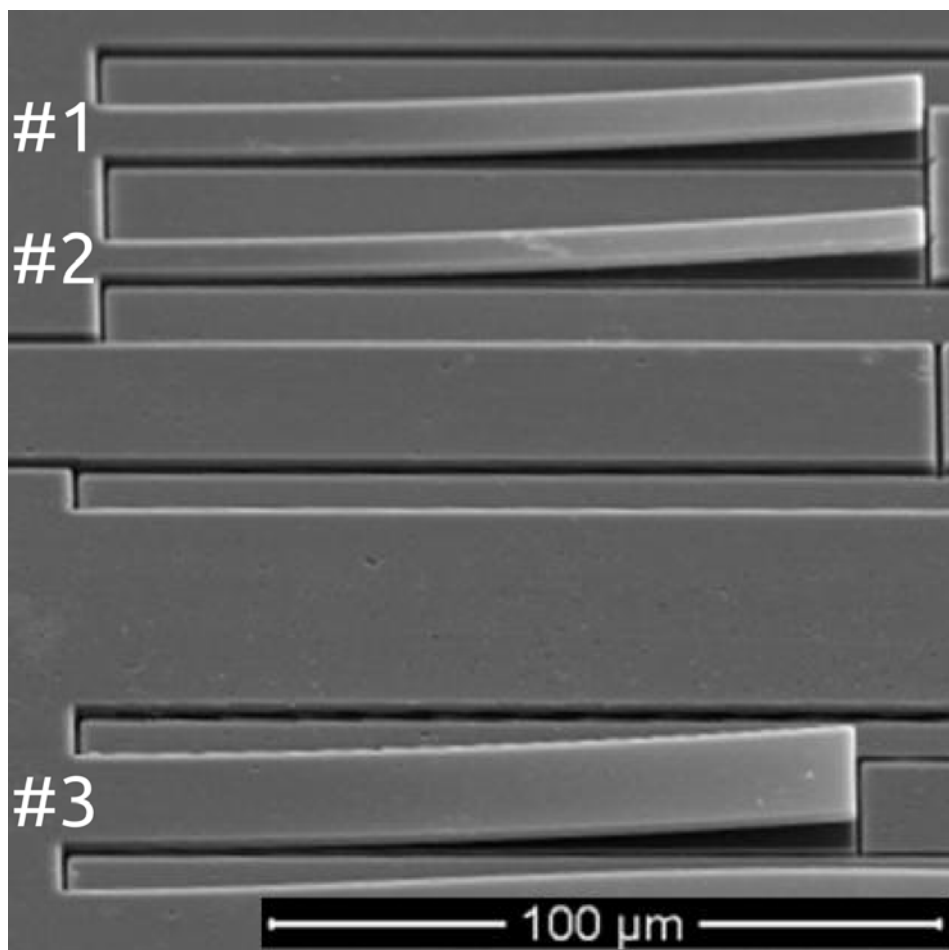
80

81 *Fig. 1: depth profile of the vacancy density induced by 800 keV He⁺ ion implantation at fluence*
82 *$1 \times 10^{17} \text{ cm}^{-2}$, as evaluated with SRIM2013.00 Monte Carlo code [25] and assuming a linear*
83 *dependence of the induced vacancy density from the implantation fluence [26].*

84

85 The sample was then annealed in high vacuum ($\sim 10^{-6}$ mbar) at 1000 °C for 1 h, to convert the
86 highly-damaged regions located at the ion end of range to a graphitic phase while removing the
87 structural sub-threshold damage introduced in the layer overlying the damaged region. Following
88 the fabrication scheme described in [1], FIB milling with 30 keV Ga⁺ ions was subsequently
89 performed on the implanted area, to expose the sub-superficial graphitic layer to the subsequent
90 etching step, while defining the geometries of three different cantilever structures characterized by
91 different widths (see Fig. 2). A thin Au film was deposited on the sample surface to avoid charge
92 effects during FIB micro-machining. The sample was then exposed to contact-less electrochemical

93 etching [27]: the sample was immersed for several hours in de-ionized water with the region of
94 interest comprised between two close (i.e. few millimeters) Pt electrodes kept at a DC voltage
95 difference of ~ 100 V. The process resulted in the selective removal of the sacrificial graphitic layer
96 and in the creation of free-standing cantilever structures with a lateral geometry defined by the
97 previous FIB micromachining, i.e. a length of $117\ \mu\text{m}$ for cantilevers #1 and #2 and of $111\ \mu\text{m}$ for
98 cantilever #3. The widths of cantilevers #1, #2 and #3 were respectively $13\ \mu\text{m}$, $9\ \mu\text{m}$ and $22\ \mu\text{m}$.
99 The thickness of all cantilevers corresponded to the penetration depth of the employed $800\ \text{keV}$
100 ions, i.e. $1.3\ \mu\text{m}$. As shown in Fig. 2, all cantilevers are slightly bent by the inner stresses caused by
101 residual damage induced during the fabrication process within the “cap layer” comprised between
102 the sub-superficial graphitic layer and the sample surface.

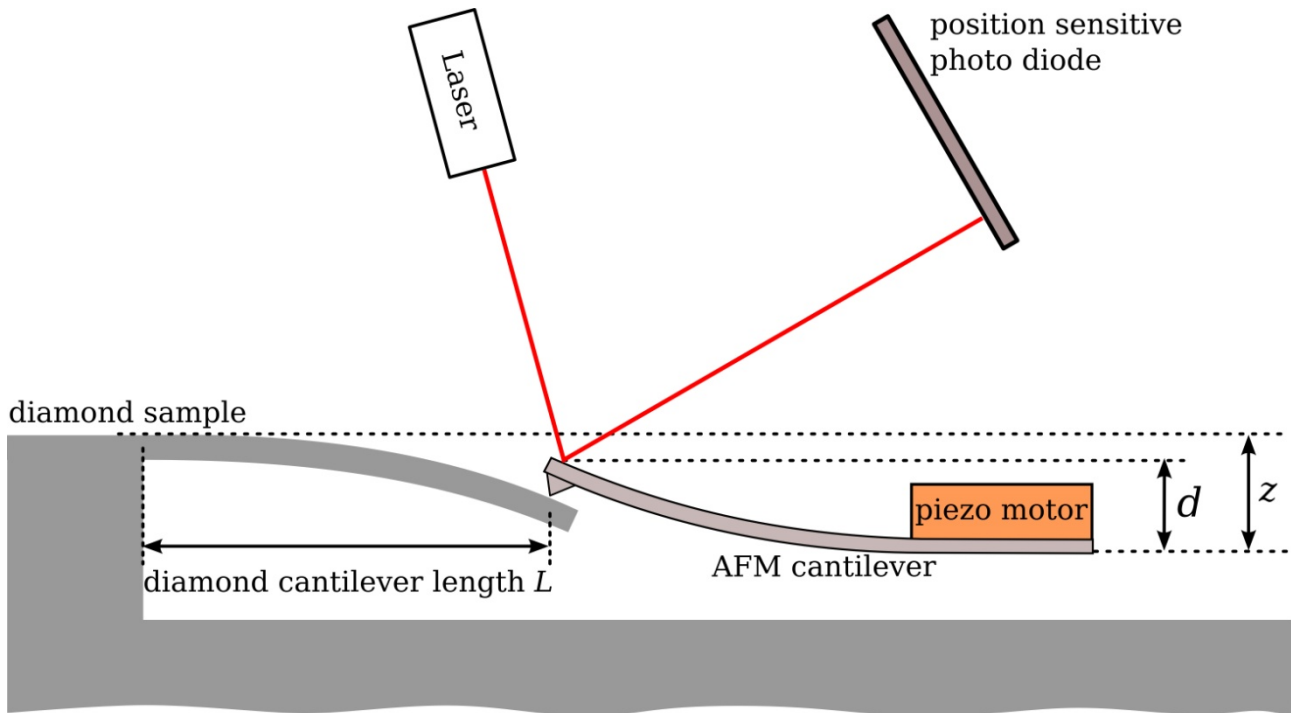


103

104 *Fig. 2: SEM micrograph of the three free-standing cantilever structures fabricated in single-crystal*
105 *diamond by means of the FIB-assisted lift-off technique.*

106 3. AFM Characterisation

107 In order to determine the Young's modulus of the diamond, a beam-bending method was employed
 108 [28-30]. The method consists in loading the microstructures using an AFM cantilever. As shown in
 109 Fig. 3, the deflection d of the probing AFM cantilever for the displacement z of the piezomotor is
 110 measured by means of a laser diode and a position-sensitive photodiode (Veeco Dimension 3100).



111
 112 *Fig. 3: Schematic representation (not to scale) of the beam-bending technique employed to measure*
 113 *the Young's modulus of the microfabricated diamond cantilevers. An AFM cantilever loads the*
 114 *diamond microstructure at a length L , while the displacement d of the AFM cantilever is measured*
 115 *as a function of the piezomotor displacement z .*

116
 117 The effective stiffness k_{eff} of the system based on the coupling of the two cantilever structures is
 118 measured by recording approach curves. The effective stiffness k_{eq} is equal to:

$$119 \quad k_{eff} = \frac{1}{\frac{1}{k_{AFM}} + \frac{1}{k_{diam}}} \quad (1)$$

120
 121

122 where k_{AFM} and k_{diam} are respectively the stiffness values of the probing AFM cantilever and of the
 123 diamond cantilever under test. The d/z value is equal to [28]:

124

$$125 \quad \frac{d}{z} = \frac{k_{eff}}{k_{AFM}} \quad (2)$$

126

127 Thus, the stiffness of the beam under test can be determined, if the stiffness of the AFM cantilever
 128 is known. The adopted AFM cantilever is a single-crystalline silicon cantilever (NCLR,
 129 Nanoworld). Its geometry is precisely determined by means of SEM microscopy and its stiffness
 130 was evaluated as $k_{AFM} = (57.0 \pm 1.2) \text{ N m}^{-1}$.

131 The three diamond cantilevers mentioned above were investigated, and for each of them the
 132 stiffness values were measured in correspondence of several (i.e. >5) different positions along the
 133 cantilever axis. The stiffness of the diamond cantilever is determined by the following formula:

134

$$135 \quad k_{diam} = \frac{3 \cdot E \cdot I}{(1 - \nu^2) \cdot L^3} \quad (3)$$

136

137 where E is its Young's modulus, I is its areal moment of inertia, ν is its Poisson's ratio, and L is its
 138 length, i.e. the distance from the clamping point where the load is applied [31]. Due to a possible
 139 systematic error in the determination of the cantilever length and the finite stiffness of the cantilever
 140 fixture, we used the following correction to fit the k_{diam} vs L trend [32, 33]:

141

$$142 \quad k_{diam} = \frac{3 \cdot E \cdot I}{(1 - \nu^2) \cdot (L + L_0)^3} \quad (4)$$

143

144 The Poisson's ratio was estimated with the value corresponding to pristine undamaged diamond, i.e.
 145 0.105 [34], considering bending along the (100) direction, consistently with the well-defined
 146 orientation of the structure with respect to the crystal orientation. The geometry of the diamond

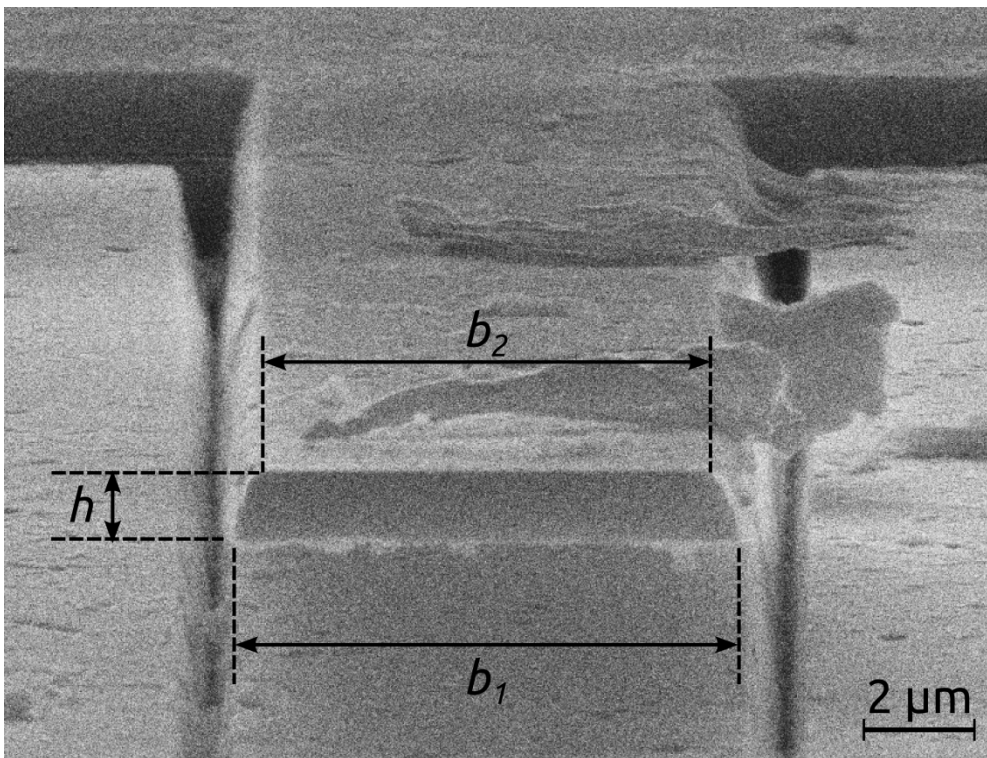
147 beams was measured by means of SEM microscopy and the moment of inertia I for each cantilever
148 was calculated by taking into consideration their slightly trapezoidal beam cross-section (see Fig.
149 4), as follows [35]:

150

$$151 \quad I = \frac{h^3}{36} \cdot \frac{(b_1^2 + 4 \cdot b_1 \cdot b_2 + b_2^2)}{(b_1 + b_2)} \quad (5)$$

152

153 where h is the thickness of the cantilever and b_1 and b_2 are the two widths of the trapezoidal cross
154 section (see Fig. 4). The Young's modulus E of the diamond cantilever is then calculated using by
155 fitting the k_{diam} vs L trend with Eq. (4), in which the moment of inertia I is estimated as reported in
156 Eq. (5).



157

158 *Fig. 4: SEM micrograph of the trapezoidal cross-section of cantilever #2. h is the thickness of the*
159 *cantilever, while b_1 and b_2 are respectively the lower and upper widths of the cross section.*

160

161 Representative results of the k_{diam} vs L measurements relative to cantilever #3 are reported in
162 Fig. 5a, together with the fitted curve (see using Eq. (4)). The fit of the experimental data is very

163 satisfactory, yielding a Young's modulus value of $E = (9.6 \pm 1.1) \times 10^2$ GPa. The Young's moduli
 164 for the three cantilevers are reported in Fig. 5b, together with their weighted average value and its
 165 relevant uncertainty, as well as with a comparison with the reference value of pristine single-crystal
 166 diamond. In the case of cantilever #1, the discrepancy between the measured Young's modulus and
 167 the reference value is statistically significant, and the calculated stiffness value is exceedingly high.
 168 This can be tentatively attributed to a non-ideal detachment of the beam from the substrate during
 169 the etching fabrication process, which potentially increases the stiffness of the structure and yields
 170 incorrect values when using the above formulas. Nevertheless, the weighted average of the three
 171 Young's modulus values yields an estimation of $E = (1.11 \pm 0.08)$ TPa, which is statistically
 172 compatible with the reference value in literature for single-crystal diamond, i.e. 1.05 TPa [36]. This
 173 compatibility is remarkable, particularly if it is considered that we assumed a value of the Poisson's
 174 ratio corresponding to the pristine diamond, thus introducing a potential systematic error.
 175 Since single-crystal diamond is mechanically anisotropic [34], with, the Young's modulus in the
 176 (100) direction can be calculated as follows:

177

$$178 \quad E_{(100)} = \frac{1}{S_{11}} \quad (6)$$

179

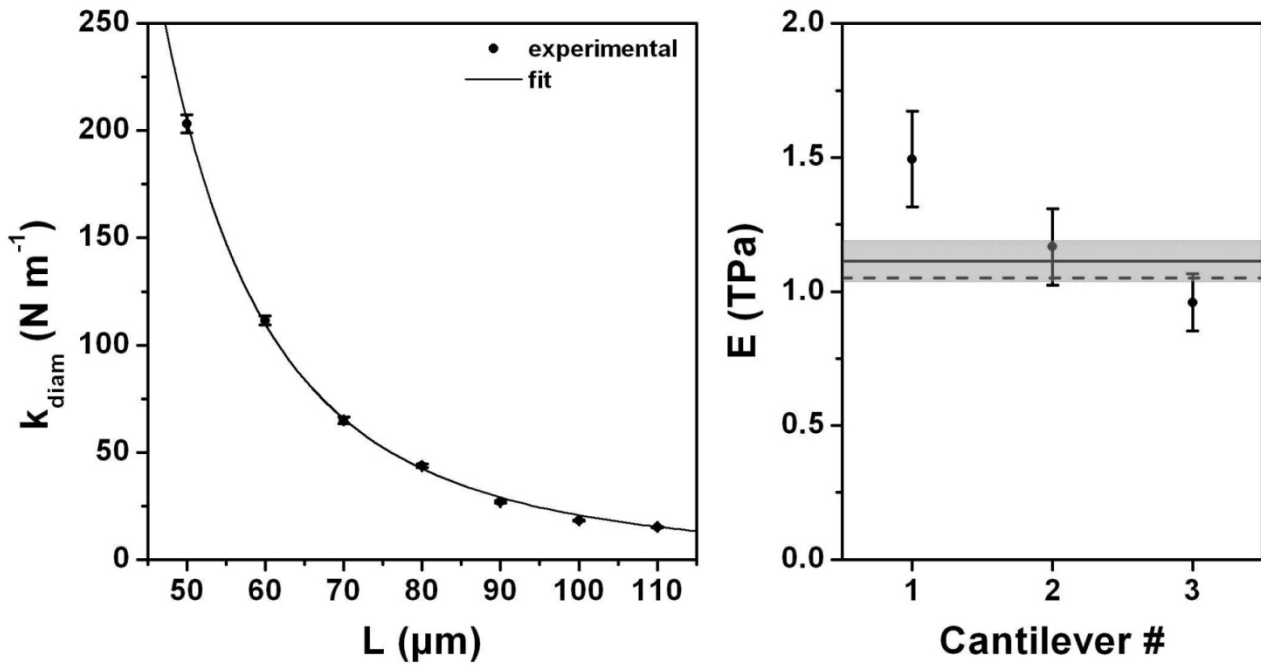
180 where S_{11} is the 11 component of elastic coefficient tensor S_{ij} according to the standard notation.
 181 Thus, the Poisson's ratio describing the contraction in the (001) direction due to tension in the (100)
 182 direction can be calculated as follows:

183

$$184 \quad \nu_{(100)} = -S_{12} \cdot E_{100} \quad (7)$$

185

186 From the values of the S_{ij} elastic coefficients reported in [37], we obtain $E_{(100)} = 1.05$ TPa and
 187 $\nu_{(100)} = 0.11$. Again, these values are close to the literature values for single-crystal diamond [36].



188

189 Fig. 5: a) experimental values (dots) of the stiffness of cantilever #3 at different beam lengths
 190 together with the relevant fitting curve (line). b) Young's moduli for the three cantilevers estimated
 191 from the fit of the experimental data (dots), together with the weighted average value (solid line)
 192 and the relevant uncertainty (grey box); the Young's modulus value for pristine single-crystal
 193 diamond taken from literature [36] is reported for comparison (dashed line).

194

195 4. Conclusions

196 We demonstrated the feasibility and reliability of an AFM-based beam-bending technique to
 197 determine the mechanical properties single-crystal diamond cantilevers, and investigated the effects
 198 of MeV ion implantation and subsequent high-temperature annealing on these mechanical
 199 properties. The obtained results provide direct evidence that both the Young's modulus and
 200 Poisson's ratio values of diamond after sub-graphitization-threshold irradiation and high-
 201 temperature annealing are fully recovered to their pristine values. These results provide useful
 202 information for the reliable design of (opto-) mechanical resonators in single-crystal diamond. We
 203 envisage to repeat these measurements on micro-structures subjected to controlled ion irradiation,

204 with the purpose of directly investigating the effect of ion-induced damage on their mechanical
205 properties, thus allowing the fine-tuning of their resonance frequencies.

206

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214 San Paolo” Foundation.

215

216 **References**

- 217 [1] N.R. Parikh, J.D. Hunn, E. McGucken, M.L. Swanson, C.W. White, R.A. Rudder, D.P. Malta,
218 J.B. Posthill, R.J. Markunas, Single-crystal diamond plate liftoff achieved by ion implantation and
219 subsequent annealing. *Applied Physics Letters*, 61 (1992) 3124-3126.
- 220 [2] J.D. Hunn, S.P. Withrow, C.W. White, R.E. Clausing, L. Heatherly, C.P. Christensen,
221 Fabrication of single-crystal diamond microcomponents. *Applied Physics Letters*, 65 (1994) 3072-
222 3074.
- 223 [3] P. Olivero, S. Rubanov, P. Reichart, B.C. Gibson, S.T. Huntington, J. Rabeau, A.D. Greentree,
224 J. Salzman, D. Moore, D.N. Jamieson, S. Prawer, Ion-beam-assisted lift-off technique for three-
225 dimensional micromachining of freestanding single-crystal diamond. *Advanced Materials*, 17
226 (2005) 2427-+.
- 227 [4] B.A. Fairchild, P. Olivero, S. Rubanov, A.D. Greentree, F. Waldermann, R.A. Taylor, I.
228 Walmsley, J.M. Smith, S. Huntington, B.C. Gibson, D.N. Jamieson, S. Prawer, Fabrication of
229 Ultrathin Single-Crystal Diamond Membranes. *Advanced Materials*, 20 (2008) 4793-4798.
- 230 [5] C.F. Wang, E.L. Hu, J. Yang, J.E. Butler, Fabrication of suspended single crystal diamond
231 devices by electrochemical etch. *Journal of Vacuum Science & Technology B*, 25 (2007) 730-
232 733.
- 233 [6] M. Liao, S. Hishita, E. Watanabe, S. Koizumi, Y. Koide, Suspended Single-Crystal Diamond
234 Nanowires for High-Performance Nanoelectromechanical Switches. *Advanced Materials*, 22 (2010)
235 5393-5397.
- 236 [7] M. Liao, C. Li, S. Hishita, Y. Koide, Batch production of single-crystal diamond bridges and
237 cantilevers for microelectromechanical systems. *J Micromech Microeng*, 20 (2010) 085002.
- 238 [8] M.K. Zalalutdinov, M.P. Ray, D.M. Photiadis, J.T. Robinson, J.W. Baldwin, J.E. Butler, T.I.
239 Feygelson, B.B. Pate, B.H. Houston, Ultrathin Single Crystal Diamond Nanomechanical Dome
240 Resonators. *Nano Letters*, 11 (2011) 4304-4308.

- 241 [9] M.P. Ray, T.I. Feygelson, J.E. Butler, J.W. Baldwin, B.H. Houston, B.B. Pate, M.K.
242 Zalalutdinov, Dissipation in single crystal diamond micromechanical annular plate resonators. *Diam*
243 *Relat Mater*, 20 (2011) 1204-1207.
- 244 [10] M. Liao, Z. Rong, S. Hishita, M. Imura, S. Koizumi, Y. Koide, Nanoelectromechanical switch
245 fabricated from single crystal diamond: Experiments and modeling. *Diam Relat Mater*, 24 (2012)
246 69-73.
- 247 [11] M. Liao, M. Toda, L. Sang, S. Hishita, S. Tanaka, Y. Koide, Energy dissipation in micron- and
248 submicron-thick single crystal diamond mechanical resonators. *Applied Physics Letters*, 105 (2014)
249 251904.
- 250 [12] J.C. Lee, D.O. Bracher, S. Cui, K. Ohno, C.A. McLellan, X. Zhang, P. Andrich, B. Alemán,
251 K.J. Russell, A.P. Magyar, I. Aharonovich, A. Bleszynski Jayich, D. Awschalom, E.L. Hu,
252 Deterministic coupling of delta-doped nitrogen vacancy centers to a nanobeam photonic crystal
253 cavity. *Applied Physics Letters*, 105 (2014) 261101.
- 254 [13] H.-J. Fecht, K. Brühne, P. Gluche, "Carbon-based Nanomaterials and Hybrids-Synthesis,
255 Properties and Commercial Applications", Pan Stanford Publishing, Singapore (2014)
- 256 [14] V. Acosta, P. Hemmer, Nitrogen-vacancy centers: Physics and applications. *MRS Bulletin*, 38
257 (2013) 127-130.
- 258 [15] P. Olivero, F. Bosia, B.A. Fairchild, B.C. Gibson, A.D. Greentree, P. Spizzirri, S. Praver,
259 Splitting of photoluminescent emission from nitrogen-vacancy centers in diamond induced by ion-
260 damage-induced stress. *New Journal of Physics*, 15 (2013).
- 261 [16] L.J. Rogers, S. Armstrong, M.J. Sellars, N.B. Manson, Infrared emission of the NV centre in
262 diamond: Zeeman and uniaxial stress studies. *New Journal of Physics*, 10 (2008) 103024.
- 263 [17] M.W. Doherty, V.V. Struzhkin, D.A. Simpson, L.P. McGuinness, Y. Meng, A. Stacey, T.J.
264 Karle, R.J. Hemley, N.B. Manson, L.C.L. Hollenberg, S. Praver, Electronic Properties and
265 Metrology Applications of the Diamond NV⁻ Center under Pressure. *Physical Review Letters*, 112
266 (2014) 047601.

- 267 [18] E.R. MacQuarrie, T.A. Gosavi, N.R. Jungwirth, S.A. Bhave, G.D. Fuchs, Mechanical Spin
268 Control of Nitrogen-Vacancy Centers in Diamond. *Phys Rev Lett*, 111 (2013) 227602.
- 269 [19] P. Ouartchaiyapong, K.W. Lee, B.A. Myers, A.C.B. Jayich, Dynamic strain-mediated coupling
270 of a single diamond spin to a mechanical resonator. *Nature Communications*, 5 (2014) 5429.
- 271 [20] J. Teissier, A. Barfuss, P. Appel, E. Neu, P. Maletinsky, Strain Coupling of a Nitrogen-
272 Vacancy Center Spin to a Diamond Mechanical Oscillator. *Physical Review Letters*, 113 (2014)
273 020503.
- 274 [21] E.R. MacQuarrie, T.A. Gosavi, A.M. Moehle, N.R. Jungwirth, S.A. Bhave, G.D. Fuchs,
275 Coherent control of a nitrogen-vacancy center spin ensemble with a diamond mechanical resonator.
276 *Optica*, 2 (2015) 233-238.
- 277 [22] P. Olivero, S. Rubanov, P. Reichart, B.C. Gibson, S.T. Huntington, J.R. Rabeau, A.D.
278 Greentree, J. Salzman, D. Moore, D.N. Jamieson, S. Praver, Characterization of three-dimensional
279 microstructures in single-crystal diamond. *Diam Relat Mater*, 15 (2006) 1614-1621.
- 280 [23] S. Pezzagna, D. Rogalla, D. Wildanger, J. Meijer, A. Zaitsev, Creation and nature of optical
281 centres in diamond for single-photon emission—overview and critical remarks. *New Journal of*
282 *Physics*, 13 (2011) 035024.
- 283 [24] R.A. Khmel'nitsky, V.A. Dravin, A.A. Tal, E.V. Zavedeev, A.A. Khomich, A.V. Khomich,
284 A.A. Alekseev, S.A. Terentiev, Damage accumulation in diamond during ion implantation. *J Mater*
285 *Res*, 30 (2015) 1583-1592.
- 286 [25] J.F. Ziegler, M.D. Ziegler, J.P. Biersack, SRIM – The stopping and range of ions in matter
287 (2010). *Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with*
288 *Materials and Atoms*, 268 (2010) 1818-1823.
- 289 [26] F. Bosia, S. Calusi, L. Giuntini, S. Lagomarsino, A. Lo Giudice, M. Massi, P. Olivero, F.
290 Picollo, S. Sciortino, A. Sordini, M. Vannoni, E. Vittone, Finite element analysis of ion-implanted
291 diamond surface swelling. *Nuclear Instruments & Methods in Physics Research Section B-Beam*
292 *Interactions with Materials and Atoms*, 268 (2010) 2991-2995.

- 293 [27] M. Marchywka, P.E. Pehrsson, S.C. Binari, D. Moses, Electrochemical Patterning of
294 Amorphous Carbon on Diamond. *Journal of The Electrochemical Society*, 140 (1993) L19-L22.
- 295 [28] C. Serre, P. Gorostiza, A. Perez-Rodriguez, F. Sanz, J.R. Morante, Measurement of
296 micromechanical properties of polysilicon microstructures with an atomic force microscope. *Sensor*
297 *Actuat a-Phys*, 67 (1998) 215-219.
- 298 [29] C. Serre, A. Perez-Rodriguez, J.R. Morante, P. Gorostiza, J. Esteve, Determination of
299 micromechanical properties of thin films by beam bending measurements with an atomic force
300 microscope. *Sensor Actuat a-Phys*, 74 (1999) 134-138.
- 301 [30] E. Sillero, O.A. Williams, V. Lebedev, V. Cimalla, C.C. Rohlig, C.E. Nebel, F. Calle, Static
302 and dynamic determination of the mechanical properties of nanocrystalline diamond
303 micromachined structures. *J Micromech Microeng*, 19 (2009).
- 304 [31] L.D. Landau, E.M. Lifshits, *Theory of elasticity*, 2d English ed., Pergamon Press, Oxford, New
305 York, 1970.
- 306 [32] S.P. Baker, W.D. Nix, Mechanical-Properties of Compositionally Modulated Au-Ni Thin-
307 Films - Nanoindentation and Microcantilever Deflection Experiments. *J Mater Res*, 9 (1994) 3131-
308 3145.
- 309 [33] T.Y. Zhang, M.H. Zhao, C.F. Qian, Effect of substrate deformation on the microcantilever
310 beam-bending test. *J Mater Res*, 15 (2000) 1868-1871.
- 311 [34] C.A. Klein, G.F. Cardinale, Young's modulus and Poisson's ratio of CVD diamond. *Diam*
312 *Relat Mater*, 2 (1993) 918-923.
- 313 [35] J.M. Gere, S. Timoshenko, *Mechanics of materials*, 4th ed., PWS Pub Co., Boston, 1997.
- 314 [36] C.A. Klein, G.F. Cardinale, Young Modulus and Poisson Ratio of Cvd Diamond. *P Soc Photo-*
315 *Opt Ins*, 1759 (1992) 178-192.
- 316 [37] R. Vogelgesang, A.K. Ramdas, S. Rodriguez, M. Grimsditch, T.R. Anthony, Brillouin and
317 Raman scattering in natural and isotopically controlled diamond. *Phys Rev B*, 54 (1996) 3989-
318 3999.

