One- and two-dimensional photonic crystal micro-cavities in single crystal diamond

Janine Riedrich-Möller¹, Laura Kipfstuhl¹, Christian Hepp¹, Elke Neu¹, Christoph Pauly², Frank Mücklich², Armin Baur³, Michael Wandt³, Sandra Wolff⁴, Martin Fischer⁵, Stefan Gsell⁵, Matthias Schreck⁵, and Christoph Becher¹

1. Universität des Saarlandes, Fachrichtung 7.2 (Experimentalphysik), 66123 Saarbrücken, Germany
2. Universität des Saarlandes, Fachrichtung 8.4 (Materialwissenschaft und Werkstofftechnik), 66123 Saarbrücken, Germany
3. University of Freiburg, Department of Microsystems Engineering (IMTEK), Cleanroom Service Center, 79110 Freiburg, Germany
4. TU Kaiserslautern, Nano+Bio Center, 67653 Kaiserslautern, Germany
5. Universität Augsburg, Lehrstuhl für Experimentalphysik IV, 86159 Augsburg, Germany

I. Photonic crystals: Simulations

Enhancement of the zero phonon emission from SiV centres in a photonic crystal cavity in diamond

The photonic crystal can both enhance and reduce the spontaneous emission rate of a colour centre. In a homogeneous diamond slab the excited state of the SiV centre decays through three channels with a total rate \( \Gamma_0 = \gamma_{ZPL} + \gamma_{PS} + \gamma_{NR} \), where \( \gamma_{ZPL} \) and \( \gamma_{PS} \) are the radiative recombination rates into the zero phonon line (ZPL) and the phonon side bands, respectively, and \( \gamma_{NR} \) denotes the non-radiative decay rate. The radiative quantum yield of SiV centres is 5% [1], whereof 80% [2] of the photons are emitted into the ZPL. For a SiV centre with dipole moment \( \vec{\mu} \) at position \( \vec{r} \) in the cavity the spontaneous emission rate is given by

\[
\Gamma_c = F_c \left( \frac{\vec{E} \cdot \vec{\mu}}{|\max \{ \vec{E} \}| |\vec{\mu}|} \right)^2 \frac{|\vec{E}|^2}{|\max \{ \vec{E} \}|^2} \frac{\Delta \lambda_c^2}{\Delta \lambda_c^2 + 4(\lambda - \lambda_c)^2} \gamma_{ZPL} + F_{PhC} \gamma_{PS},
\]

(1)

Here, \( F_c \) denotes the Purcell factor of an emitter that is in resonance with the cavity and has a dipole moment aligned with the field

\[
F_c = \frac{3}{4\pi^2} \frac{Q}{V_{mod}} \left( \frac{\lambda_c}{n} \right)^3,
\]

(2)
where $V_{\text{mod}}$ is the modal volume. The factors $R_{\Delta \lambda} = \Delta \lambda^2 / (\Delta \lambda^2 + 4(\lambda - \lambda_c)^2)$ and $R_r = |\vec{E}_r|^2 / \max(\vec{E})^2$ account for the spectral and spatial detuning from the cavity resonance, where $\lambda_c$ and $\Delta \lambda_c$ are the cavity resonance wavelength and linewidth, respectively. For the derivation of eq. (1), one assumes an emitter with central wavelength $\lambda$ and vanishing emission bandwidth $\Delta \lambda \ll \Delta \lambda_c$. The factor $R_\mu = (\vec{E} \cdot \vec{\mu} / |\max(\vec{E})||\vec{\mu}|)^2$ considers the alignment of the dipole moment with respect to the electric field. The term $F_{\text{PhC}}$ describes the inhibition of the spontaneous emission rate by the photonic band gap effect.

To estimate the enhancement of the PL signal when the cavity is tuned in resonance with the ZPL of the SiV centres, we calculate the ratio of total intensities measured by the spectrometer. For on-resonance emitters, the total intensity $I_c$ is given by the emission rate $\Gamma_c$ integrated over the spectral and spatial density $\rho(\vec{r}, \vec{\mu}, \lambda) = \rho(\vec{r})\rho(\vec{\mu})\rho(\lambda)$ of an ensemble of emitters [3]:

$$I_c = \int \int \int d\vec{r} d\vec{\mu} d\lambda \rho(\vec{r}, \vec{\mu}, \lambda) \left( \eta_c F_c R_r R_\mu R_{\Delta \lambda} \gamma_{\text{ZPL}} + \eta_{\text{PhC}} F_{\text{PhC}} \gamma_{\text{PS}} \right)$$

(3)

Here $\eta_c$ and $\eta_{\text{PhC}}$ are the collection efficiencies of the objective lens for the on- and off-resonant emission, respectively. The total intensity for emitters spectrally detuned from the cavity mode is given by $I_{\text{PhC}} = \int \int \int d\vec{r} d\vec{\mu} d\lambda \rho(\vec{r}, \vec{\mu}, \lambda) \eta_{\text{PhC}} F_{\text{PhC}} (\gamma_{\text{ZPL}} + \gamma_{\text{PS}})$. This situation corresponds to spectrum “0” in Figure 3(a) in the main text. The ratio of the integrated intensities $C_{\text{ZPL}} = I_c / I_{\text{PhC}}$ describes the enhancement of the ZPL when the cavity is tuned in resonance with the emission line of the SiV centres.

Assuming a random dipole orientation, the integral over $\vec{\mu}$ in eq. (3) is $\frac{1}{2}$. For the ensemble of SiV centres we have to account for the emission bandwidth $\Delta \lambda > \Delta \lambda_c$: We measure the spectral distribution $\rho(\lambda)$ of the SiV centres to be Lorentzian with a FWHM of 5 nm. The spatial density $\rho(\vec{r})$ corresponds to the excitation of an ensemble of SiV centres by a Gaussian beam with FWHM of 600 nm in the $x,y$ plane (given by the N.A. of our confocal microscope) and uniform in $z$-direction. The spatial overlap factor $\approx 0.35$ is calculated numerically by integrating over the simulated electric field intensity of the cavity mode. We calculate the collection efficiency of the dipole emission coupled to a cavity mode $\eta_c \approx 0.23 \pm 0.06$ and a periodic photonic crystal lattice $\eta_{\text{PhC}} \approx 0.26 \pm 0.02$ by numerically integrating the far field distribution of the radiated power over the collection angle defined by the objective lens (N.A. = 0.8). The error of the collection efficiencies $\eta_c$ and $\eta_{\text{PhC}}$ accounts for a variation of the air hole radii within the fabrication tolerances and tilt of the air hole sidewalls by an angle of $6^\circ$ in the simulation.

For the cavity mode $o2$ with $Q = 400$ shifted into resonance with the SiV centres, we calculate $F_c \approx 20$ with a modal volume of $V_{\text{mod}} = 1.5(\lambda / n)^3$. The modification due to the reduced density of states of the photonic crystal lattice $F_{\text{PhC}} \approx 0.23 \pm 0.03$ is calculated by FDTD simulations (see below). Considering the collection efficiencies and the spectral and spatial mismatch described above, we calculate the resonant enhance-
Figure S1: Enhancement of the SiV ZPL intensity due to resonant coupling: By tuning the cavity mode into resonance with the emission line of the SiV centres, the ZPL is enhanced by a factor of 2.8. The gray (black) curve is the cavity spectrum off (on) resonance taken before and after the oxidation procedure.

The enhancement of ZPL intensity compared to the off resonant situation $C_{ZPL} = I_c/I_{PhC} = 3 \pm 1$. In the experiment, we measure an enhancement of the intensity $C_{ZPL, Exp} = 2.8$ (Fig. S1). The large error of the intensity enhancement factor $C_{ZPL}$ is mainly due to a change of the collection efficiency when including variations of the air hole radii and tilted hole sidewalls in the simulation.

### Enhancement of the spontaneous emission rate

Analogous to the enhancement of the spectrally resolved intensity of the ZPL, we can estimate the enhancement of the spontaneous emission rate when the photonic crystal cavity is tuned into resonance with the colour centres in the diamond film. The modification of the spontaneous decay rate of an emitter placed in a cavity compared to its emission rate in free space is given by (c.f. [4])

$$\frac{\Gamma_{c, tot}}{\Gamma_0} = \frac{F_c R_e R_\mu R_{\Delta \lambda} \gamma_{ZPL} + F_{PhC} \gamma_{PS} + \gamma_{NR}}{\gamma_{ZPL} + \gamma_{PS} + \gamma_{NR}}. \quad (4)$$

Considering the spatial detuning $R_e$ and the alignment of the dipole moment with respect to the electric field $R_\mu$ described above as well as averaging over the spectral detuning $R_{\Delta \lambda}$, we find that the spontaneous emission rate is essentially unchanged $\Gamma_{c, tot} \approx \Gamma_0$.

### Purcell factor $F_{PhC}$ of the photonic crystal lattice

The calculation of the Purcell factor $F_{PhC}$ of the photonic crystal lattice without a cavity is performed numerically using FDTD simulations. The classical dipole radiation power
Figure S2: Purcell factor of a photonic crystal lattice: (a) Dipole positions in the photonic structure. (b) Calculated spontaneous emission rate and (c) emission efficiency into vertical modes, normalised to the emission in a homogeneous diamond slab.

$P$ in a FDTD calculation can be used to determine the spontaneous emission lifetime $\tau_c$ in a micro-cavity compared to the emission lifetime $\tau_0$ in bulk material $\tau_c/\tau_0 = P_c/P_0$ [5]. A dipole with transverse-electric (TE) polarisation (dipole moment oriented parallel to the slab), is placed at the centre of the simulation cell. The radiated power is obtained by calculating the pointing vectors passing through six planes at the edges of the photonic crystal structure. The simulations are performed for dipoles at four different locations (A, B, C, D) in the photonic crystal lattice shown in Figure S2(a) and for two orthogonal in-plane polarisations [6]. The set of results is averaged and normalised to the power transmission of a dipole in a homogeneous diamond slab. Depending on the frequencies within the band gap, we obtain Purcell factors of $F_{\text{PhC}} = P_c/P_0 = 0.19 - 0.24$ (Fig. S2(b)). Thus, the spontaneous emission rate is inhibited by a factor of four to five due to the band gap effect. Simultaneously, the power radiated in the vertical direction is increased by a factor of up to four compared to the dipole emission in a homogeneous diamond slab (Fig. S2(c)). This leads to an increased PL signal measured on the photonic structures compared to the bare diamond membrane. This effect has also been observed in our experiments. The PL signal of the M7-cavity in Figure 2(a) in the main text is a factor of six higher compared to the intensity of the reference spectrum measured on the unstructured membrane.

**Limitations of the experimental Q-factor**

Comparing the experimental Q-factors with the simulated values, we measured a discrepancy of one to three orders of magnitude for the 2D and 1D photonic crystal cavities, respectively. The limitation of the experimental Q-factors could have various origins. The dominant sources of losses can be categorised as either (A) imperfections of the cavity geometry, or (B) imperfections of the cavity material. As imperfections of the cavity geometry induced by fabrication tolerances, we consider (A1) variation of the air
hole positions and radii and (A2) tilt of the air hole sidewalls. As imperfection of the cavity material, we investigate (B) material absorption. In the following, we analyse the main sources of losses and discuss the impact on the cavity Q-factor.

(A1) Variation of hole positions and radii The main discrepancy between an ideal M7-cavity and the actual fabricated structure is the variation in the hole positions. During the FIB milling, a drift control is used, which compares the actual position to the ideal pattern after every third hole and compensates a possible drift. This compensation results in a rather random variation of the hole position from ideal values which is measured to be $\sim 13$ nm on average.

The imperfections of the air hole radii are much smaller. Here the fabrication tolerance is measured to be $\sim 6$ nm on average. The outer rows of the air holes, which are milled first, are slightly larger than the inner air holes surrounding the defect, which were patterned at last.

To quantify the influence of the fabrication tolerances on the Q-factors of the cavity modes, we convert the SEM image of the actual fabricated M7-cavity into a dielectric structure and calculate the Q-factor using FDTD simulations. To account only for TE-like modes, we apply a mirror symmetry with respect to the plane at $z = 0$. The quality factors $Q_{\text{SEM}}$ of the five lowest M7-cavity modes calculated for the dielectric structure based on the imported SEM image are summarised in Table S1. The quality factor of the fundamental mode $e_1$ drops by a factor of $\sim 3$ to $Q_{\text{SEM}} = 3,700$ whereas the Q-factors of the $e_2$ and $e_3$ modes are almost unaffected. The quality factors $Q_{\text{SEM}}$ of the odd cavity modes $o_1$ and $o_2$ calculated from the imported SEM image are comparable to each other and are even higher than the Q-factors of the ideal M7-cavity. As the field of the $o_2$-Mode (see Fig. 2(a)) is mainly localised in the defect region and at the first upper and lower row of air holes surrounding the defect, the radii and positions of these air holes have a major impact on the Q-factor of the odd modes. Thus, the incidental variation of the air holes surrounding the cavity centre lead to the high experimental Q-factors of the odd cavity modes. In summary, we find that the incidental departure of the fabricated structure from the ideal in-plane geometry reduces the high Q-factor of the $e_1$ mode but enhances the Q-factors of the odd modes $o_1$ and $o_2$.

<table>
<thead>
<tr>
<th>Modes</th>
<th>$e_1$</th>
<th>$e_2$</th>
<th>$e_3$</th>
<th>$o_1$</th>
<th>$o_2$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$Q_{\text{Theory}}$</td>
<td>11,800</td>
<td>1,350</td>
<td>255</td>
<td>450</td>
<td>110</td>
</tr>
<tr>
<td>$Q_{\text{SEM}}$</td>
<td>3,700</td>
<td>1,100</td>
<td>250</td>
<td>600</td>
<td>590</td>
</tr>
</tbody>
</table>

Table S1: Simulated quality factors of an ideal M7-cavity and of the dielectric structure based on the imported SEM image of the actual fabricated M7 structure (assuming vertical sidewalls of the air holes).
Figure S3: Influence of material absorption on the Q-factor of the fundamental M7-cavity mode: The dots denote the FDTD simulation results of a M7-cavity including lossy material and the line is the calculated Q-factor using equation 5. For an absorption coefficient $\alpha < 10 \text{ cm}^{-1}$ of the diamond membrane the quality factor is limited to $Q > 8,000$.

FDTD simulations based on the imported SEM image also reveal that fabrication tolerances are responsible for the slight discrepancy of $< 4 \text{ nm}$ between the wavelengths of the simulated modes of the ideal M7-cavity and the measured spectra as shown in Figure 2.

(A2) Tilt sidewalls of air holes From the side view SEM images (Fig. 1(c)) of the fabricated M7-cavity structure, we deduce a tilt angle of the air hole sidewalls of $\sim 6^\circ$. The impact of non-vertical hole sidewalls on the M7 quality factor has been discussed in the main text in Table 1. The cone shape of the air holes leads to a reduction of the maximal Q-factor from 11,800 to 900, which primarily affects the high-Q $e_1$ and $e_2$ modes.

(B) Material absorption In order to study the influence of material absorption on the M7-cavity Q-factor, we include a complex dielectric function $\varepsilon$ in our simulation, such that the imaginary part $\varepsilon_i$ is proportional to the absorption coefficient $\alpha$ of the diamond material, whereas the real part $\varepsilon_r$ is almost constant. The dependence of $Q$ on $\alpha$ can be approximated by a very simple model of a linear cavity with a homogeneous diamond slab placed between two planar mirror [7]:

$$Q^{-1} = Q_0^{-1} + Q_{\text{abs}}^{-1},$$

where $Q_0$ denotes the Q-factor of an ideal lossless cavity and $Q_{\text{abs}}$ the Q-factor including material absorption. The absorption quality factor can be written as $Q_{\text{abs}} = k/\alpha$, with the wavevector $k = 2\pi\sqrt{\varepsilon_r}/\lambda$. Figure S3 shows the dependence
of the M7 quality factor on the absorption coefficient $\alpha$, calculated by FDTD simulations and using equation (5). For nano-crystalline diamond films absorption coefficients can reach values as high as $\alpha \approx 4000 \text{ cm}^{-1}$. This would strongly decrease the M7 cavity Q-factor to only $\sim 100$. For the heteroepitaxial diamond films used to fabricate the PhC cavities, the absorption coefficient $\alpha$ depends on the thickness of the film used to fabricate the membrane: For the first hundred nanometers of the diamond nucleation layer, we measure $\alpha \approx 200 \text{ cm}^{-1}$. Compared to nano-crystalline diamond films this is already an improvement by more than one order of magnitude. Such an absorption coefficient would limit the Q-factor to $Q \sim 100$, which is on the order of the limitation caused by fabrication tolerances. However, with increasing film thickness the absorption coefficient of the heteroepitaxial diamond films is drastically reduced: For very large thicknesses (500-800 $\mu$m), the absorption coefficient of the film was measured to be $\alpha \sim 2.5 \text{ cm}^{-1}$ (the nucleation layer had been removed). For the fabrication of photonic crystals we thin the heteroepitaxial diamond films from 12 $\mu$m to 300 nm starting from the backside, thus removing the nucleation layer and leaving a thin diamond membrane with low absorption coefficient. Based on measurements of comparable samples the absorption coefficient can be estimated to be $\alpha < 10 \text{ cm}^{-1}$. Considering material absorption, the cavity quality factor of the fundamental $e1$ mode is limited to $Q > 8,000$. Compared to fabrication tolerances, material absorption has a significant smaller impact on the cavity Q-factor.

To summarise, we have demonstrated that fabrication tolerances such as the variation of the air hole positions, radii and tilt of the air hole sidewalls have a strong impact on the cavity Q-factors. The deviation of the air hole positions and radii from the ideal structure reduces the Q-factor of the $e1$ mode to $Q = 3,700$ and leads to an increase of the experimental quality factor of the $o2$-mode compared to theoretical calculations assuming equally spaced and sized air holes. The cone shape of the air hole sidewalls primarily effects the high-Q cavity modes $e1$ and $e2$ and limits the Q-factor to maximally $Q = 900$. In contrast, the impact of the material absorption plays only a minor role on the Q-factor. By removing the nucleation layer of the diamond films using reactive ion etching, the PhC are placed in the layer of minimal absorption $\alpha < 10 \text{ cm}^{-1}$, which limits the Q-factor of the $e1$-mode to $Q > 8,000$. Thus, the cavity Q-factor is mainly limited by fabrication tolerances and not by the material absorption of the diamond membrane.

**Polarisation analysis**

From the experiments described in the main text we obtain that the modes of the M7-cavity and the nanobeam cavity are linearly polarised. All even modes ($e$) are polarised in the $y$-direction of the PhC cavities whereas the odd modes ($o$) are polarised in the
Figure S4: Far field radiation patterns of the e1 and o1 mode of the M7-cavity: The far field is obtained by spatial Fourier transform of the in-plane field components. The far field data is presented in a spherical coordinate system where \( x = \sin(\theta) \cos(\phi) \) and \( y = \sin(\theta) \sin(\phi) \). In the case of the e1 mode the \( E_x \) component cancels out in the far field, whereas the \( E_y \) vanishes for the o1 mode. This results in a net polarisation in the \( y(x) \)-direction of the e1(o1)-cavity mode, respectively.

The far field cancelation effect can be understood by considering the symmetry of the near field components at \( y = 0 \) (centre line of the cavity). The \( E_x \) in-plane component...
of the $e_1$ mode shown in Figure 2 in the main text has a node along the cavity centre line. One can consider the field distribution as two identical oscillators separated by the mirror plane [9]. The radiation of the two out-of-phase oscillators tends to cancel out in the far field. On the other hand, the $E_y$ in-plane component of the $e_1$ mode is symmetric with respect to the cavity centre line. The even symmetry leads to a constructive interference in the far field. Therefore, the $E_y$ component of the $e_1$ mode is dominant in the far field and determines the polarisation of the even cavity mode. The same arguments holds for the $E_x$ component of the $o_1$ mode.

II. Photonic crystals: Fabrication

Cavity tuning by oxidation of the diamond film

In order to actively tune the M7-cavity modes, we make use of the fact, that the photonic crystal cavity modes are very sensitive to structural parameters like the slab thickness $h$ and the hole radius $R$. Figure S5 shows that the resonant modes are shifted to smaller wavelengths $\lambda$ for both increased radii $R$ and decreased slab thickness $h$. In particular, the size of the air hole has a strong impact on the resonant wavelength: Increasing the radius $R$ by only 1.5 nm results in a blue-shift of the resonant wavelength by $\sim$3 nm on average. For comparison the measured resonant wavelengths of the M7-cavity for successive oxidation steps is shown in Figure S5(a). The experimental data corresponds very well with the theoretical prediction for an increase in the radius of 1.5 nm per oxidation step and an almost constant film thickness.
Figure S6: Energy dispersive X-ray (EDX) spectroscopy of the photonic crystal structures: (a) Calculations of stopping range of 30 keV Ga-ions in the diamond material (SRIM [10]) reveal that a thin layer of gallium is implanted ∼15 nm beneath the diamond surface with a lateral straggle of ∼4 nm. (b) SEM image of the PhC structure used for EDX spectroscopy with the analysed area marked by the white rectangle. (c) EDX spectrum of the PhC directly after the FIB milling process. The peak at 1.1 keV is attributed to gallium that is incorporated during the patterning of the diamond membrane. (d) After the extensive annealing and cleaning procedure, no signal attributed to gallium can be observed in the EDX spectrum of the PhC.

Postprocessing cleaning of the sample: Removal of gallium ions

In this section we discuss the incorporation of gallium by FIB milling and the removal of the gallium by the post-processing annealing procedure. Simulations of the stopping range of gallium ions with an energy of 30 keV in the diamond material show that a thin layer of gallium is implanted ∼15 nm beneath the diamond surface with a lateral straggle of ∼4 nm (see Fig. S6(a)). This means that after the FIB milling with an ion current of 10 pA one would expect a thin layer of implanted gallium surrounding the air hole sidewalls of the PhC. To analyse the incorporation of gallium in the diamond material after the FIB milling, we performed energy dispersive X-ray (EDX) spectroscopy of the fabricated structures. Figure S6(b) shows a SEM image of the PhC with the area under investigation marked by a white rectangle. The EDX spectrum (Fig. S6(c)) directly after the FIB milling shows a strong peak attributed to the carbon material as well as oxygen, silicon and iridium related peaks originating from the sample substrate. The aluminium peak is due to the signal of the sample holder. Among all these peaks a clear signal at 1.1 keV related to gallium can be observed, which is absent in an EDX spectrum taken on the unstructured diamond membrane. This is a clear hint, that gallium is incorporated
in the diamond material by FIB milling. In order to remove the implanted gallium after the FIB milling, the sample is annealed in vacuum at 1000 °C for 2 h. Several groups have studied the diffusion of gallium ions implanted by FIB in diamond [11], diamond like carbon films [12] and amorphous carbon pillars [13] towards the sample surface and the removal of gallium by annealing at 700 °C [13]. Figure S6(d) shows the EDX spectrum taken after the extensive annealing and cleaning procedure described in the Methods section. No signal attributed to gallium is observed after the postprocessing step. Therefore, we conclude that the amount of gallium incorporated in the diamond material has been significantly reduced by thermal annealing below the detection limit of the EDX analysis (∼1%).

Eventually, the optical fluorescence properties of the diamond remain unchanged, as we have never observed any additional signal in the spectral region of NV or SiV centres that could be related to additional defect centers introduced by gallium ions.

**Post-processing cleaning of the sample: Removal of ion-induced damages**

Besides the removal of incorporated gallium ions, the reduction of implantation damages induced by the FIB milling is a necessary step to recover the quality of the diamond films. To study the implantation induced damages we perform Raman spectroscopy using a confocal microscope setup with an excitation laser at a wavelength $\lambda = 532$ nm. Figure S7(a) shows the Raman spectrum of a PhC cavity at room temperature after the

Figure S7: Raman spectroscopy of the PhC structures: (a) The Raman spectrum of the FIB milled PhC cavity after the high temperature annealing at 1000 °C for 2 h shows the diamond Raman line at 572.8 nm and a further clear Raman signal at ∼580 nm of graphite-like inclusions and $sp^{2}$ hybridized carbon. (b) After an extensive cleaning procedure no indication of non diamond carbon phases can be observed in the spectrum.
high temperature annealing at 1000°C for 2 h subsequent to the FIB milling. Besides the diamond Raman line at 572.8 nm ($\approx 1337\pm 7 \text{ cm}^{-1}$) a broad peak around 580 nm ($\approx 1554\pm 7 \text{ cm}^{-1}$) attributed to the G-Band of graphite-like inclusions and sp² hybridized carbon can be observed in the spectrum. The slight shift of the diamond Raman line with respect to the ideal position of 1332 cm$^{-1}$ can be attributed to stress in the diamond films [14]. Note, however, that the Raman spectra have been measured with a fluorescence setup without careful wavelength calibration, thus the measurement accuracy is not high enough to provide a detailed analysis of stress. Notably, after the extensive cleaning procedure described in the Methods section, no signal related to non diamond carbon phases around 1400-1600 cm$^{-1}$ can be observed in the Raman spectrum as can be seen in figure S7(b). The absence of the G-Band Raman peak after the cleaning procedure also indicates a low overall content of sp²-hybridized carbon which is correlated with a small optical absorption coefficient <10 cm$^{-1}$ in the wavelength range of the SiV zero phonon line [15]. This value agrees very well with the absorption coefficient determined for single crystal diamond material (see section I). Therefore, we conclude that the amount of damages induced by the FIB milling has been significantly reduced by the post processing steps using wet etching and thermal oxidation in air.

References


