

Microwave Plasma-Activated Chemical Vapour Deposition of Nitrogen-Doped Diamond, II: CH/N/H Plasmas

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ABSTRACT

We report a combined experimental and modelling study of microwave-activated dilute CH₄/N₂/H₂ plasmas, as used for chemical vapour deposition (CVD) of diamond, under very similar conditions to previous studies of CH₄/H₂, CH₄/H₂/Ar and N₂/H₂ gas mixtures. Using cavity ring-down spectroscopy, absolute column densities of CH(X, $\nu=0$), CN(X, $\nu=0$) and NH(X, $\nu=0$) radicals in the hot plasma have been determined as functions of height, z , source gas mixing ratio, total gas pressure, p , and input power, P . Optical emission spectroscopy has been used to investigate, with respect to the same variables, the relative number densities of electronically excited species, namely H atoms, CH, C₂, CN and NH radicals, and triplet N₂ molecules. The measurements have been reproduced and rationalised from first principles by 2-D (r, z) coupled kinetic and transport modelling, and comparison between experiment and simulation has afforded a detailed understanding of C/N/H plasma-chemical reactivity and variations with process conditions and with location within the reactor. The experimentally-validated simulations have been extended to much lower N₂ input fractions and higher microwave powers than were probed experimentally, providing predictions for the gas-phase chemistry adjacent to the diamond surface and its variation across a wide range of conditions employed in practical diamond-growing CVD processes. The strongly bound N₂ molecule is very resistant to dissociation at the input MW powers and pressures prevailing in typical diamond CVD reactors, but its chemical reactivity is boosted through energy pooling in its lowest-lying (metastable) triplet state and subsequent reactions with H atoms. For a CH₄ input mole fraction of 4%, with N₂ present at 1–6000 ppm, at pressure $p = 150$ Torr and with applied microwave power $P = 1.5$ kW, the near-substrate gas-phase N atom concentration, $[N]_{\text{ns}}$, scales linearly with the N₂ input mole fraction and exceeds the concentrations $[NH]_{\text{ns}}$, $[NH_2]_{\text{ns}}$, and $[CN]_{\text{ns}}$ of other reactive nitrogen-containing species by up to an order of magnitude. The ratio $[N]_{\text{ns}}/[CH_3]_{\text{ns}}$ scales proportionally with (but is 10^2 – 10^3 times smaller than) the ratio of the N₂ to CH₄ input mole fractions for the given values of p and P , but $[N]_{\text{ns}}/[CN]_{\text{ns}}$ decreases (and thus the potential importance of CN in contributing to N-doped diamond growth increases) as p and P increase. Possible insights regarding the well-documented effects of trace N₂ additions on the growth rates and morphologies of diamond films formed by CVD using MW-activated CH₄/H₂ gas mixtures are briefly considered.

1. INTRODUCTION

Nitrogen is a common impurity in both natural and high-pressure/high-temperature (HPHT) synthetic diamond. In natural diamonds, nitrogen impurities are usually found aggregated in clusters (defined as type Ia diamond), whereas in synthetic HPHT diamonds nitrogen is typically present at lower overall concentration and located in substitutional sites throughout the lattice (type Ib diamond).¹ Nitrogen is an n-type dopant in diamond, and thus nitrogen-doped diamond has attracted interest as a potential high-electron-mobility semiconductor. Nitrogen is a deep donor,² however, and the resulting material has not proved suitable for most electronic applications.

Given the abundance of nitrogen on Earth, it is very challenging to achieve nitrogen-free HPHT diamond growth. Producing such material by chemical vapour deposition (CVD) methods has long been seen as more practicable, but still requires great care regarding source gas purity and the minimization of air leaks into the reactor.^{3,4} Several previous studies have demonstrated that the presence of trace amounts of nitrogen significantly increases the rate of diamond growth in a microwave (MW) plasma-activated (PA) CVD process.⁵⁻¹⁴ Small nitrogen additions have also been shown to affect the surface morphology,^{5,6,14-16} and in particular to encourage the formation of {100}- rather than {111}-faceted surfaces: the former are typically less rough and hence attractive for mechanical applications.¹⁷ Too much nitrogen in the source gas mixture, however, leads to smaller and less-well-oriented surface facets, and a higher sp^2 fraction in the deposited material.^{5,18} Another, less significant but non-negligible, consequence of adding large amounts of N_2 is a reduction in the thermal conductivity of the process gas mixture, which can benefit power coupling efficiency by reducing diffusive transport of heat to the reactor walls.¹⁹

How nitrogen reacts at the diamond surface, and why its presence in the gas phase increases the growth rate and influences the surface morphology, is still not fully understood. Various nitrogen-containing species have been proposed as participants in gas-surface reactions contributing to diamond growth. CN radicals have attracted attention based on observed correlations between $CN(B \rightarrow X)$ emission intensities from the hot plasma region and measured growth rates,^{14,20-22} and CN adsorption on a diamond {111} surface has been suggested as a route to nucleating new layer growth.²³ Cao *et al.*¹⁵ offered a more general view, recognising possible contributions from a range of gas-phase NH_x and CNH_x species. On the computational front, Larsson and co-workers^{24,25} have explored how pre-adsorbed

NH_x ($x = 1, 2$) species might affect gas–surface reactions involving CH_x radicals (which are generally viewed as the dominant C precursor in diamond CVD²⁶), and ways in which previously incorporated near-surface substitutional N atoms can influence the energetics, and thus the rates, of the elementary reactions involved in CH_x incorporation.^{27,28}

Here, we report spatially-resolved absorption and/or emission measurements of several gas-phase species — H($n=2, 3$) atoms, NH, CH, CN and C₂ radicals, and triplet N₂ molecules — in MW-activated CH₄/N₂/H₂ plasmas operating at pressures (≈ 150 Torr) and powers (≈ 1.5 kW) relevant to contemporary MW-PACVD processes. The work builds on complementary diagnoses of N₂/H₂ and NH₃/H₂ plasmas presented previously (henceforth paper I²⁹), and the experimental measurements are used to inform and tension companion 2-D modelling of the C/N/H plasma chemistry. Similarities and differences between the present model outputs and those from the one previous 2-D simulation of MW activated C/N/H plasmas³⁰ are highlighted, and possible insights these data provide towards explaining documented effects of trace N₂ additions on the growth rates and morphologies of diamond films formed by CVD using MW-activated CH₄/H₂ gas mixtures are briefly considered.

2. EXPERIMENTS

The MW-PACVD reactor, the laser system, and the optical arrangements for the spatially-resolved cavity ring down spectroscopy (CRDS) and optical emission spectroscopy (OES) measurements as a function of height (z) above the substrate surface are detailed in paper I²⁹ or in prior publications cited therein. Table 1 lists the species and transitions probed in the present study.

Table 1

Probe Transitions used for Monitoring H*, NH, CH, C₂, CN and N₂* Species.

Species	CRDS	OES	[Spectroscopic constants]; (A -coefficients)
H*	$n=3 \leftarrow n=2$	$n=3 \rightarrow n=2$	[31]; (31)
NH	$A^3\Pi \leftarrow X^3\Sigma^-$	$A \rightarrow X$	[32]; (33,34)
CH	$A^2\Delta \leftarrow X^2\Pi$ $B^2\Sigma^- \leftarrow X^2\Pi$	$A \rightarrow X$	[35]; (36) [37]; (38)
C ₂	$d^3\Pi_g \leftarrow a^3\Pi_u$	$d \rightarrow a$	[39]; (36)
CN	$B^2\Sigma^+ \leftarrow X^2\Sigma^+$	$B \rightarrow X$	[40]; (41)

N_2^*	—	$C^3\Pi_u \rightarrow B^3\Pi_g$	[42]; (43)
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CRDS was used to determine column densities of electronically excited $H(n=2)$ atoms, $NH(X)$, $CH(X)$ and $C_2(a)$ radicals as functions of z , applied microwave power, P , total pressure, p , and gas mixing ratio, as described in previous publications.^{29,36,44} The present work also relies on column density measurements of $CN(X)$ radicals, as well as further measurements of $CH(X)$ radicals using the complementary $B^2\Sigma^- \leftarrow X^2\Pi$ transition rather than the more traditional $A-X$ system. All of these species, plus electronically excited (triplet) N_2 molecules, were also monitored by OES, using one or other of two similar optical set-ups.^{29,45} H_2 , CH_4 and N_2 source gases were supplied via separate, calibrated mass flow controllers and mixed before entering through two diametrically opposed inlets located close below the top of the reactor, situated at angle of $\approx 45^\circ$ to the laser propagation axis. ‘Base’ conditions for these experimental studies were defined as follows: $p = 150$ Torr, $P = 1.5$ kW, and input flow rates $F(N_2) = 3$ standard cm^3 per minute (sccm), $F(CH_4) = 20$ sccm and $F(H_2) = 500$ sccm, i.e. an $[N]/[C]$ ratio in the input gas mixture of 0.3. When varying one parameter, all others were maintained at their base values unless noted otherwise. The substrate temperature was monitored by two-color optical pyrometry, returning values $T_{sub} \approx 1100$ K. This source gas mixture represents a much higher N/C ratio than is used in the growth of high-quality CVD diamond, but was chosen to allow more detailed study of the gas-phase chemistry of N_2 . The experimentally established plasma chemistry informs simulations extended to lower N/C ratios later in the manuscript.

3. EXPERIMENTAL RESULTS

Figure 1a shows a CRD spectrum measured over the wavenumber range $25732\text{--}25823\text{ cm}^{-1}$ at $z = 8$ mm for a $CH_4/N_2/H_2$ plasma operating under base conditions. The spectrum is dominated by the P-branch band head of the $CN(B-X)$ (0,0) transition, but as the accompanying PGOPHER⁴⁶ simulation in Figure 1b shows, also displays lines associated with the $CH(B-X)$ (0,0) transition. For completeness, we note a previous CRDS study, in the context of diamond CVD, of CN radicals in an oxyacetylene flame with nitrogen addition,⁴⁷ and a study of $CH_4/O_2/N_2$ and $CH_4/NO/O_2/N_2$ flames that exploited this same spectral region.⁴⁸ Figure 1c shows an expanded view of a small region of the CRD spectrum centred around 25749 cm^{-1} . This is attractive from a diagnostic perspective as it is free from any

contaminating CH(B–X) transitions and includes CN(B–X) (0,0) transitions originating from both high- and low- J'' levels. As such, it offers a convenient probe of the CN rotational temperature, which, given the operating pressure and prevailing collision frequency, and as in our previous analyses of the C₂(d–a) spectra,⁴⁴ we regard as diagnostic of the gas temperature ($T_{\text{gas}} \approx 2900\text{--}3000$ K) in the region containing the radicals of interest. The CH(B–X) features used for column density measurements are shown in Figure 1a and again on an expanded scale in Figure 1d.

Absolute column densities $\{M(\nu=0)\}$ (where M = C₂, CH, CN or NH) can be derived from such spectra using

$$\{M(\nu=0)\} = \frac{8\pi L \bar{\nu}^2}{A p_{\text{line}}} \frac{g_l}{g_u} \int \Delta k d\bar{\nu}, \quad (1)$$

where L is the length of the cavity (here, 92 cm), g_l and g_u are the degeneracies of the lower and upper states involved in the respective transitions, A is the Einstein A -coefficient for the $\nu'=0\text{--}\nu''=0$ transition, Δk is the measured change in ring-down rate (in s⁻¹) at a given wavenumber ($\bar{\nu}$, in cm⁻¹) and p_{line} is the ratio of the integrated intensity of the spectral line under study to the total (0,0) band intensity, which can be calculated using PGOPHER and the relevant spectroscopic constants (Table 1) if the radical is localised in a region of reasonably constant T_{gas} . Degeneracies, Einstein A -coefficients and favourable lines for probing C₂, CH (via the A–X transition), NH radicals, and H($n=2$) atoms by CRDS have been detailed in previous publications.^{29,36,44} The corresponding quantities used for the CN(B–X) transition are $g_l = g_u = 2$ and $A = 1.48 \times 10^7$ s⁻¹ (ref. 41) and, for the CH(B–X) transition, $g_l = 4$, $g_u = 2$ and $A = 2.80 \times 10^6$ s⁻¹ (ref. 38). The present analyses assume $p_{\text{line}} = (6.27 \pm 0.45) \times 10^{-3}$ for the P₁(18.5) line of the CN(B–X) (0,0) band at 25750.70 cm⁻¹ and $p_{\text{line}} = (6.56 \pm 0.16) \times 10^{-3}$ for the R₁(13.5) line of the CH(B–X) (0,0) band at 25736.53 cm⁻¹, where the uncertainty in the effective T_{gas} along the column determines the quoted uncertainties on p_{line} on the basis that $T_{\text{gas}} = 2900 \pm 300$ K. To reduce the influence of baseline variations and other interferences, the CRDS spectra were fitted with respect to the intensities of these lines within the groups of near-lying lines shown in Figures 1c and 1d, accounting for their known relative intensities and the temperature dependences thereof, rather than to the lines individually. To convert the experimental $\{M(\nu=0)\}$ values to total column densities (sums over all vibrational states) requires multiplication by the appropriate vibrational partition

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3 functions: namely, 1.83 for $C_2(a)$, 1.36 for CH, 1.58 for CN and 1.28 for NH, all calculated
4 assuming $T_{\text{vib}} = T_{\text{gas}} = 2900$ K.
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7 The more obvious differences between optical emission spectra from MW-activated
8 $CH_4/N_2/H_2$ and CH_4/H_2 plasmas are in the near-UV region, where the former shows features
9 attributable to some or all of CN^* , N_2^* and/or NH^* , depending on the relative N and C
10 fractions. The H^* , C_2^* and CH^* emissions, in contrast, show no obvious changes upon
11 addition of small $F(N_2)$ to a CH_4/H_2 plasma. The dependence of the near-UV (324–360 nm)
12 part of the optical emission spectrum on the C/N ratio is illustrated in Figure 2a, which
13 compares spectra of MW-activated gas mixtures comprising 3 sccm N_2 and, respectively, 0, 3
14 and 10 sccm CH_4 along with 500 sccm of H_2 , all operating at base input power and pressure.
15 As Figure 2b shows, increasing $F(CH_4)$ leads to a strong initial increase in CN^* emission and
16 a progressive decrease in the NH^* emission, while the N_2^* emission intensity is relatively
17 insensitive to changing $F(CH_4)$.
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26 Figure 3a shows z -profiles of the $C_2(d-a)$, $H(n=4-n=2)$ and $CH(A-X)$ emission intensities
27 from a $CH_4/N_2/H_2$ plasma operating under base conditions measured using the earlier optical
28 set-up.⁴⁵ Figure 3b shows profiles for the $N_2(C-B)$, $NH(A-X)$ and $CN(B-X)$ emissions,
29 obtained using the more sensitive optical telescope arrangement described in paper I²⁹
30 because of the relatively weak near-UV emission. The spatial resolutions obtained with these
31 two set-ups are estimated as ~ 0.5 and ~ 3 mm, respectively. Each profile is normalised such
32 that the peak emission intensity is unity. The distributions shown in Figure 3a match those
33 reported previously for the same species in a MW-activated CH_4/H_2 gas mixture operating
34 under very similar conditions in this same reactor.⁴⁵ As in the N_2/H_2 plasma,²⁹ the N_2^*
35 emission profile peaks at low z ; lower than that of the H^* emission. The NH^* profile also
36 peaks at low z , below the emission maxima of any of the C-containing species, and is less
37 spatially extensive in the $CH_4/N_2/H_2$ plasma than in a CH_4 -free N_2/H_2 plasma. The CN^*
38 emission profile maximizes at slightly larger z and is similar in shape to the CH^* emission.
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49 From here on, we recognise that the C_2^* , CH^* and H^* emissions (and, as shown below, the
50 absolute column densities and spatial profiles of these species as determined by CRDS) are
51 changed little by small additions of N_2 , and focus on the possible diagnostic value of the
52 NH^* , N_2^* and CN^* emissions and their variations with process conditions. Figure 4a, for
53 example, shows the variation in the respective emission intensities with increasing MW
54 power. Trebling P from 0.6 to 1.8 kW results in an approximately twofold increase in the N_2^*
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3 emission intensity (measured at $z = 7$ mm), similar to that observed in a pure N_2/H_2 plasma
4 operating in the same reactor and primarily attributable to an increase in plasma volume.²⁹
5 The NH^* and CN^* emission intensities show much steeper P -dependences, increasing by
6 factors of ≈ 4 and ≈ 15 , respectively. These differences are emphasised by the NH^*/N_2^* and
7 CN^*/N_2^* intensity ratio plots shown in Figure 4b, wherein N_2 (by virtue of its comparative
8 unreactivity) is essentially acting as an actinometer. As discussed alongside the C/N/H
9 plasma modelling (section 4, below), the greater increases in the NH^* and, particularly, CN^*
10 emission intensities can be understood in terms of the small P -induced increase in the
11 maximal gas temperature, since a concomitant increase in the H atom density in the hot
12 plasma region accelerates the chemistry responsible for forming these species.
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20 Absorption (CRDS) measurements return absolute column densities and thus provide a more
21 direct measure of the effects of changes in process condition. Figure 5 shows z -dependent
22 profiles of $\{NH(v=0)\}$ measured using the $NH(A-X)$ lines detailed in paper I,²⁹ of
23 $\{CN(v=0)\}$ and $\{CH(v=0)\}$ measured using the $CN(B-X)$ and $CH(B-X)$ lines shown in
24 Figures 1c and 1d, and of $\{CH(v=0)\}$ measured using $CH(A-X)$ lines, as previously,⁴⁴ with
25 an assumption in all cases that $T_{rot} = 2900 \pm 300$ K. We recognise that this is likely to be an
26 over-estimate of T_{gas} at the lowest z value (2 mm) for which we report data but, using NH as
27 an example, even if the effective T_{gas} is as low as 2200 K, the $\{NH(v=0)\}$ value plotted in
28 fig. 5 would only need to be increased by a factor of 1.1 (*i.e.* $\sim 10\%$). The $\{CN(v=0)\}$ and
29 $\{CH(v=0)\}$ data were both determined under base conditions of 20/3/500 sccm $CH_4/N_2/H_2$
30 flow rates, $p = 150$ Torr and $P = 1.5$ kW. As Figure 6 will show, $\{NH(v=0)\}$ declines greatly
31 with increasing $F(CH_4)$; the z -profile for $\{NH(v=0)\}$ shown in Figure 5 was thus measured
32 with a CH_4 -lean, N_2 -rich, 2/15/500 sccm input mixture. As Figure 5 also shows, the
33 $\{CH(v=0)\}$ values obtained from analysis of the B-X lines shown in Figure 1d agree well
34 with those derived using the same $CH(A-X)$ lines as in our previous studies of C/H plasmas,
35 though we note that both are slightly ($\approx 10\%$) lower than had been measured in this same
36 reactor under nominally identical process conditions in 2008.⁴⁴ Compared with $\{CN(v=0)\}$
37 and $\{CH(v=0)\}$, $\{NH(v=0)\}$ peaks lower, at $z \approx 4-5$ mm, and declines gently with increasing
38 z . Relative to the CH_4 -free N_2/H_2 plasma,²⁹ the absolute magnitude of $\{NH(v=0)\}$ measured
39 at $z \approx 4-5$ mm is similar (although $F(N_2)$ is 2.5 times greater in the present experiments), and
40 the decline to higher z is steeper, mimicking the spatial distribution of NH^* emission shown
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3 Figure 6a illustrates the contrasting dependencies of these three species (measured at $z = 8$
4 mm) upon introducing progressively greater $F(\text{CH}_4)$ to a pre-existing N_2/H_2 plasma operating
5 at base power and pressure. Again, the $\{\text{CH}(v=0)\}$ and $\{\text{CN}(v=0)\}$ data were both recorded
6 using $F(\text{N}_2) = 3$ sccm whereas, to increase signal levels, the $\{\text{NH}(v=0)\}$ data were recorded at
7 $F(\text{N}_2) = 15$ sccm. $\{\text{CH}(v=0)\}$ is seen to exhibit the same $X_0(\text{CH}_4)^{0.5}$ dependence as found
8 previously in the case of (N_2 -free) CH_4/H_2 plasmas, where $X_0(\text{CH}_4)$ is the CH_4 input mole
9 fraction.^{44,49} $\{\text{CN}(v=0)\}$ shows a similar initial rise upon adding CH_4 , but plateaus at $F(\text{CH}_4)$
10 ≈ 2.5 sccm under the prevailing plasma conditions, while $\{\text{NH}(v=0)\}$ declines as $X_0(\text{CH}_4)^{-0.5}$.
11 The corresponding trends for $\{\text{CH}(v=0)\}$ and $\{\text{CN}(v=0)\}$ upon adding N_2 to a pre-existing
12 $F(\text{CH}_4)/F(\text{H}_2) = 20/500$ sccm plasma operating at base power and pressure are shown in
13 Figure 6b. The former shows a modest ($\approx 33\%$) increase as $F(\text{N}_2)$ is increased to ≈ 1.5 sccm,
14 while $\{\text{CN}(v=0)\}$ scales almost proportionally with $0 \leq F(\text{N}_2) \leq 7$ sccm.

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24 Figure 7 shows the measured (at $z = 8$ mm) variations in $\{\text{CH}(v=0)\}$, $\{\text{NH}(v=0)\}$ and
25 $\{\text{CN}(v=0)\}$ as a function of applied MW power. Again, practical considerations dictated that
26 the $\{\text{CH}(v=0)\}$ and $\{\text{CN}(v=0)\}$ data were both recorded for base conditions with
27 $F(\text{CH}_4)/F(\text{N}_2)/F(\text{H}_2) = 20/3/500$ sccm while the $\{\text{NH}(v=0)\}$ data were obtained using
28 modified flow rates of $2/15/500$ sccm. $\{\text{CH}(v=0)\}$ is seen to increase near-linearly with P
29 over the range $0.75\text{--}1.85$ kW, as observed previously when using (nominally) N_2 -free C/H
30 plasmas.⁴⁴ $\{\text{NH}(v=0)\}$ shows a similar P -dependence to $\{\text{CH}(v=0)\}$ in this $\text{CH}_4/\text{N}_2/\text{H}_2$
31 plasma, and to $\{\text{NH}(v=0)\}$ measured in the CH_4 -free N_2/H_2 plasma.²⁹ Comparing the absolute
32 magnitudes of $\{\text{NH}(v=0)\}$ measured in the $\text{CH}_4/\text{N}_2/\text{H}_2$ and N_2/H_2 plasmas at any given P ,
33 however, we again see that the $\{\text{NH}(v=0)\}$ values measured in the $\text{CH}_4/\text{N}_2/\text{H}_2$ plasma at $z = 8$
34 mm (Figure 7) are only $\approx 40\%$ those measured in the N_2/H_2 plasma, even though $F(\text{N}_2)$ was
35 2.5 times higher and $F(\text{CH}_4)$ was only 2 sccm. $\{\text{CN}(v=0)\}$ shows the steepest P -dependence,
36 increasing more than 10-fold over the measured range.

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46 $\{\text{CN}(v=0)\}$ also shows greater sensitivity to total pressure than $\{\text{CH}(v=0)\}$. Figure 8 depicts
47 data for two very different N/C input ratio ranges. As Figure 8a shows, $\{\text{CN}(v=0)\}$ and
48 $\{\text{CH}(v=0)\}$ (monitored via the B–X transition and colour coded accordingly), measured
49 under base conditions at $z = 8$ mm, both scale with p across the range $75\text{--}200$ Torr.
50 $\{\text{CN}(v=0)\}$ is a tenth of $\{\text{CH}(v=0)\}$ at 75 Torr, but has a steeper rate of increase with p and
51 approaches one-fifth of $\{\text{CH}(v=0)\}$ at 200 Torr. Figure 8b shows data recorded under rather
52 different conditions, closer to those used in practical CVD diamond growth, and over a wider
53 range of p . Again, the measurements were made at $z = 8$ mm and with $F(\text{CH}_4) = 20$ sccm (in
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3 a total flow rate of 500 sccm). The incident MW power was higher ($P = 1.8$ kW), but the
4 most significant difference was a much lower $F(\text{N}_2)$, equivalent to 0.1 sccm or 200 ppm,
5 introduced as 10 sccm of a 1% N_2 in H_2 mixture. Again, $\{\text{CN}(v=0)\}$ is very much smaller
6 than $\{\text{CH}(v=0)\}$ (here monitored via the A–X transition) at low p (120 Torr), but $\{\text{CN}(v=0)\}$
7 increases much more steeply, such that at $p = 300$ Torr, the measured $\{\text{CN}(v=0)\}/\{\text{CH}(v=0)\}$
8 ratio has increased to ≈ 0.1 .
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13 As in paper I,²⁹ all of the measured trends are now discussed and interpreted in light of
14 companion modelling studies of the prevailing plasma chemistry and composition.
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17 18 4. C/N/H PLASMA MODELLING 19

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21 The 2-D (r, z) model used in the present C/N/H plasma modelling draws on previously
22 reported plasma-chemical mechanisms for the two-component N/H and C/H gas
23 mixtures.^{29,49} To these are added a C/N/H chemical mechanism for neutral species — H, H_2 ,
24 CH_x ($x = 0-4$), C_2H_y ($y = 0-6$), C_3H_x ($x = 0-2$), C_4H_x ($x = 0-2$), NH_x ($x = 0-3$), N_2 and H_xCN
25 ($x = 0-2$)⁴⁹⁻⁵² — and kinetic data for C/N coupling, H-shifting and thermal decomposition
26 reactions involving the additional species H_2CNH , H_3CNH , H_3CNH_2 .⁵³ Also considered were
27 the reaction kinetics of electrons in different C/N/H mixtures,^{29,49,54,55} for electron-ion
28 recombination reactions, and ion inter-conversion reactions involving H_2^+ , H_3^+ , C_2H_2^+ , C_2H_3^+ ,
29 N_2H^+ , NH_4^+ and HCNH^+ .⁵⁶ The most important of the N_2 dissociation reactions and C/N
30 coupling reactions are listed in Table 2, but the full base reaction mechanism involved 45
31 species and ≈ 350 direct and reverse reactions. The effects of adding a few further species
32 (e.g. HCCN , NCCN , CH_2CNH , CH_3CN) were probed, but none were found to have any
33 serious consequence and thus were ultimately omitted. All of the important plasma-chemical
34 conversions identified in the C/H and N/H plasma modelling studies still play significant
35 roles in the C/N/H plasma; but as these have been elaborated previously,^{29,49} we henceforth
36 concentrate particularly on C/N coupling effects. ‘Base’ conditions for the calculations were
37 the same as in the experiments except that the modelling assumes $F_{\text{total}} = 500$ sccm, i.e. $F(\text{H}_2)$
38 = 477 sccm rather than the 500 sccm used in most of the experiments.
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51 4.1 Plasma-chemical conversions in C/N/H plasmas. Modelling the effects of adding 52 CH_4 to a N/H plasma. 53 54

55 Important findings from our previous investigations of C/H plasmas include that: (i) the
56 absorbed MW power is expended mainly on gas heating, via rotational and vibrational
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3 excitation of H₂; (ii) there is rapid redistribution within the CH_x and C₂H_y groups as a result
4 of fast H-shifting reactions; and (iii) there exist three characteristic regions within the reactor
5 volume, distinguished by the prevailing C_xH_y interconversion reactions.^{44,49} A key result of
6 our analyses of MW-activated N/H plasmas²⁹ was that the dominant N₂ decomposition
7 mechanism in an N₂/H₂ plasma involves formation of various N₂* states by electron impact
8 excitation, the radiative or collisional relaxation of which results in an over-population
9 (relative to local thermodynamic equilibrium) of the lowest, metastable A³Σ_u⁺ triplet state,
10 henceforth abbreviated as N₂(A3). That is,
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20 which can be followed by reaction with H atoms:



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25 In the case of C/N/H plasmas, this source is complemented by reaction (4), which was
26 assumed to be the dominant source of N atoms in the one previous modelling study of a MW-
27 activated C/N/H plasma:³⁰
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33 Reaction (4) is only mildly endothermic ($\Delta_r H < 0.2$ eV), with a calculated maximal rate $R_4 \approx$
34 $1.6 \times 10^{14} \text{ cm}^{-3} \text{ s}^{-1}$ in the hot plasma centre under the present base conditions. As such, it is of
35 comparable importance to reaction (3) as a source of N and NH species in the plasma core,
36 and its impact extends further into the cooler regions. Integrating over the whole reactor
37 volume, reaction (4), rather than reaction (3), is calculated to make the greater contribution to
38 N atom production for $p \geq 150$ Torr and input methane fractions $\geq 4\%$. R_4 drops sharply with
39 decreasing p (e.g. maximal $R_4 \approx 3 \times 10^{13} \text{ cm}^{-3} \text{ s}^{-1}$ at $p = 75$ Torr) due to the fall of both [N₂]
40 and [CH], while the maximal rates of reaction (3) only vary by $\approx 30\%$ upon decreasing p from
41 150 to 75 Torr. This latter result can be explained by recognising that the ≈ 3 -fold decrease in
42 [H] upon decreasing p from 150 to 75 Torr is compensated by a corresponding increase in
43 [N₂(A3)] as a result of its reduced quenching by H and H₂. Reaction (5),
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3 is more strongly endothermic ($\Delta_r H \approx 2$ eV) and its calculated rate is correspondingly lower
4 than (namely, around a quarter) that of reaction (4) under base conditions in the hot plasma
5 region.
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9 Reactions (4) and (5) contribute also to H_xCN ($x = 0, 1$) production, but as in our previous
10 modelling of C/N/H gas mixtures in a hot filament CVD reactor,⁵¹ the present analysis reveals
11 other, more important, sources within the family of reactions involving the H_yCNH_z ($y = 0-2$
12 for $z = 0$, and $y = 2$ for $z = 1$) group. The observed decrease in $\{NH(v=0)\}$ upon CH_4 addition
13 (recall Figure 6b) is one indicator of a family of reactions between NH_x and CH_x ($x = 0-3$)
14 radicals that, taken together, are an important source of H_yCNH_z species. Of this set, reactions
15 (6)–(8) involving CH_3 radicals predominate under the present conditions:
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29 Other members of the family, e.g. $CH_2 + N \rightleftharpoons HCN + H$ and $CH + NH_3 \rightleftharpoons H_2CNH + H$,
30 make lesser contributions. The NH_x and H_yCNH_z species are processed further, by thermal
31 decomposition and through their participation in fast H-shifting reactions, in favour of NH_3
32 and HCN (which is the most stable CN-containing species in the present environment). That
33 said, N_2 remains the dominant N-containing species, as in the MW-activated N_2/H_2 and
34 NH_3/H_2 mixtures.²⁹ For the base C/N/H gas mixture, the present calculations suggest that N_2
35 constitutes >99.75% of the total nitrogen content within the reactor, and $\approx 99.5\%$ of the
36 nitrogen content even in the hot plasma region. HCN accounts for $\leq 0.25\%$ of the nitrogen
37 content in the entire reactor; the total NH_3 content is roughly two orders of magnitude further
38 less; and the fractions of all other N-containing species included in the model are orders of
39 magnitude lower still.
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48 Figure 9 shows the spatial distributions of the CN and NH radical number densities, $[CN]$ and
49 $[NH]$, returned by the 2-D model for base conditions. The observed localization is consistent
50 with the combined effects of primary production of CN and NH_x radicals in the hot plasma
51 region, the abovementioned species interconversions, and diffusional and thermodiffusional
52 transfer of both radical and stable species. The calculated $[CH](r, z)$ distribution is very
53 similar to that of $[CN]$, and thus not shown; the calculated forms of the $[CH]$ and $[C_2]$
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distributions are also very similar to those reported in our earlier modelling of MW-activated C/H plasmas.⁴⁹ The predicted localization of these radical species within the hot plasma region is fully consistent with the T_{tot} values returned by the corresponding CRDS measurements (Figure 1) and the z -profiles shown in Figures 3 and 5.

The predicted (r, z) distributions of $[\text{N}_2]$, $[\text{N}]$ and $[\text{NH}_3]$ are each similar to the corresponding distributions in an N_2/H_2 plasma²⁹ and so are not repeated here. The present calculations show HCN distributed throughout the whole reactor volume, in spite of its production being concentrated in the hot plasma region, with a mole fraction distribution that maximizes in the cold (near-wall) regions as a result of thermodiffusional transfer. In contrast to the radical species featured in Figure 9, for which the production and loss terms tend to be in local balance, the HCN distribution is determined by the balance between the production reactions outlined above and the outflow of HCN from the reactor.

We now consider the spatial distribution and the absolute values of the CN concentration in detail. The $[\text{CN}]$ spatial distribution is determined by the product of $[\text{HCN}]$ and the $[\text{H}]/[\text{H}_2]$ ratio as a result of the fast equilibration reaction



The forward reaction is exothermic ($\Delta_r H \approx -1.3$ eV), and the excess energy is preferentially partitioned into HCN product vibration, particularly the C–H stretch mode (ν_3).⁵⁷ The rates of the forward (R_{+9}) and reverse (R_{-9}) reactions in the hot plasma region under base conditions are both calculated to be $\approx 2.5 \times 10^{18} \text{ cm}^{-3} \text{ s}^{-1}$. These rates are higher than the vibrational–translational (V–T) relaxation rate of $\text{HCN}(\nu > 0)$ molecules through collision with H_2 , C_2H_2 or HCN ,⁵⁸ and could be comparable with the (unknown) rate of V–T relaxation through collision with H atoms. The measured CN column densities shown in Figures 5–7 are all ≈ 3.5 times those simulated on the basis of vibrational–translational equilibrium: this implies, in particular, the assumption that the vibrational temperature $T_{\text{vib}}(\text{HCN}, \nu_3) = T_{\text{gas}}$. However, given the rapidity of reaction (9) relative to likely relaxation processes, we cannot exclude the possibility that $T_{\text{vib}}(\text{HCN}, \nu_3) \gg T_{\text{gas}}$. Thus, while the 3.5-fold discrepancy could be due to imperfections in the assumed reaction mechanisms and/or temperature-dependent rate coefficients, given the quantitative accuracy with which the density distributions of the other species are reproduced, it could also be explained in a more restricted and physically motivated sense. Assigning an enhanced rate constant for $\text{HCN}(\nu_3 > 0)$ molecules in the

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endothermic reaction (–9) would have the required effect of increasing the steady-state CN concentration by some factor b . As Figures 5–7 show, the experimental and model $\{\text{CN}(v=0)\}$ values are in excellent accord if we take $b \approx 3.5$.

A square-root dependence, $\{\text{CH}(v=0)\} \sim F(\text{CH}_4)^{0.5}$, reminiscent of that shown in Figure 6a, was observed and explained previously for C/H plasmas.⁴⁹ $\{\text{CN}(v=0)\}$ in the present C/N/H plasmas shows a similar $F(\text{CH}_4)^{0.5}$ dependence for $F(\text{CH}_4) < 0.5 \times F(\text{N}_2)$, but saturates for $F(\text{CH}_4) \approx F(\text{N}_2)$, whereas $\{\text{NH}(v=0)\}$ varies as $F(\text{CH}_4)^{-0.5}$ while N_2 is in excess. As Figure 6a shows, the present 2-D modelling reproduces all of these trends and dependences well. The saturation in $\{\text{CN}(v=0)\}$ with increasing $F(\text{CH}_4)$, and thus increasing $[\text{CH}_x]$ ($x = 0-3$), reflects the concomitant reduction in $[\text{NH}_x]$ ($x = 0-2$) due to reactions (6)–(8) and the saturation of H_yCNH_z sources.

The dominant ions in the plasma also change upon CH_4 addition. The most abundant ions in the base N/H plasma considered in paper I are NH_4^+ and N_2H^+ ,²⁹ whereas the present calculations identify the most abundant ions in the base C/N/H plasma as C_2H_2^+ and C_2H_3^+ , as in a C/H plasma, but supplemented by HCNH^+ and NH_4^+ . Other more complex $\text{H}_x\text{C}_y\text{N}_z^+$ ions are not included in the reaction scheme as we assume them to be decomposed effectively in the hot plasma region.

4.2 Effects of varying the applied microwave power and the total pressure.

The consequences of varying power and pressure on N/H and C/N/H plasmas are deduced to be very similar. As for the N/H plasma,²⁹ the observed variations with increasing P can be explained in terms of a progressive increase in the plasma volume ($V_{\text{pl}} \sim P$, with $V_{\text{pl}} \approx 70 \text{ cm}^3$ under base conditions, giving a spatially averaged $Q \approx 21.5 \text{ W cm}^{-3}$) while maintaining a broadly constant $T_e \approx 1.25 \text{ eV}$ at the plasma center. The 2-D modelling shows the maximum gas temperature, T_{max} , increasing by $\approx 4\%$ (from 2770 to 2890 K) as P is increased from 750 W to 1500 W. As Figure 7 shows, the predicted variations in $\{\text{CH}(v=0)\}$, $\{\text{CN}(v=0)\}$ and $\{\text{NH}(v=0)\}$ match the measured trends well.

Modelling also shows that decreasing p at constant P is accommodated by a modest (less than proportional to the pressure drop) increase in the plasma volume, V_{pl} , while maintaining n_e broadly constant and with a minor increase in the electron temperature: T_e increases $\approx 10\%$ upon decreasing p from 150 to 75 Torr. The 2-D model succeeds in capturing all of the observed p -dependent trends in the species column densities, as shown in Figure 8a. As with

the N/H plasma,²⁹ the z -dependent $\{\text{NH}(v=0)\}$ profile (shown in Figure 5 for the case of $p = 150$ Torr only) is shown by both experiment and modelling to become flatter at lower pressure.

The measured $\{\text{CN}(v=0)\}$ column densities and CN* emission intensities both increase more steeply with increasing P or p than do the corresponding $\{\text{CH}(v=0)\}$ and CH* emissions (recall Figures 4, 7 and 8). The p -dependence can be understood by recognising that $[\text{CN}]$ is determined by the equilibrium (9): $[\text{CN}] = [\text{H}] \times ([\text{HCN}]/[\text{H}_2]) \times k_{-9}/k_{+9}$. $[\text{H}_2]$ and $[\text{HCN}]$ are both stable species with concentrations that scale as $[\text{H}_2] \sim p$ and $[\text{HCN}] \sim p^{1.5}$. The latter trend reflects the enhanced decomposition of N_2 with increasing p via reactions (3–5), followed by reactions (6–9). $[\text{H}]$ scales with $[\text{H}_2]^2$, given that the main H atom production route is



This simple analysis predicts that $[\text{CN}]$ will show a $p^{2.5}$ dependence, as should $\{\text{CN}(v=0)\}$ if we ignore the small p -dependence of the plasma radius, R_{pl} .

The equilibrium (9) was also analysed at different applied microwave powers P . At a constant pressure $p = 150$ Torr, modelling returns $[\text{HCN}] \sim P^{0.5}$ and $[\text{H}] \sim P$. $[\text{H}_2]$ is essentially independent of P , and thus we predict the functional behaviour $[\text{CN}] \sim P^{1.5}$. Recognising the plasma expansion with increasing power ($R_{\text{pl}} \sim P^{0.5}$), we have $\{\text{CN}\} \sim P^2$, which is a little less steep than the experimentally observed dependence of $\{\text{CN}(v=0)\} \sim P^{2.5}$ (Figure 7).

4.3 Effects of varying $F(\text{N}_2)$ and implications for N-doping of diamond.

The observed linear dependence of $\{\text{CN}(v=0)\}$ and $\{\text{NH}(v=0)\}$ on $F(\text{N}_2)$ (Figure 6) is simply a consequence of their main sources, reactions (3)–(8). As discussed above in the context of adding CH_4 to a N/H plasma, introducing N_2 into a C/H plasma can both change the dominant ions and introduce additional subsidiary, but relatively complex and reactive, $\text{H}_x\text{C}_y\text{N}_z^+$ ions. The observed jump in $\{\text{CH}(v=0)\}$ at low $F(\text{N}_2)$ (also seen in Figure 6) provides indirect evidence for the appearance of such $\text{H}_x\text{C}_y\text{N}_z^+$ species. Introducing $X_0(\text{N}_2) < 0.1\%$ to a 4% CH_4/H_2 mixture cannot have a significant effect on the neutral C/H chemistry or the C_xH_y species concentrations, but by replacing some of the dominant C_xH_y^+ ions by more complex $\text{H}_x\text{C}_y\text{N}_z^+$ ions having higher electron–ion recombination rates, could change the plasma

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3 volume, power density, and/or maximal gas temperature sufficiently to induce the observed
4 jump in $\{\text{CH}(v=0)\}$. We have previously observed and explained a more dramatic jump in
5 $\{\text{H}(n=2)\}$ induced by a change in dominant ion from H_3^+ in a pure H_2 plasma to a mixture of
6 C_2H_2^+ and C_2H_3^+ ions upon introducing CH_4 .^{44,49}
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10 As noted in the Introduction, longstanding unresolved aspects of diamond CVD from C/N/H
11 plasmas include the nature of the gas-phase precursor(s) responsible for N-doping and the
12 cause of the growth rate enhancement upon small (even down to the level of a few ppm)
13 additions of N_2 to the process gas.^{5-7,9-15} The current study directly addresses the first of these
14 questions. Table 3 presents calculated species number densities just above the substrate
15 centre ($r = 0$, $z = 0.5$ mm) for four different N_2 input mole fractions (1, 20, 100 and 6000
16 ppm) under otherwise base conditions; and for two other values of P (0.75 and 3 kW) and one
17 other value of p (75 Torr) with the base, 0.6% N_2 /4% CH_4 / H_2 mixture. Two other C/N/H gas
18 mixtures are also considered for which the input N mole fraction (0.6% and 3% N_2 ,
19 respectively) exceeds that of C (0.4% CH_4), again with the balance being H_2 and at base
20 conditions of P and p . The values reported in Table 3 are the raw model outputs, apart from
21 the case of CN, where the values have been increased by the empirical factor $b \approx 3.5$. Of the
22 directly incorporable N-containing species included in the model, N, NH, NH_2 and CN,
23 atomic nitrogen is the most abundant close to the diamond surface under base P and p , and
24 the near-surface N atom number densities, $[\text{N}]_{\text{ns}}$, returned by the modelling are typically an
25 order of magnitude higher than $[\text{CN}]_{\text{ns}}$. However, $[\text{CN}]_{\text{ns}}$ increases more rapidly than $[\text{N}]_{\text{ns}}$
26 upon increasing P or p , so that the predicted $[\text{N}]_{\text{ns}}/[\text{CN}]_{\text{ns}}$ ratio shows a ≈ 5 -fold decrease upon
27 doubling p from 75 to 150 Torr or P from 1.5 to 3 kW. This trend suggests that gas-surface
28 reactions involving CN may become an increasingly important route to incorporating N
29 within diamond grown at high P and p .
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44 The near-surface species concentrations returned by the plasma modelling are necessary but
45 not sufficient information for estimating the relative contributions different species make to
46 diamond growth. This determination is sensitive to the relative sticking coefficients, γ , of the
47 various species at a growing diamond surface. These quantities, and their variation with
48 process conditions, are still not well characterized however. Prior molecular dynamics
49 simulations of CH_x ($x = 0-3$) encounters with diamond (100) and (111) surfaces at
50 temperatures relevant to diamond CVD found that sticking is more probable if the incident
51 species has more free electrons and fewer H atoms.⁵⁹ for example, C atoms were predicted to
52 have an order of magnitude higher sticking probability than CH_3 radicals. The present
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3 modelling assumes a net sticking probability for CH₃ radicals that has been derived by
4 comparing near-surface gas-phase model outputs with experimentally measured growth
5 rates,⁶⁰ while the sticking coefficients for other small, potentially reactive radical species
6 (CH₂, CH, C, NH₂, NH, N and CN) were all set at 0.1. This latter value is based on the
7 assumptions that these species each have unit incorporation probability at a non-H-terminated
8 surface radical site (henceforth C_s*), and that the calculated steady-state fraction $X(C_s^*)$ of
9 such sites at base growth conditions is $X(C_s^*) \sim 0.1$.⁶⁰ These sticking probabilities are thus
10 ≈ 25 times greater than that derived for CH₃ radicals under the present base conditions, but
11 since [CH₂]_{ns}, [CH]_{ns} and [C]_{ns} are all much lower than [CH₃]_{ns} (Table 3), even with their
12 much higher assumed net incorporation probabilities $\sim X(C_s^*)$, these species are still predicted
13 to make little contribution to the overall growth rate. Furthermore, the rates R_{+9} and R_{-9} are so
14 high that [CN]_{ns} is rather insensitive to the choice of γ_{CN} . However, the situation with the
15 remaining species, and especially N atoms, is less clear. Given the choice of what is
16 essentially an upper-limit value of γ_N , the ratios of the net incorporation rates
17 ($R_{inc}(N)/R_{inc}(CH_3) \sim \gamma_{inc}(N) \times [N]_{ns} / \gamma_{inc}(CH_3) \times [CH_3]_{ns}$) reported in Table 3 should definitely
18 also be taken as upper limits.

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31 The only difference in the input parameters for the data listed in the first four columns of
32 Table 3 is the value of $X_0(N_2)$. The predicted value of $[N]_{ns}/[CH_3]_{ns}$ increases from $\approx 4 \times 10^{-8}$
33 for $X_0(N_2) = 0.0001\%$ (1 ppm) to 9×10^{-7} for $X_0(N_2) = 0.002\%$, 4.4×10^{-6} when $X_0(N_2) =$
34 0.01% , and 2.3×10^{-4} for $X_0(N_2) = 0.6\%$. These are each much smaller than the respective
35 $X_0(N_2)/X_0(CH_4)$ ratios, i.e. those in the input source gas mixtures, but the ratio of these ratios,
36 the “relative nitrogen activation fraction” ($[N]_{ns}/[CH_3]_{ns} / (X_0(N_2)/X_0(CH_4))$), is consistently
37 $(1.6 \pm 0.1) \times 10^{-3}$. The absolute value of the activation fraction will be process-dependent, but
38 for small $X_0(N_2)$ and an otherwise consistent set of process conditions, the $[N]_{ns}/[CH_3]_{ns}$ ratio
39 varies essentially proportionally with input $X_0(N_2)$. As Table 3 shows, doubling P from 1.5 to
40 3 kW is predicted to result in a ≈ 5 -fold increase in relative nitrogen activation, which may
41 have a yet larger impact on the relative N:C incorporation efficiency given the decrease in
42 $[N]_{ns}/[CN]_{ns}$ that also accompanies such an increase in P . However, that the activation
43 fraction is always $\ll 1$, and the ratio of ratios ($R_{inc}(N)/R_{inc}(CH_3) / (X_0(N_2)/X_0(CH_4))$) (i.e. the
44 normalized incorporation rate) is fairly constant across a broad range of nitrogen input
45 fractions and consistently < 1 , should offer a useful guide when it comes to predicting N
46 concentrations and N incorporation efficiencies in CVD diamond.

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3 Finally, it is instructive to compare the present findings with the predictions of the one
4 previous modelling study of a MW-activated C/N/H plasma operating at pressures and
5 temperatures relevant to diamond CVD, by Yamada.³⁰ The earlier work treated the following
6 conditions: $F(\text{CH}_4) = 25$ sccm, $F(\text{N}_2) = 2.5$ sccm, $F(\text{H}_2) = 500$ sccm (i.e. $X_0(\text{CH}_4) = 4.7\%$ and
7 $X_0(\text{N}_2) = 0.47\%$), $p = 120$ Torr, and $P = 3$ kW into a plasma volume seemingly about twice
8 that of the present work. The calculated maximum gas temperature in the hot plasma core
9 was $T_{\text{max}} \approx 3000$ K and the near-substrate gas temperature $T_{\text{gas}} \approx 1500$ K. These temperatures
10 are a little higher than found from the present modelling, while the pressure is a little lower.
11 Differences between the earlier data and that shown in the fourth column of Table 3 are
12 generally minor: $[\text{NH}_3]_{\text{ns}}$ is here about one order of magnitude larger than in the earlier work,
13 even after correcting for the difference in pressure, but the $[\text{NH}]_{\text{ns}}$ and $[\text{N}]_{\text{ns}}$ values agree
14 between the two studies to within a factor of 2. Our higher $[\text{NH}_3]_{\text{ns}}$ can be traced to the role of
15 reactions (2) and (3) in providing a non-thermal route to activating and dissociating N_2 ,
16 which was not considered in the earlier modelling, while the lower $[\text{N}]_{\text{ns}}$ is likely due to a
17 high assumed value of γ_{N} . Importantly, the relative nitrogen activation fraction ($\approx 6.7 \times 10^{-3}$)
18 found by Yamada is not very different to ours, highlighting the predominant roles of thermal
19 chemistry and transport in determining the near-substrate species concentrations.
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32 5. CONCLUSIONS

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34 Spatially resolved optical emission and line-of-sight absorption spectroscopy methods have
35 been used to probe selected atomic (H), radical (CH, C_2 , CN and NH), and triplet N_2
36 molecule densities in MW-activated $\text{CH}_4/\text{N}_2/\text{H}_2$ gas mixtures such as are used in diamond
37 CVD, as functions of the source gas mole fractions, total pressure, and applied MW power.
38 These data have been rationalised using complementary 2-D (r, z) coupled kinetic and
39 transport modelling, which succeeds, mostly quantitatively, in reproducing all of the
40 measured trends in species column densities and OES intensities. After calibration against
41 experiment, the model was run over a wider range of N/C input ratios, $2.5 \times 10^{-5} \leq$
42 $X_0(\text{N}_2)/X_0(\text{CH}_4) \leq 7.5$, than could be explored experimentally, as well as with a higher MW
43 power of 3 kW.
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52 Key findings include:

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55 i) For base conditions of $p = 150$ Torr and $P = 1.5$ kW, strongly bound N_2 molecules
56 constitute $>99.75\%$ of the total nitrogen content in the reactor, falling only to $\approx 99.5\%$ even in
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3 the hot plasma core. Less than 0.25% of the supplied nitrogen becomes HCN, with all other
4 N-containing species two or more orders of magnitude less abundant still.
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7 ii) Two reaction sequences enable N_2 to participate in the plasma chemistry. Reaction (4),
8 proposed as the dominant source of N atoms in the one previous modelling study of a MW-
9 activated C/N/H plasma,³⁰ involves the reaction of N_2 with CH radicals. Reactions (2) and
10 (3), identified in our recent studies of MW-activated N_2/H_2 plasmas,²⁹ involve electron
11 impact excitation of N_2 in the hot plasma region, energy pooling in the metastable $N_2(A^3\Sigma_u^+)$
12 state, and subsequent reaction with H atoms. The former pathway is the more important route
13 to forming N atoms at higher gas pressures, input powers, and/or CH_4 input fractions.
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19 iii) Of the N-containing species that can be considered potentially reactive at the growing
20 diamond surface, namely N, NH, NH_2 and CN, the near-surface gas-phase number density of
21 atomic nitrogen under base conditions is higher than $[NH]_{ns}$ or $[NH_2]_{ns}$ and typically an order
22 of magnitude higher than $[CN]_{ns}$.
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27 iv) Comparing the measured $\{CN(v=0)\}$ data with model predictions reveals an
28 underestimation that hints at an unusual (for high pressures, $p > 100$ Torr) non-thermal
29 vibrational population distribution in HCN molecules formed in the fast exothermic reaction
30 (9), and significantly enhanced rates for subsequent reactions involving these “hot” HCN
31 molecules.
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36 v) Changing the input N/C ratio in the process gas mixture under base conditions causes a
37 proportional change in the $[N]_{ns}/[CH_3]_{ns}$ ratio, but has little effect on the $[N]_{ns}/[NH]_{ns}/[CN]_{ns}$
38 ratios just above the growing surface. The $[N]_{ns}/[CH_3]_{ns}$ ratio is consistently much smaller
39 than the $X_0(N_2)/X_0(CH_4)$ ratio in the input gas mixture, reflecting the stability of N_2 under
40 these process conditions. Increasing p or P promotes N_2 dissociation, and so raises both the
41 $[N]_{ns}/[CH_3]_{ns}$ and $[CN]_{ns}/[CH_3]_{ns}$ ratios for the same N input fraction.
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47 Finally, we return briefly to consider the longstanding issue raised in the Introduction: how
48 the presence of small amounts of nitrogen in the gas phase leads to an increase in diamond
49 growth rate and influences the surface morphology. H atoms and CH_3 radicals are generally
50 accepted as the key species driving diamond CVD from MW-activated gas mixtures. As
51 Table 3 shows, increasing $X_0(N_2)$ from 1 to 20 ppm has no perceptible effect on the $[H]_{ns}$ or
52 $[CH_3]_{ns}$ values. Even at $X_0(N_2) = 100$ ppm, $[CH_3]_{ns}$ increases by little more than 1%. Clearly,
53 the present analysis confirms that trace additions of N_2 (a rather inert species) has very little
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3 impact on the C/H chemistry or on [H] or [CH₃] close to the growing diamond surface. N
4 atoms, NH and CN radicals will all be present in the near-surface volume, but for $X_0(\text{N}_2) =$
5 100 ppm, their number densities will be some five to six orders of magnitude smaller than
6 [CH₃]_{ns}. Because of the small relative nitrogen activation fraction, this is some three orders
7 less than the $X_0(\text{N}_2)/X_0(\text{CH}_4)$ ratio, although this disparity in nitrogen activation versus
8 methane may be partially compensated by the higher (assumed) incorporation efficiency of N
9 atoms versus CH₃ radicals at the growing diamond surface. Increasing p and/or P produces an
10 obvious increase in [CN]_{ns} relative to [NH_{*x*}]_{ns} ($x=0-2$), so we also recognise that different
11 gas-surface chemistry could drive N incorporation under conditions of low and high gas
12 activation. Energetically feasible reaction sequences providing for N, NH, or CN to be
13 accommodated on a model diamond (100) surface have been identified, and are described in
14 a companion paper,⁶¹ but it is hard to imagine that such rare encounters could directly
15 account for the observed rate enhancements or morphological changes. It is also widely
16 accepted that these N-induced effects are just one factor in a multi-parameter growth space,
17 so that the result of adding N₂ to the process mixture also depends on the substrate condition
18 and its temperature during growth.¹⁴ Hence, the present study tends to support prior
19 suggestions that the key role of trace N incorporation is in locally chemically activating the
20 diamond surface, or otherwise enabling faster growth at high substrate temperature by
21 somehow limiting strain⁶² or non-epitaxial-growth¹⁴ in the resulting material that would
22 typically result under such conditions. An additional effect of incorporated nitrogen could
23 arise if the migration of an NH surface group along the diamond surface is significantly
24 hindered relative to that of CH₂. Such immobile NH groups could then serve as anchors for
25 migrating CH₂ groups (as does the step edge in regular step-flow growth), thus enhancing
26 formation of difficult-to-etch chains of CH₂ surface bridges. This decrease in the average
27 migration length of CH₂ groups before incorporation would reduce the rate at which they are
28 etched, and thus accelerate diamond growth.

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50 Notes

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Table 2

Most Important N₂ Dissociation and C/N Coupling Reactions Included in the Present Study with *T*-Dependent Rate Coefficients *k* (cm³ mol⁻¹ s⁻¹).^a

Reaction	Rate coefficient $k = AT^b \exp(-E/RT)$			Ref.
	<i>A</i>	<i>b</i>	<i>E</i>	
N ₂ (A3) + H ⇌ NH + N	1.2 × 10 ¹²	0	3850	29
CH ₃ + N ⇌ H ₂ CN + H	6.10 × 10 ¹⁴	-0.31	290	50
CH ₃ + N ⇌ HCN + H ₂	3.70 × 10 ¹²	0.15	-90	50
CH ₃ + NH ⇌ H ₂ CNH + H	4.00 × 10 ¹³	0	0	52
CH + N ₂ ⇌ HCN + N	3.12 × 10 ⁹	0.88	20130	50
C + N ₂ ⇌ CN + N	6.30 × 10 ¹³	0	46020	50
CN + H ₂ ⇌ HCN + H	2.95 × 10 ⁵	2.45	2240	50
H + H ₂ CN ⇌ HCN + H ₂	7.80 × 10 ¹³	0	0	51

^a Units: cal, cm, s, $R = 1.9873 \text{ cal (mol K)}^{-1}$. N₂(A3) represents the metastable A³Σ_u⁺ state (the lowest-energy triplet state) of N₂, and the gas temperature *T* is quoted in K.

Table 3

Calculated Gas Temperatures, T_{gas} , $[N]_{\text{ns}}/([CN]_{\text{ns}}\times 3.5)$ and $[N]_{\text{ns}}/[CH_3]_{\text{ns}}$ Concentration Ratios, $R_{\text{inc}}(N)/R_{\text{inc}}(CH_3)$ and $(R_{\text{inc}}(N)/R_{\text{inc}}(CH_3))/(X_0(N_2)/X_0(CH_4))$ Incorporation Rate Ratios, and Selected Species Concentrations (in cm^{-3}) above the Substrate Centre (at $r = 0$, $z = 0.5$ mm) from which these Ratios are Derived for a Range of C/N/H Gas Mixtures and Process Conditions.

$X_0(N_2) / \%$	0.0001	0.002	0.01	0.6	0.6	0.6	0.6	0.6	3
$X_0(CH_4) / \%$	4	4	4	4	4	4	4	0.4	0.4
p / Torr	150	150	150	150	150	150	75	150	150
P / kW	1.5	1.5	1.5	1.5	0.75	3.0	1.5	1.5	1.5
$T_{\text{gas}} / \text{K}$	1402	1403	1404	1399	1399	1453	1334	1376	1363
$[N]_{\text{ns}}/([CN]_{\text{ns}}\times 3.5)$	8.16	8.30	8.05	6.75	11.9	1.23	32.0	14.8	9.57
$[N]_{\text{ns}}/[CH_3]_{\text{ns}}$	4.28×10^{-8}	8.78×10^{-7}	4.42×10^{-6}	2.32×10^{-4}	1.54×10^{-4}	1.08×10^{-3}	3.94×10^{-4}	1.34×10^{-3}	4.58×10^{-3}
$([N]_{\text{ns}}/[CH_3]_{\text{ns}})/(X_0(N_2)/X_0(CH_4))$	1.71×10^{-3}	1.76×10^{-3}	1.77×10^{-3}	1.55×10^{-3}	1.03×10^{-3}	7.20×10^{-3}	2.63×10^{-3}	8.93×10^{-4}	6.11×10^{-4}
$R_{\text{inc}}(N)/R_{\text{inc}}(CH_3)$	1.09×10^{-6}	2.24×10^{-5}	1.12×10^{-4}	5.94×10^{-3}	4.64×10^{-3}	2.39×10^{-2}	9.67×10^{-3}	3.34×10^{-2}	1.19×10^{-1}
$(R_{\text{inc}}(N)/R_{\text{inc}}(CH_3))/(X_0(N_2)/X_0(CH_4))$	4.37×10^{-2}	4.47×10^{-2}	4.48×10^{-2}	3.96×10^{-2}	3.10×10^{-2}	1.59×10^{-1}	6.44×10^{-2}	2.23×10^{-2}	1.59×10^{-2}
H	7.49×10^{15}	7.58×10^{15}	7.60×10^{15}	7.25×10^{15}	4.19×10^{15}	1.67×10^{16}	2.35×10^{15}	7.89×10^{15}	6.62×10^{15}
CH ₄	4.15×10^{14}	4.10×10^{14}	4.12×10^{14}	4.45×10^{14}	6.93×10^{14}	1.55×10^{14}	3.57×10^{14}	1.54×10^{14}	2.21×10^{14}
CH ₃	5.25×10^{13}	5.23×10^{13}	5.29×10^{13}	5.48×10^{13}	5.36×10^{13}	3.99×10^{13}	3.19×10^{13}	1.87×10^{13}	2.33×10^{13}
³ CH ₂	2.67×10^{11}	2.70×10^{11}	2.74×10^{11}	2.69×10^{11}	1.57×10^{11}	4.32×10^{11}	9.50×10^{10}	1.03×10^{11}	1.05×10^{11}
¹ CH ₂	7.35×10^9	7.45×10^9	7.58×10^9	7.36×10^9	4.18×10^9	1.50×10^{10}	2.13×10^9	2.52×10^9	2.51×10^9
CH	8.96×10^9	9.16×10^9	9.31×10^9	8.73×10^9	2.96×10^9	3.21×10^{10}	2.01×10^9	3.71×10^9	3.24×10^9
C	2.88×10^{10}	2.97×10^{10}	3.00×10^{10}	2.65×10^{10}	4.77×10^9	2.35×10^{11}	3.65×10^9	2.92×10^{10}	1.92×10^{10}
C ₂ (a)	4.93×10^8	5.00×10^8	5.04×10^8	4.45×10^8	5.00×10^8	1.16×10^9	8.22×10^8	5.78×10^8	4.06×10^8
C ₂ (X)	1.50×10^7	1.55×10^7	1.61×10^7	1.45×10^7	5.67×10^6	1.38×10^8	5.27×10^6	3.47×10^6	2.77×10^6
C ₂ H	4.49×10^{10}	4.59×10^{10}	4.76×10^{10}	4.59×10^{10}	2.68×10^{10}	1.79×10^{11}	9.98×10^9	5.73×10^9	6.33×10^9
C ₂ H ₂	8.10×10^{15}	8.11×10^{15}	8.31×10^{15}	8.73×10^{15}	8.81×10^{15}	9.60×10^{15}	4.91×10^{15}	1.22×10^{15}	1.77×10^{15}
C ₂ H ₃	9.72×10^{12}	9.74×10^{12}	9.94×10^{12}	1.04×10^{13}	7.47×10^{12}	1.25×10^{13}	2.84×10^{12}	1.68×10^{12}	2.34×10^{12}
C ₂ H ₄	2.34×10^{14}	2.32×10^{14}	2.36×10^{14}	2.58×10^{14}	2.92×10^{14}	1.33×10^{14}	7.59×10^{13}	4.05×10^{13}	6.60×10^{13}
C ₂ H ₅	8.76×10^{10}	8.64×10^{10}	8.74×10^{10}	9.70×10^{10}	1.07×10^{11}	4.15×10^{10}	2.19×10^{10}	1.66×10^{10}	2.79×10^{10}
C ₂ H ₆	1.61×10^{11}	1.58×10^{11}	1.59×10^{11}	1.84×10^{11}	2.94×10^{11}	3.57×10^{10}	1.19×10^{11}	2.72×10^{10}	5.29×10^{10}
C ₃	3.35×10^{12}	3.44×10^{12}	3.54×10^{12}	3.44×10^{12}	6.28×10^{11}	2.50×10^{13}	7.88×10^{11}	4.39×10^{11}	4.94×10^{11}
C ₃ H	6.12×10^{10}	6.23×10^{10}	6.42×10^{10}	6.42×10^{10}	1.92×10^{10}	2.62×10^{11}	1.53×10^{10}	6.49×10^9	8.15×10^9
C ₃ H ₂	7.07×10^{13}	7.11×10^{13}	7.29×10^{13}	7.66×10^{13}	3.97×10^{13}	1.28×10^{14}	2.99×10^{13}	7.31×10^{12}	1.09×10^{13}
C ₄	1.69×10^5	1.75×10^5	1.85×10^5	1.75×10^5	6.47×10^4	2.00×10^6	6.68×10^4	1.02×10^4	1.02×10^4
C ₄ H	7.35×10^7	7.52×10^7	7.92×10^7	7.86×10^7	5.28×10^7	3.38×10^8	5.17×10^7	4.37×10^6	5.21×10^6
C ₄ H ₂	6.23×10^{12}	6.26×10^{12}	6.56×10^{12}	7.19×10^{12}	6.83×10^{12}	9.94×10^{12}	4.28×10^{12}	1.73×10^{11}	3.37×10^{11}
H($n=2$)	2.49×10^6	2.55×10^6	2.56×10^6	2.18×10^6	1.56×10^6	7.58×10^6	1.64×10^6	3.58×10^6	2.17×10^6
H($n=3$)	1.37×10^5	1.40×10^5	1.41×10^5	1.19×10^5	8.61×10^4	4.22×10^5	1.16×10^5	2.13×10^5	1.25×10^5

H ₂	1.02×10 ¹⁸	1.02×10 ¹⁸	1.02×10 ¹⁸	1.02×10 ¹⁸	1.02×10 ¹⁸	9.67×10 ¹⁷	5.34×10 ¹⁷	1.04×10 ¹⁸	1.03×10 ¹⁸
N ₂	4.90×10 ¹¹	9.82×10 ¹²	5.01×10 ¹³	3.18×10 ¹⁵	3.25×10 ¹⁵	3.38×10 ¹⁵	1.73×10 ¹⁵	2.94×10 ¹⁵	2.16×10 ¹⁶
N ₂ (A3)	5.74×10 ⁵	1.16×10 ⁷	5.89×10 ⁷	3.44×10 ⁹	4.77×10 ⁹	3.67×10 ⁹	6.57×10 ⁹	5.04×10 ⁹	3.05×10 ¹⁰
NH ₃	7.21×10 ⁷	1.44×10 ⁹	7.25×10 ⁹	4.37×10 ¹¹	1.32×10 ¹²	1.40×10 ¹¹	1.26×10 ¹²	6.53×10 ¹¹	3.98×10 ¹²
NH ₂	8.73×10 ⁵	1.76×10 ⁷	8.94×10 ⁷	5.13×10 ⁹	9.38×10 ⁹	3.78×10 ⁹	8.70×10 ⁹	7.68×10 ⁹	3.97×10 ¹⁰
NH	4.95×10 ⁵	1.00×10 ⁷	5.11×10 ⁷	2.86×10 ⁹	3.44×10 ⁹	3.96×10 ⁹	3.92×10 ⁹	4.61×10 ⁹	2.20×10 ¹⁰
N	2.24×10 ⁶	4.59×10 ⁷	2.33×10 ⁸	1.27×10 ¹⁰	8.26×10 ⁹	4.30×10 ¹⁰	1.26×10 ¹⁰	2.51×10 ¹⁰	1.07×10 ¹¹
CN(×3.5)	2.75×10 ⁵	5.54×10 ⁶	2.90×10 ⁷	1.88×10 ⁹	6.94×10 ⁸	3.48×10 ¹⁰	3.93×10 ⁸	1.70×10 ⁹	1.12×10 ¹⁰
HCN	4.11×10 ⁹	8.13×10 ¹⁰	4.21×10 ¹¹	2.95×10 ¹³	1.83×10 ¹³	1.77×10 ¹⁴	1.16×10 ¹³	2.80×10 ¹³	2.36×10 ¹⁴
H ₂ CN	9.58×10 ⁴	1.90×10 ⁶	9.80×10 ⁶	6.76×10 ⁸	3.10×10 ⁸	4.65×10 ⁹	1.93×10 ⁸	7.38×10 ⁸	5.92×10 ⁹
H ₂ CNH	1.86×10 ⁵	3.71×10 ⁶	1.89×10 ⁷	1.18×10 ⁹	2.28×10 ⁹	6.31×10 ⁸	3.24×10 ⁹	7.13×10 ⁸	5.43×10 ⁹
H ₃ CNH	1.33×10 ²	2.65×10 ³	1.35×10 ⁴	8.26×10 ⁵	1.29×10 ⁶	3.60×10 ⁵	1.08×10 ⁶	5.18×10 ⁵	3.59×10 ⁶
H ₃ CNH ₂	1.14×10 ⁴	2.25×10 ⁵	1.14×10 ⁶	7.28×10 ⁷	1.95×10 ⁸	1.37×10 ⁷	1.39×10 ⁸	4.14×10 ⁷	3.34×10 ⁸
e	8.99×10 ¹⁰	9.07×10 ¹⁰	9.17×10 ¹⁰	8.75×10 ¹⁰	9.83×10 ¹⁰	1.21×10 ¹¹	8.47×10 ¹⁰	6.34×10 ¹⁰	5.58×10 ¹⁰
C ₂ H ₂ ⁺	6.51×10 ¹⁰	6.56×10 ¹⁰	6.68×10 ¹⁰	5.90×10 ¹⁰	6.62×10 ¹⁰	6.62×10 ¹⁰	5.56×10 ¹⁰	1.50×10 ¹⁰	8.39×10 ⁹
C ₂ H ₃ ⁺	2.48×10 ¹⁰	2.49×10 ¹⁰	2.44×10 ¹⁰	9.35×10 ⁹	1.20×10 ¹⁰	2.72×10 ⁹	1.62×10 ¹⁰	1.32×10 ¹⁰	5.84×10 ⁸
H ₃ ⁺	1.82×10 ⁷	1.84×10 ⁷	1.77×10 ⁷	7.90×10 ⁶	9.96×10 ⁶	5.93×10 ⁶	1.57×10 ⁷	9.71×10 ⁷	1.34×10 ⁷
H ₂ ⁺	2.52×10 ⁴	2.56×10 ⁴	2.55×10 ⁴	2.20×10 ⁴	2.85×10 ⁴	3.42×10 ⁴	7.60×10 ⁴	4.20×10 ⁴	2.68×10 ⁴
N ₂ H ⁺	6.35×10 ¹	1.29×10 ³	6.32×10 ³	1.80×10 ⁵	2.31×10 ⁵	1.38×10 ⁵	4.03×10 ⁵	2.08×10 ⁶	2.15×10 ⁶
NH ₄ ⁺	6.90×10 ⁵	1.38×10 ⁷	6.97×10 ⁷	3.58×10 ⁹	9.11×10 ⁹	1.95×10 ⁹	6.02×10 ⁹	5.41×10 ⁹	1.81×10 ¹⁰
HCNH ⁺	4.07×10 ⁶	8.07×10 ⁷	4.09×10 ⁸	1.56×10 ¹⁰	1.10×10 ¹⁰	4.96×10 ¹⁰	6.89×10 ⁹	2.97×10 ¹⁰	2.88×10 ¹⁰

Figure Captions

Figure 1

Part of the CN(B–X) and CH(B–X) $\Delta v=0$ systems (a) as measured by CRDS at $z = 8$ mm in a $\text{CH}_4/\text{N}_2/\text{H}_2$ plasma operating under base conditions along with (b) a PGOPHER simulation that assumes $T_{\text{rot}} = 3000$ K and serves to illustrate lines associated with the different carriers. Expanded views of the spectral regions used for monitoring CN(X) and CH(X) column densities are shown in panels (c) and (d), respectively, along with accompanying PGOPHER simulations that illustrate the spectral sensitivity to T_{rot} and, by inference, T_{gas} , in the case of the CN(B–X) lines. The CH(B–X) features, in contrast, depend only weakly on temperature.

Figure 2

(a) Optical emission spectra, measured at $z = 7$ mm, of MW activated gas mixtures comprising 3 sccm N_2 and, respectively, (i) 0, (ii) 3 and (iii) 10 sccm CH_4 along with 500 sccm of H_2 , operating at base input power and pressure. (b) Plot illustrating the variation in relative CN^* , N_2^* and NH^* emission intensities with increasing $F(\text{CH}_4)$, with the maximum intensity of each emission normalised to unity.

Figure 3

z -profiles of (a) the $\text{C}_2(\text{d-a})$, $\text{H}(n=4-n=2)$ and $\text{CH}(\text{A-X})$ emission intensities and (b) the $\text{N}_2(\text{C-B})$, $\text{NH}(\text{A-X})$ and $\text{CN}(\text{B-X})$ emissions from a $\text{CH}_4/\text{N}_2/\text{H}_2$ plasma operating under base conditions measured using the two complementary optical set-ups summarised in the text.

Figure 4

(a) NH^* , N_2^* and CN^* emission intensities measured at $z = 7$ mm ($\text{CH}_4/\text{N}_2/\text{H}_2$ 20/3/500 sccm plasma) as a function of applied MW power under otherwise base conditions. The emission intensities of each species are normalised to the maximal value measured at any P . The P -dependence of the NH^*/N_2^* and CN^*/N_2^* intensity ratios are shown in panel (b).

Figure 5

Profiles of $\{\text{NH}(v=0)\}$, $\{\text{CN}(v=0)\}$ and $\{\text{CH}(v=0)\}$ as a function of z , obtained by CRDS probing of $\text{CH}_4/\text{N}_2/\text{H}_2$ plasmas operating with respective flow rates of 2/15/500 sccm (for NH) and 20/3/500 sccm (for CN and CH) and base values of total pressure and applied power. Note the good agreement in the $\{\text{CH}(v=0)\}$ values determined when monitoring via the two different electronic transitions. The solid curves through these data show the z -dependent column densities of these three species returned by the modelling described in

1
2
3 Section 4. Note that the calculated $\{\text{CN}(v=0)\}$ values have been increased by a factor of 3.5
4 prior to display.
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7 **Figure 6**

8 The solid points show the measured variations in: (a) $\{\text{CH}(v=0)\}$, $\{\text{CN}(v=0)\}$ and $\{\text{NH}(v=0)\}$
9 following addition of CH_4 to pre-existing N_2/H_2 plasmas (3/500 sccm when probing CH and
10 CN, 15/500 when monitoring NH); and (b) $\{\text{CH}(v=0)\}$ and $\{\text{CN}(v=0)\}$ upon adding N_2 to a
11 pre-existing CH_4/H_2 (20/500 sccm) plasma. All measurements were made at $z = 8$ mm and all
12 plasmas were operating at base power and pressure. The corresponding quantities returned by
13 the model calculations described in Section 4 are indicated by open symbols. As in Figure 5,
14 the calculated $\{\text{CN}(v=0)\}$ values have been increased by a factor of 3.5 prior to display.
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21 **Figure 7**

22 The solid points show measured variations in $\{\text{CH}(v=0)\}$, $\{\text{NH}(v=0)\}$ and $\{\text{CN}(v=0)\}$ with
23 increasing MW power for plasmas formed using $\text{CH}_4/\text{N}_2/\text{H}_2$ flow rates of 20/3/500 sccm (for
24 CH and CN) and 2/15/500 sccm (for NH). All measurements were made at $z = 8$ mm. The
25 corresponding quantities returned by the model calculations described in Section 4 are
26 indicated by open symbols. As in Figure 5, the calculated $\{\text{CN}(v=0)\}$ values have been
27 increased by a factor of 3.5 prior to display.
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34 **Figure 8**

35 Measured variations in $\{\text{CH}(v=0)\}$ and $\{\text{CN}(v=0)\}$ as a function of total gas pressure
36 measured: (a) under base conditions, over the range 75–200 Torr; and (b) at $P = 1.8$ kW with
37 $F(\text{CH}_4) = 20$ sccm and an effective $F(\text{N}_2) = 0.1$ sccm (in a total flow rate of 500 sccm) over
38 the range $120 \leq p \leq 300$ Torr. All measurements were made at $z = 8$ mm. The corresponding
39 quantities returned by the model calculations described in Section 4 are shown by open
40 symbols in panel (a). As in Figure 5, the calculated $\{\text{CN}(v=0)\}$ values have been increased by
41 a factor of 3.5 prior to display.
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49 **Figure 9**

50 2-D (r, z) plots showing the predicted total number densities of CN and NH radicals in a
51 4% $\text{CH}_4/0.6\%\text{N}_2/\text{H}_2$ plasma, total flow rate $F = 500$ sccm, $P = 1.5$ kW and $p = 150$ Torr. The
52 model assumes cylindrical symmetry, a substrate diameter of 3 cm, and a reactor radius, $r = 6$
53 cm, and height, $h = 6.2$ cm.
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Figure 1

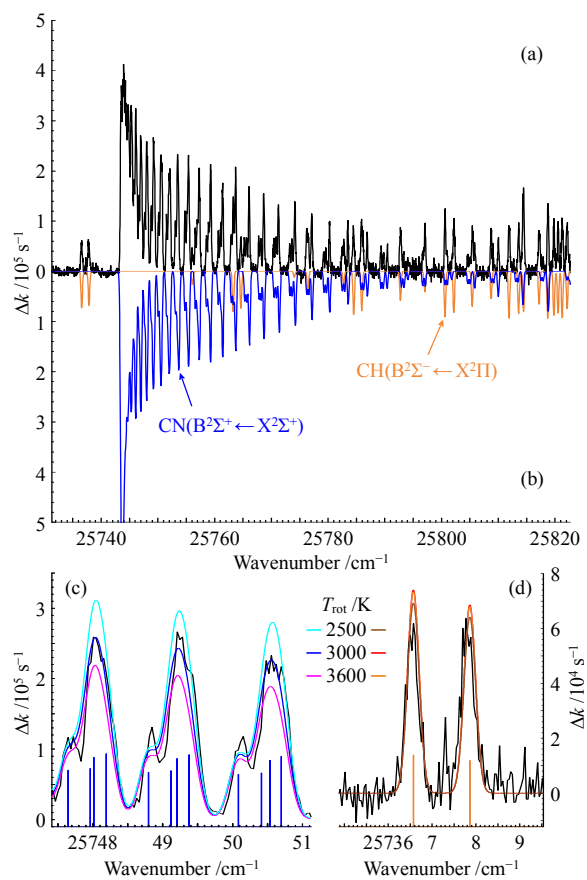


Figure 2

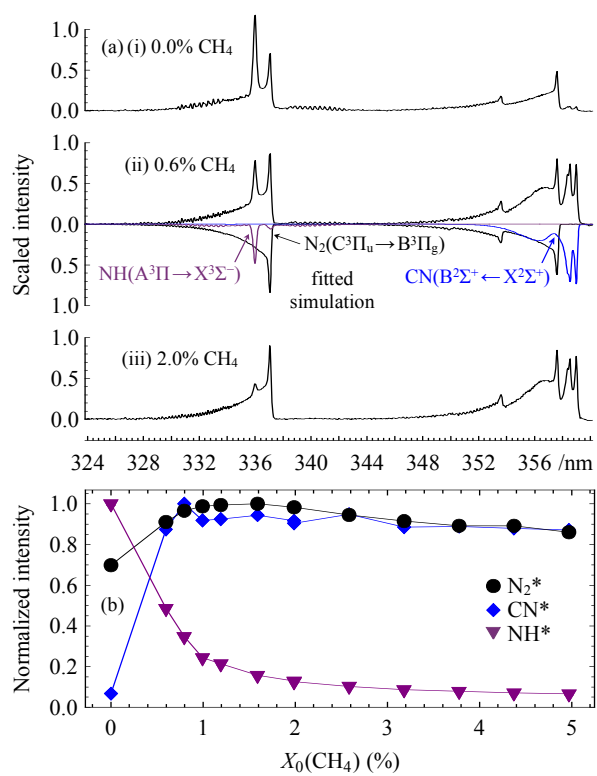


Figure 3

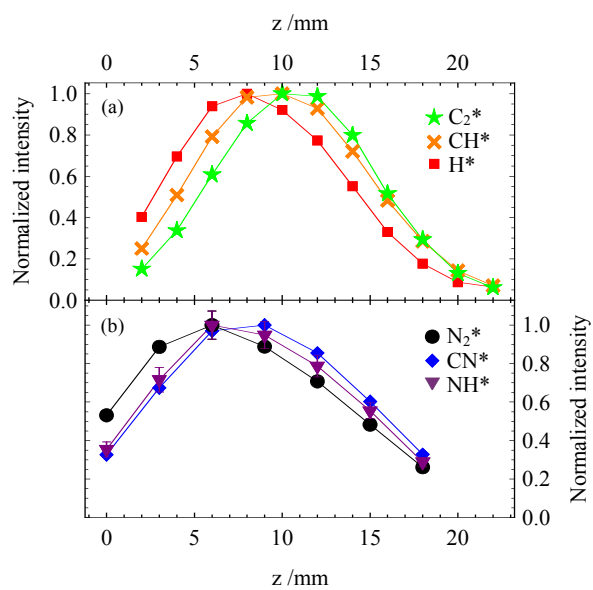


Figure 4

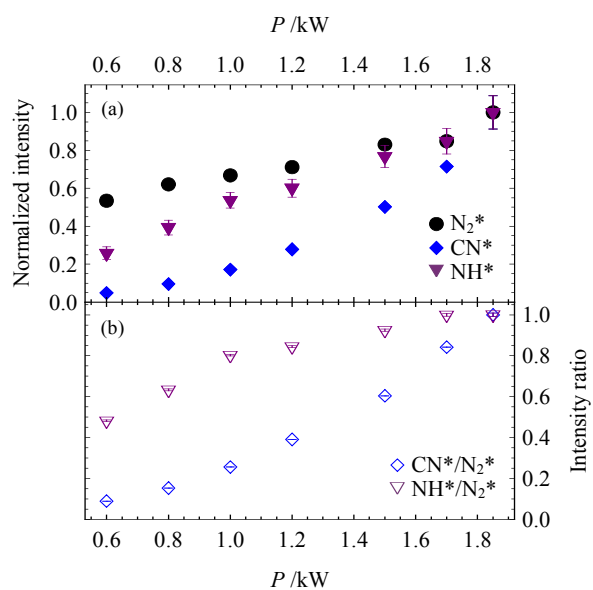


Figure 5

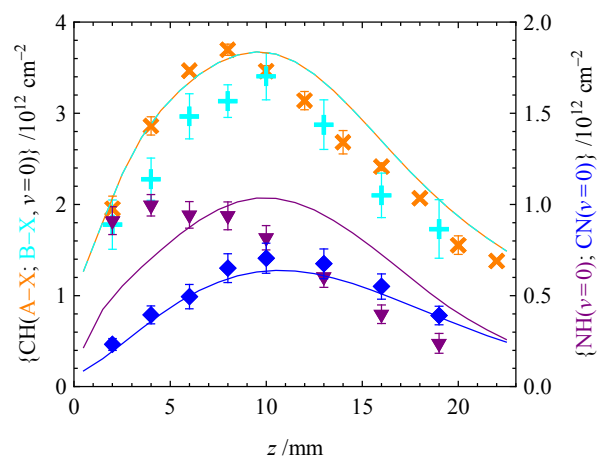


Figure 6

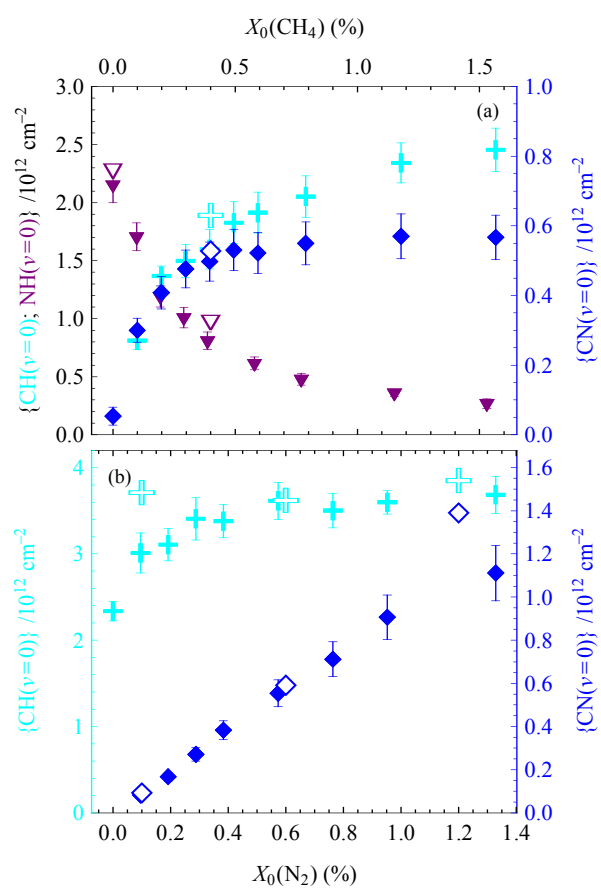


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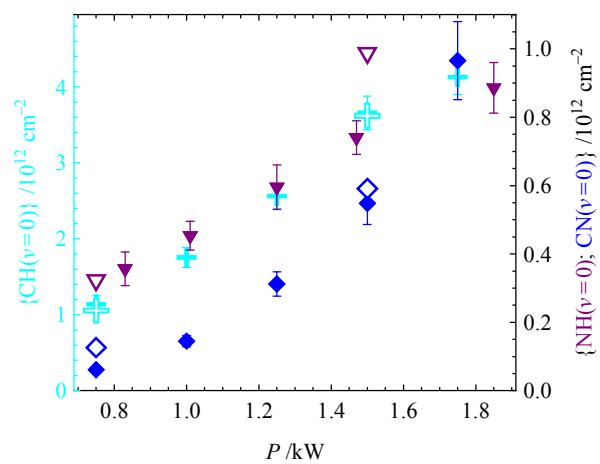


Figure 8

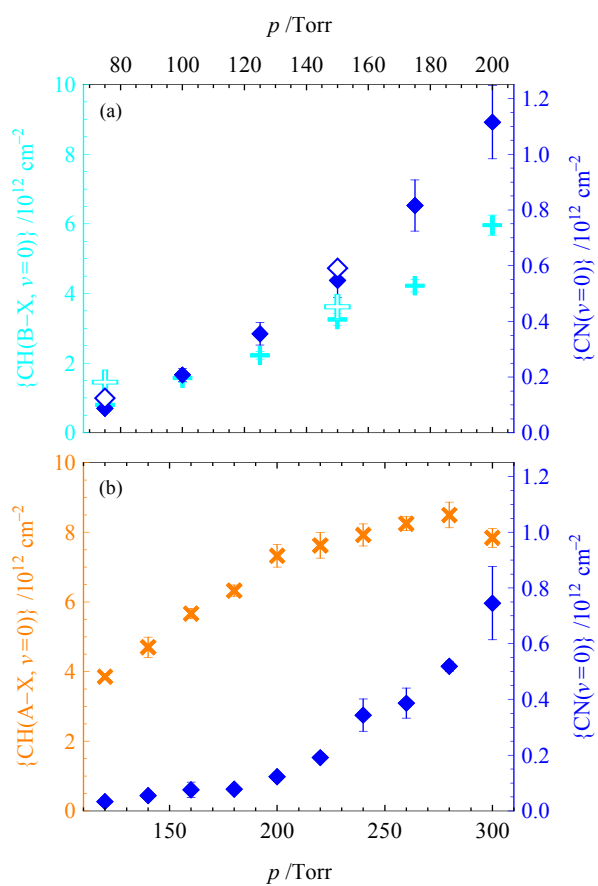
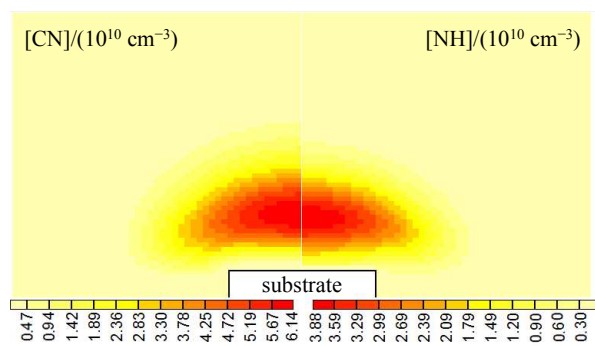
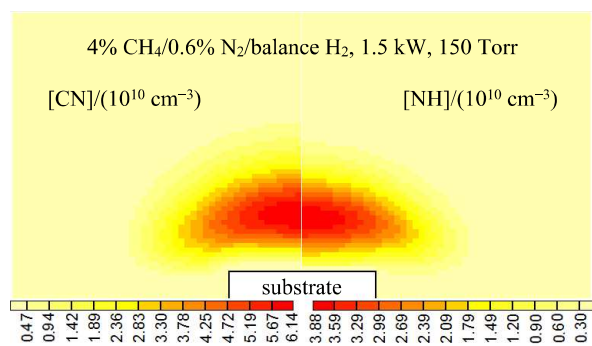
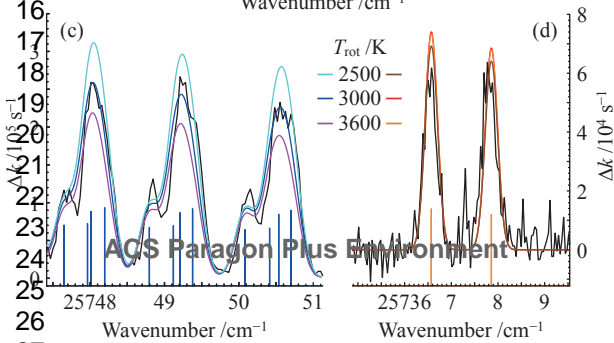
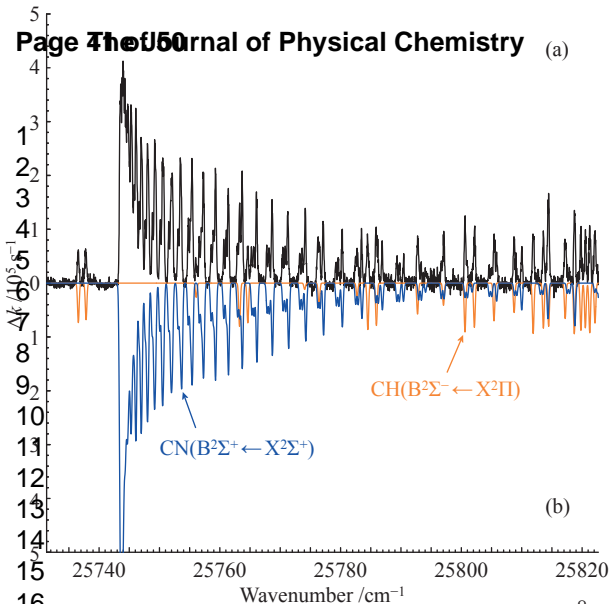


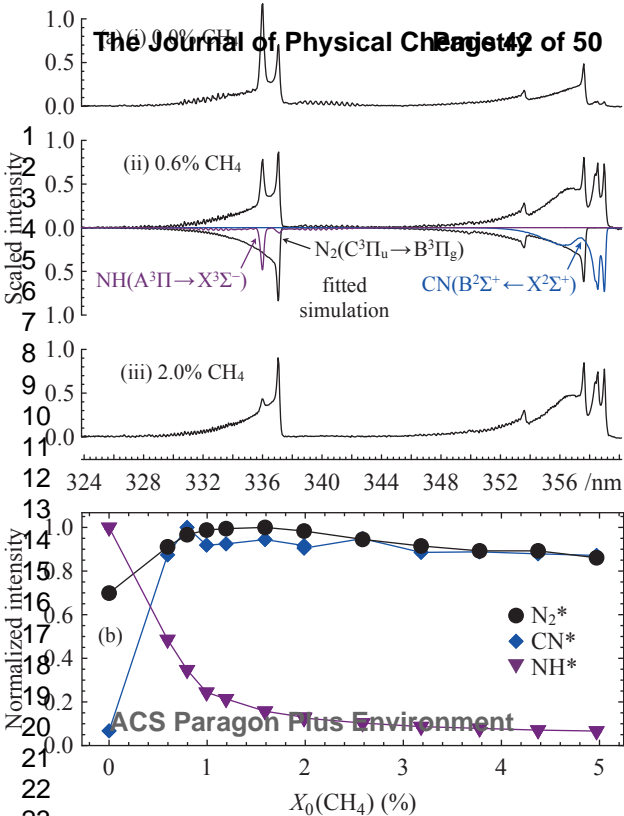
Figure 9

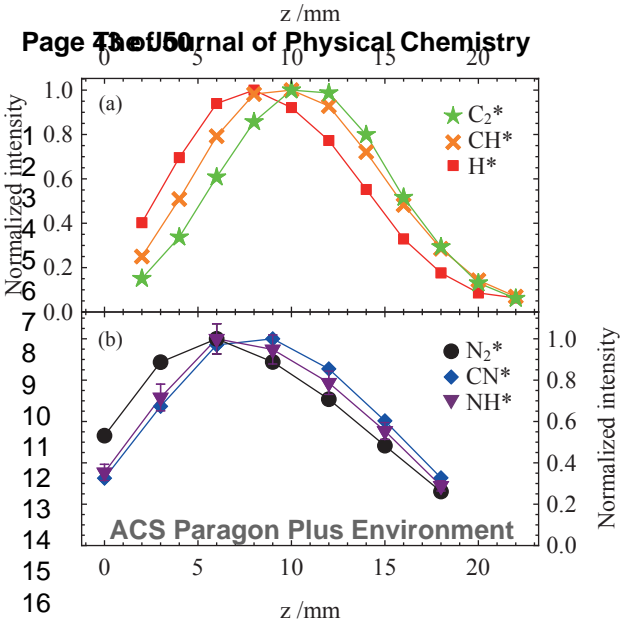


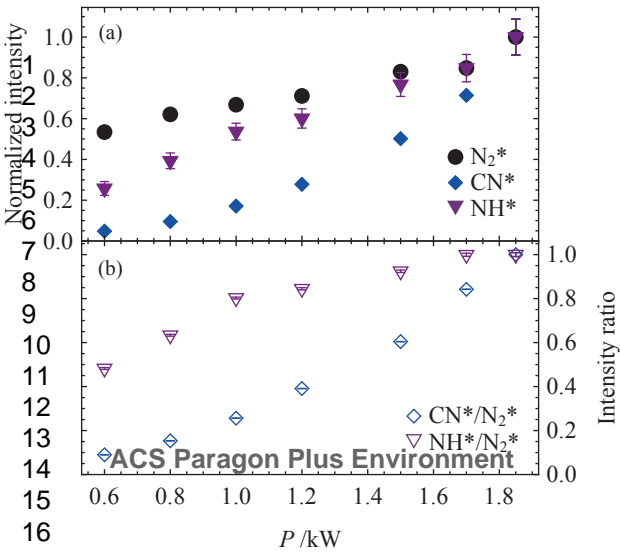
TOC graphic

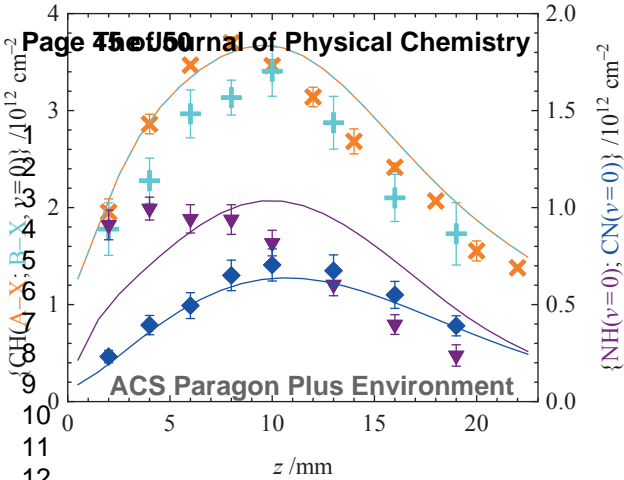


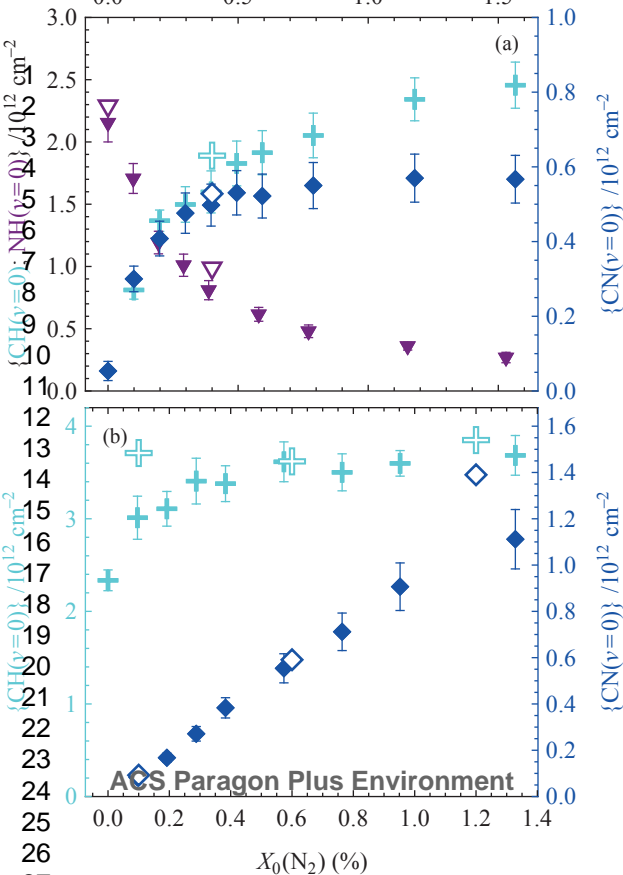


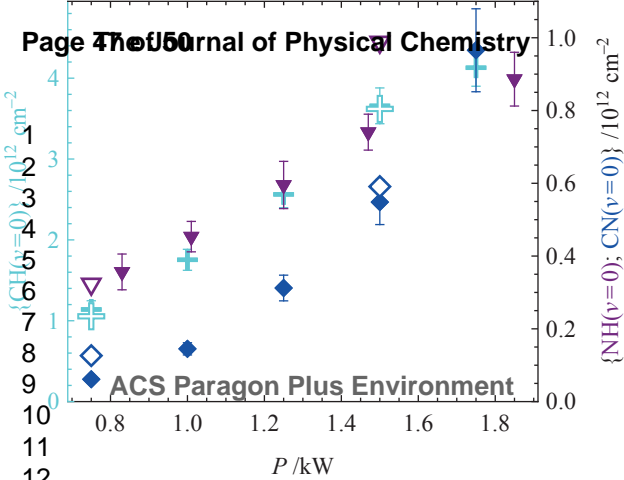


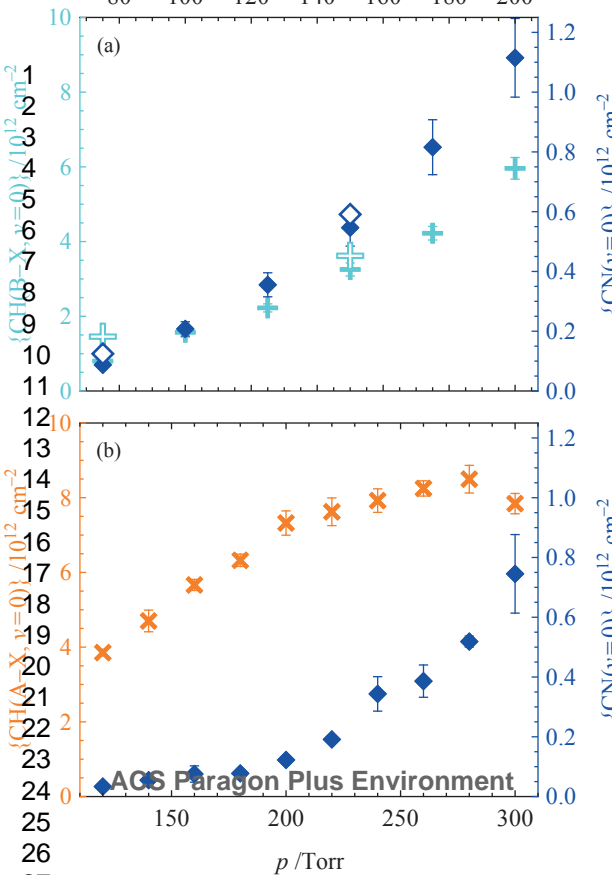












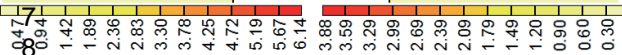
[CN]/(10^{10} cm^{-3})

[NH]/(10^{10} cm^{-3})

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ACS Paragon Plus Environment

substrate



The Journal of Physical Chemistry of 50

