1100 Wayne Avenue, Suite 1100
Silver Spring, Maryland 20910
301/587-8202

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Substrate Temperature Measurement and Control during Thermal Plasma CVD

Q.D. Zhuang, H. Guo, Q.Y. Han, J.V.R. Heberlein, and E. Pfender

High Temperature Laboratory
Department of Mechanical Engineering
University of Minnesota
Minneapolis, MN55455

Abstract

A technique is proposed for the substrate temperature control, with emphasis on the temperature uniformity across the substrate. The technique includes a substrate holder design employing non-uniform water cooling and a means of substrate attachment featured by controlled thermal contact resistance for a given heat flux distribution from the plasma. The technique was applied to deposit diamond films over a 5 cm diameter area in a DC thermal plasma reactor, and proved to be adequate. The performance of single-color ($0.655\text{ }\mu\text{m}$) and two-color (2.1 and $2.4\text{ }\mu\text{m}$) pyrometers were evaluated against DC thermal plasma radiation. It was found that both line and continuum emission of plasma jets caused large errors in temperature measurement of the single-color pyrometer. The two-color pyrometer, however, is shown to be less sensitive to the plasma radiation. The way the substrate temperature was controlled and monitored in this study is in general applicable to other TPCVD processes where intense local heating and a bright plasma background exist.

1. Introduction

Parameters that control thermal plasma chemical vapor deposition (hereafter referred to as TPCVD) vary for different processes [1-7]. One parameter, the substrate temperature, however, appears to be critical to most of the TPCVD processes [1,5,8,9]. This is probably due to the fact that the role of surface kinetics is particularly important under the environment created by a thermal plasma. For instance, a DC thermal plasma jet usually has high velocities ($\sim 100\text{ m/s}$), resulting in a thin boundary layer above the substrate ($< 1\text{ mm}$).

Considerable efforts have been made to study the substrate-temperature dependent properties of TPCVD products and our understanding of effects of the substrate temperature on the type of material formed, on nucleation, on film morphology, etc., has been substantially improved over the past years. Work has also been done to appropriately control and accurately measure the substrate temperature *in situ* [10]. However, progress has been hindered by the difficulty associated with the characteristics of thermal plasmas.

For TPCVD, the substrate is usually placed close to the plasma plume to ensure a high chemical reaction rate at elevated temperatures (~15,000 K in the core of a DC plasma jet at the exit of the torch). Steep temperature gradients and intense heat fluxes generated by the plasma plume form a major obstacle for the substrate temperature control. This is particularly true for large area deposition, where the diameter of the plasma plume is much smaller than that of a substrate and thereby creates a hot spot. At this position the substrate tends to bend and loose contact with the cooled substrate holder surface. The steep temperature gradient and thus the high residual stress on the substrate surface not only prohibit the desired material to grow, but also damage the substrate itself.

To carefully control the substrate temperature, two issues must be addressed: (1) proper design of the substrate holder; and (2) improved thermal properties of the bonding layer between the substrate and its holder. Reports for work that tackled the first issue are scarce, and there are no published results, according to our survey, for the study of the second issue. While the emphasis on TPCVD has been shifting to process and quality control, it is felt that there is a pressing need for a systematic investigation of substrate temperature control.

Substrate temperature control is critically dependent on the capability to accurately measure the substrate temperature *in situ*. Among various possible techniques for measuring the substrate temperature, thermocouples and optical pyrometers are widely used due to their simplicity and adaptability to the harsh environment usually encountered in TPCVD [12,13]. Thermocouples are accurate but suffer from the requirement for an intimate contact with the substrate. There are also uncertainties associated with the way the substrate surface temperature is inferred. Optical pyrometers have the advantage of being non-contact and thus making a direct measurement of the surface temperature. Single-color pyrometers (SCPs) provide excellent spatial resolution, e.g. ~0.25 mm target size at a distance of ~1 m. However, their accuracy depends strongly on both the plasma radiation and the surface emissivity of the substrate, which may be unknown, or time dependent due to film growth. Furthermore, when the substrate temperature is low, a SCP is likely to lose its temperature resolution since the filament is not bright enough against the strong plasma background. Two-color pyrometers (TCPs), which obtain the temperature from the measurement of the spectral radiance at two wavelengths, are able to minimize uncertainties caused by plasma radiation and surface emissivity. A shortcoming, however, is their low spatial resolution, e.g. 5 mm minimum target size and the assumption of grey body emissivity of the surface. Despite their disadvantages, the optical pyrometers appear to be the principal means for substrate temperature measurement in TPCVD, because of their simplicity and straight forward temperature response compared with more sophisticated techniques, such as thermal imaging and

interferometry. Strong gas flow and fluctuations of heat fluxes and gas densities in DC thermal plasma reactors make it difficult to obtain quantitative measurements of substrate temperatures using techniques like thermal imaging and interferometry. Plasma background radiation also poses a problem for optical pyrometers. Caution must be exercised to carefully calibrate the optical pyrometers under plasma operation conditions, and identify uncertainties [12,13].

There are reports regarding the performance of SCPs for TPCVD, suggesting [12] that a narrow-band spectral filter centered at 630.5 nm rather than 655.0 nm be used in a SCP, because the latter wavelength coincides with the strong H_{α} line emission during diamond deposition. Although an improvement in temperature measurement is expected, it is not clear if the plasma continuum emission at ~630.5 nm would still exert a strong influence on the temperature measurement. Ortega *et al* [13] attributed the uncertainties associated with a SCP to the substrate emissivity, even when the optical path of the SCP passed through the entire RF plasma plume. It is felt that the absence of measured temperatures below 1,395 K in [13] is probably due to the poor temperature resolution of the SCP caused by strong plasma radiation.

Systematic studies on the performance of TCPs for various TPCVD processes have not yet been published. Insufficient information about the performance of TCPs and SCPs makes it premature to discuss the spatial resolution of substrate temperature measurements, which are of great interest for large area deposition in particular and for process and quality control of TPCVD in general.

In the following, a technique for substrate temperature control is proposed, which includes substrate holder design and means to improve the thermal properties of the bonding layer between the substrate and its holder. The results of numerical and experimental studies for the substrate holder designs are both presented for a DC plasma reactor. An approach for improving the thermal properties of the bonding layer between the substrate and its holder is discussed, including calibration of a TCP and a SCP under various plasma operating conditions. Finally, results of large area diamond deposition, which is possible only when the substrate temperature is carefully controlled and monitored, are presented for the triple-torch DC plasma reactor.

2. Numerical analysis

The numerical analysis was aimed at providing guidelines for determining the geometry and material of a substrate holder for given plasma heating and water cooling conditions, and for achieving a satisfactory temperature distribution on the holder surface.

2.1. Problem description

The heat flux coming from a DC thermal plasma jet to the substrate holder surface is highly non-uniform, approximating a Gaussian distribution as suggested by Kishigami *et al* ^[14] and by Venuti *et al* ^[15]. The cooling of the substrate holder must therefore correspond to the features of the heat flux on the upper surface.

To establish the boundary conditions for the water-jet cooling on the backside of the holder was a challenging task, because the heat transfer coefficient at the bottom depends strongly on the geometry and material of the holder, the water flow conditions, and the heat flux from the plasma. A literature survey revealed that no work was done on submerged jet cooling with a jet diameter to length ratio as low as 0.3. To maintain the highest degree of confidence, the heat transfer coefficient used on the backside of the substrate holder was calculated, Figure 1, by adjusting its value and profile to match the reported upper-surface temperature profile of Kishigami *et al* ^[14] with the corresponding heat flux profile. A constant cooling water temperature of 20 °C was assumed, based on an estimate that there would be only several degrees of temperature rise of the cooling water.

The radial edge of the holder was assumed to be adiabatic. Neglecting the lateral heat flux at the holder edge may result in an overestimate of the upper surface temperature should a material of high thermal conductivity be used. If, however, the holder is made of Stainless Steel with relatively low thermal conductivity, the assumption is justified.

Four selected holder designs for modelling are shown in Figure 2 with various configurations and different materials. To simplify the problem, the heating and thus the temperature distribution inside the substrate holder are assumed to be axi-symmetrical.

2.2. Computer package

A computer package titled CONDUCT developed by Patankar ^[16] was adopted for the numerical analysis. The package solves two-dimensional heat conduction problems subject to the given boundary conditions, thermal properties and geometries.

The 2-D thermal conduction equation and its boundary conditions are given in the following (refer to Figure 2 for the coordinates),

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$$\frac{\partial}{\partial z}(kT) + \frac{1}{r} \frac{\partial}{\partial r} \left(kr \frac{\partial T}{\partial r} \right) = 0$$

$$r = 0, \quad \frac{\partial T}{\partial r} = 0; \quad r = R, \quad q = 0;$$

$$z = L, \quad q = q(r); \quad z = l(r), \quad h(T_{\infty} - T_1) = -k \left(\frac{\partial T}{\partial z} \right)_1$$

where $l(r)$ represents the bottom boundary of the holder. The meaning of the other symbols are as conventionally defined. The convective heat transfer boundary condition is taken into account in the computation by introducing a source term in the governing equation [16].

2.3. Discussion and the proposed design

The computed temperature profiles are plotted in Figure 3 for different holder designs. The temperature profile measured from the original holder, which is made of copper and with a flat bottom, is also given for comparison. It is worth noting that the temperature difference across the surface of the 8 cm diameter holder is about 400 °C. The spherical bottom was designed to promote cooling at the center and reduce axial heat fluxes at the edge. It is seen that the curved-bottom effectively reduces the temperature difference across the holder surface as compared with the flat-bottom. Each of the simulated holder designs has its strength and weakness as shown in Figure 3.

For the same dimensions, a pure copper holder shows a poor surface temperature distribution. The high thermal conductivity of copper makes the bottom geometry ineffective. An improvement can be seen for the stainless steel holder. The temperature difference across 8 cm is only ~50 °C.

The composite holder consisted of a stainless steel lower part and a thin copper upper part soldered together, and an ideal contact was assumed. Obviously, the temperature distribution is improved as compared to the stainless steel holder. However, this holder is difficult to fabricate due to the poor thermal properties of the bonding layer between the copper and the stainless steel (maybe caused by the large difference in the thermal expansion coefficient of the two metals and/or by defects in the bonding layer).

The temperature difference from the center to the edge of the 8 cm diameter surface of the stainless steel holder may be reduced with an electric heater to ~10 °C. While this design can be modeled conveniently and has been shown to be effective, it would require a heater of considerable power, e.g. 3 kW, increasing the complexity of the design.

The choice of holder design depends on the degree of temperature uniformity necessary for a particular TPCVD process. For instance, diamond deposition

allows a much larger temperature window than the deposition of the superconductor ($\text{YBa}_2\text{Cu}_3\text{O}_{7-x}$). It appears that the stainless steel holder would provide sufficient uniformity of the surface temperature for the diamond deposition in one of our plasma reactors.

It is not useful to numerically simulate the thermal contact between the substrate and its holder, because rather arbitrary assumptions have to be made for the properties of the bonding layer. Thus, the investigation on the thermal contact was carried out experimentally.

3. Experimental details

Experiments were performed with the triple-torch DC plasma reactor [1], shown schematically in Figure 4.

The performance of the single-color pyrometer (SCP), model Micro-Therm, centered at 655 nm was evaluated against plasma radiation under various torch operating conditions. The performance of a TCP, model 8220, with two channels centered at 2.1 μm and 2.4 μm respectively, was also evaluated under the same conditions. The setup is sketched in Figure 5. In Figure 5(a), the SCP sees through the lower part of plasma plume and measures temperatures of the tungsten ribbon lamp (calibrated by NBS, now NIST, at 655 nm assuming blackbody radiation) placed at the other side of the reactor as a temperature standard. Using the tungsten lamp (the lamp) eliminated the uncertainties associated with the surface emissivity, thus making it possible to evaluate the effect of plasma radiation (both direct and reflection) on the temperature measurements of the SCP. However, the overwhelming brightness of plasma plume resulted in a blurred image of the tungsten ribbon seen from the SCP, causing large uncertainties in the temperature measurements. Thus, an alternative approach was taken as illustrated in Figure 5(b), where the lamp sits between the plasma reactor and the SCP. The SCP sees part of the plasma radiation, which gets into its field of view due to the off-center-line arrangement of the lamp. Obviously, the effect of plasma radiation on the SCP is weaker in the case of Figure 5(b) than Figure 5(a), which is closer to the actual situation of substrate temperature measurement. If there is a large disagreement between the tungsten ribbon temperatures and those measured by the SCP for the setup of Figure 5(b), however, a stronger effect of plasma radiation can be expected for the arrangement of Figure 5(a) and thus the real situation of substrate temperature measurement.

In both Figure 5(a) and Figure 5(b) the SCP is aligned to the lower part of the plasma plume to evaluate the effect of plasma radiation. The SCP simultaneously views the tungsten lamp and the plasma. This was done because, when measuring the substrate temperature, the optical path of the SCP usually passes through the lower part of the plasma plume and a portion of reflected plasma radiation from the substrate surface enters the SCP.

The calibration tests for the TCP and SCP were first carried out without plasma to identify possible uncertainties other than plasma radiation. Then measurements were taken with plasma emission, forming a very bright background, which varies with different torch operation conditions. The measurements were taken for three different gas compositions: argon, argon with CH₄, and argon with hydrogen. For all the three cases, the lamp calibration temperatures and those measured with the SCP were compared. For the third case, two filters, centered at 655 and 630.5 nm, were inserted alternatively in the SCP in order to evaluate the effect of the H α line emission. This line emission should be filtered out by the 630.5 nm bandpass filter. The experiments were also performed for different plasma power inputs. The plasma operating conditions for the above tests are summarized in Table 1.

The chosen pyrometer was then used to evaluate the holder designs. The pyrometer was mounted on a one-dimensional translation stage for spatial resolution of the temperature measurement. The stainless steel holder was first tested, and it was then modified to include an electrical heater as shown in Figure 2.

An additional series of tests was performed for different designs in order to improve the thermal properties of the bonding layer between the substrate and its holder for the same heat flux distribution, which was used for evaluating the substrate holder design. The experimental conditions were the same as summarized in Table 1.

Diamond deposition was chosen to demonstrate the improved substrate temperature and its uniformity. A 5-cm diameter and 1 mm thick molybdenum substrate was used. The conditions for diamond deposition are listed in Table 2.

4. Results and discussion

4.1. Pyrometer calibration

The SCP and TCP were first evaluated without plasma so that the uncertainties which are not caused by the plasma radiation are either known or can be eliminated. The calibrated tungsten ribbon lamp and an oven with thermocouples were used. A very good agreement was achieved as shown in Figure 6. Various tests were also arranged to clarify the possible effects of the quartz window and measuring distance, and no noticeable effects were found.

Two bandpass filters centered at 655.0 nm and 630.5 nm were tested with the SCP in order to investigate the effect of the H α line emission and the Ar plasma continuum emission at the corresponding wavelengths (using the setup of Figure 5(b)). The temperature profiles plotted in Figure 7 are those

including the background radiation from the plasma jet without hydrogen. There is a large discrepancy between the SCP measurement and the lamp reading at ~800 °C. The discrepancy tends to decrease when the tungsten-ribbon temperature increases. Above 1,200 °C there is no noticeable influence due to the plasma radiation. This is due to the fact that the ambiguity arises from filament adjustment if the background is very bright and the ribbon temperature is low. There is virtually no difference between the measurements with the two different filters for the plasma jet without hydrogen. If hydrogen was added, however, the filter centered at 630.5 nm resulted in relatively the same error as in the measurement without hydrogen, whereas the measurements with the 655 nm filter showed an increased error of ~40 °C. The results indicate that although the filter centered at 630.5 nm is effective to absorb the H_{α} line emission, the continuum radiation of the plasma within the bandwidth (10 nm) around 630.5 nm exerts a considerable influence on the temperature measurement of the SCP in the lower temperature range. Temperatures measured from the setup of Figure 5(a) show the similar trend but with a much larger discrepancy as compared with the lamp temperatures.

It is important to know if the discrepancies illustrated in Figures 7 and 8 are a strong function of plasma operating conditions, such as torch power input. Experiments were thus performed at different power levels, and the results are given in Figure 9. It is seen that the temperature difference between the tungsten-ribbon and the SCP readings is more than doubled in the lower temperature range, when the plasma power is increased from 20 kW to 30 kW. This and the above observations cast serious doubts on the applicability of the SCP for measuring the substrate temperature for TPCVD, even without considering other uncertainties, such as that of changing surface emissivity.

The performance of the TCP can not be evaluated using the lamp, since the minimum target size of the TCP is 5 mm (diameter) while the width of the ribbon is only 2.5 mm. A different approach was taken to study the effects of plasma radiation on the temperature measurements of the TCP. An order-of-magnitude estimate was first performed. As an approximation, the radiance that enters either one of the two channels of the TCP was assumed to be the sum of the true substrate radiance and the plasma radiance at the given wavelength,

$$R(T) \approx \frac{I_s(\lambda_1, T_0) + I_p(\lambda_1, T_1)}{I_s(\lambda_2, T_0) + I_p(\lambda_2, T_2)}$$

where R is a unique function of the target temperature. λ_1 and λ_2 are the two wavelengths of the TCP. I_s and I_p are the radiance from the surface emission and from the plasma radiation, respectively, at a given wavelength, that enter the TCP. It is assumed that the plasma radiation has the same effect on both

channels of a TCP. Obviously, if I_v is much lower than I_s , the effect of plasma radiation on R is negligible.

An estimate was made for the TCP with two wavelengths, 2.1 and 2.4 μm . For an argon plasma at atmospheric pressure and at 10,000 °C, the emission coefficients of the continuum at 2.1 μm is $\sim 7 \times 10^4$ ($\text{W}/\text{m}^3\text{sr}\mu\text{m}$) which was calculated using the equations given by Richter [17]. The lines of the free-bound spectra above 1.24 μm [18] were assumed to be fully merged [19], and the intensity was added to that of the free-bound continuum by taking the value of the ξ -factor as 3 in the calculation [19]. The surface emissivity of a tungsten substrate at 1,000 °C and at 2.1 μm is ~ 0.2 [20]. The ratio of the spectral intensity of the argon plasma to that of the tungsten substrate surface at 2.1 μm and at respective gas and surface temperatures is $\sim 10^{-2}$, seen from the TCP and assuming an optically thin plasma of 10 mm width. A similar conclusion can be drawn for the channel centered at 2.4 μm . The result, though qualitative, suggests that R in equation (1) would not be greatly affected by the argon plasma radiation at the two particular wavelengths of the TCP. The above analysis needs to be justified experimentally, since there may be other gases, besides argon, involved in TPCVD, such as CH_4 and H_2 .

A test was performed to verify the above analysis for the TCP. A pure copper foil was placed on the substrate holder in the reactor. The melting point of the copper foil is 1,083 °C. The melting point measured by the TCP under operating conditions on the triple-torch reactor for diamond deposition was close to 1,100 °C. The agreement is satisfactory. Therefore, it was decided that the TCP could be used for controlling and monitoring the substrate temperature.

The TCP was mounted onto a one-dimensional translation stage in order to improve the spatial resolution of the temperature measurement. The translation stage renders a spatial resolution of 0.5 mm. This is more than sufficient because of the uncertainties in the temperature measurement of the TCP under operating conditions.

4.2. Trial tests for the substrate holder designs

The designs selected from the numerical analysis underwent trial tests in the triple-torch reactor (stainless steel holder and molybdenum substrate). Substrate surface temperatures were measured using the TCP on a one-dimensional translation stage. The measured temperatures are given in Figure 10 for the flat-bottom and the spherical-bottom holders for comparison, using identical bonding layers. The temperature difference across the substrate is considerably improved with the new holder. Since the introduction of an edge heater did not, as expected, bring a substantial improvement in reducing the temperature difference across the substrate, substrate holders with heaters were not considered any further.

It is understood that a relatively uniform temperature distribution on the holder surface is only the first step. A poor thermal contact between the substrate and its holder can easily destroy the achievement made on the *holder surface* and give rise to steep temperature gradients on the *substrate surface*, as indicated in Figure 10. For TPCVD processes, particularly the large area deposition, it is believed that the thermal properties of the bonding layer between the substrate and its holder plays a critical role in the substrate temperature control.

4.3. *Improvement on thermal contact resistance*

A common practice for attaching a substrate to its holder in the case of TPCVD is using high temperature pastes, such as silver print, hoping that the chosen paste can mechanically bind the substrate to its holder while providing a reasonably good thermal contact. However, it is extremely difficult to make a layer of uniform paste without defects, and usually the high temperature pastes have limited thermal conductivity. The defects in the bonding layer degrade the thermal contact, resulting in an elevated substrate temperature in the areas of poor thermal contact, and a steeper temperature gradient on the substrate surface.

A technique for improving thermal properties of the bonding layer has been developed using the configuration of the substrate-holder assembly as shown in Figure 11. The bonding force is provided by a cap bolted onto the holder, thus pressing the substrate tightly down. High thermal conductivity is provided by a metal filler, which is composed of a piece of copper foil at the center and a molybdenum ring making up the remaining area of the substrate bottom. The size of the copper foil at the center is about the same as that of the plasma plume.

Figure 12 shows measured temperature profiles for various materials serving as the bonding layer and for different arrangements. It is seen that the combination of the composite bonding layer, i.e. the copper-molybdenum, renders the best temperature distribution on the substrate surface for the reactor tested. A careful examination shows that the copper foil of the composite bonding layer is melted. The flexibility of the thin copper and molybdenum foils leads to a very good surface contact between the substrate and its holder. This results in a high axial heat flux at the center and a lower flux in the outer area, thus leveling the temperature distribution on the surface. Because of the reduced temperature gradient on the surface, the tendency for a substrate to buckle in the case of large area deposition due to an intense local heating at the center was not observed.

The configuration shown in Figure 11 is generally applicable to other types of thermal plasma reactors, since the size of the copper and molybdenum foil can be adjusted to match the features of heat flux distributions on the substrate surface.

4.4. An application: diamond deposition

The proposed technique for substrate temperature control and monitoring was applied to diamond deposition in the triple-torch DC plasma reactor. Semi-transparent diamond films were obtained on a 5 cm diameter molybdenum substrate (refer to Table 2 for deposition conditions). The distance between the torch and the substrate was adjusted so that the *substrate temperature* for the given torch power input was about 1000 °C. The *substrate temperature distribution* was similar to that given in Figure 12 for the copper and moly composite bonding layer. The average growth rate of the diamond films was ~200 $\mu\text{m/hr}$. SEM photographs for the as-deposited diamond film are given in Figure 13. It is seen from the photographs that across the diamond film there is a change of morphology from randomly oriented crystal facets at the center to highly uniform {100} facets at the edge. This is probably caused by the non-uniform features of the boundary layer on the substrate surface, due to the relatively large ratio of the diameter of the plasma jet to that of the substrate (~ 0.2).

5. Conclusions

- 1). Plasma radiation has a strong effect on substrate temperature measurements of a SCP. An interference filter centered at 630.5 nm for the SCP only renders limited improvement in the case of diamond deposition. The effect of continuum radiation from the plasma at this wavelength can be substantial for substrate temperatures below 1,000 °C. A TCP is found to be less sensitive to the plasma radiation, and thus it is suitable for monitoring the substrate temperature during TPCVD. Our measurements determined that the accuracy of the TCP is sufficient to measure spatial substrate temperature distributions with a resolution better than 30 °C.
- 2). A stainless steel holder with a spherical bottom cavity and a water-jet cooling has provided adequate temperature uniformity when combined with a good thermal bonding layer.
- 3). The thermal properties of the bonding layer between a substrate and its holder are crucial for achieving a uniform temperature distribution on the substrate surface. The composite (copper-molybdenum) bonding layer possesses the required thermal contact resistance for the given heat flux distribution, helping to smooth out the temperature distribution on the substrate surface. A cap is necessary to press the substrate tightly onto its holder with the bonding layer in between. The size of the copper and the molybdenum parts of the bonding layer can be adjusted to match the characteristics of the heat flux distribution on the substrate surface.
- 4). The proposed technique for controlling and monitoring substrate temperatures has proved to be adequate for diamond deposition in the triple

torch DC plasma reactor over a 5 cm diameter area. The technique is also applicable to other TPCVD processes where intense heating and steep temperature gradients exist, though caution must be exercised for each process has its own characteristics. We believe that this concept of achieving uniform substrate temperature control can be scaled up to larger dimensions.

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Figure Captions

Figure 1 The curve fit for the heat transfer coefficient at the bottom of the holder for the conditions given by Kishigami et al ^[14]

Figure 2 Selected substrate holder designs for modelling

Figure 3 Calculated temperature profiles for the selected substrate holder designs

Figure 4 Schematic drawing of the triple-torch DC plasma reactor ^[11]

Figure 5 Schematic of the setup for performance evaluation of the single-color pyrometer against plasma radiation (Top view)

Figure 6 Calibration of single- and two-color pyrometer

Figure 7 Influence of plasma radiation (without H₂) on temperature measurements of the single-color pyrometer
Chamber pressure = 1 atm, Power input = 20 kW
Argon flow rate = 30 liter/min

Figure 8 Influence of plasma radiation (with H₂) on temperature measurements of the single-color pyrometer
Chamber pressure = 1 atm, Power input = 20 kW
Argon flow rate = 30 liter/min

Figure 9 Temperature measurements of the single-color pyrometer for different plasma power input (Refer to Figure 8 for experimental conditions.)

Figure 10 Measured temperature profiles for the flat-bottom and spherical-bottom holders with a silver print bonding layer.
Chamber pressure = 1 atm, Power input = 20 kW
Argon flow rate = 30 liter/min

Figure 11 Sketch of the proposed configuration of the holder-substrate assembly

Figure 12 Measured substrate temperatures for different types of bonding layer. Refer to Figure 10 for the experimental conditions.

Figure 13 SEM photographs of the as-deposited diamond film

Table 1 Summary of plasma operating conditions

Table 2 Conditions for diamond deposition

Table 1 Plasma operation conditions

power input	Ar flow rate	H2 flow rate	chamber pressure
20 - 35 kW	30 liter/min	0 - 1 liter/min	250 - 760 torr

Table 2 Diamond deposition conditions

Ar flow rate	H2 flow rate	substrate temperature	concentration of CH4 in H2
30 liter/min	1 liter/min	1000 °C	2 - 4 %
power input = 20 kW		chamber pressure = 250 torr

Fig. 1 The fitted heat transfer coefficient at the bottom of the holder for the conditions given by Kishigami et al [15].

Fig. 2 Selected substrate holder designs for modeling.

Fig. 3 Calculated temperature profiles for selected substrate holder designs using the fitted heat transfer coefficient at the bottom of the holder.

Fig. 4 Schematic drawing of the triple-torch DC plasma reactor

(a)

(b)

Fig.5 Schematic of the set-up for performance evaluation of the single-color pyrometer against plasma radiation. (Top view)

Fig. 6 Calibration of single- and two-color pyrometer

Fig.7 Influence of plasma radiation without H_2 on temperature measurements of the single-color pyrometer
Pressure=1 atm, Power input=20 kW, Ar flowrate=10 liter/min.

Fig. 8 Influence of the plasma radiation with hydrogen on temperature measurements of the single-color pyrometer. Pressure=1 atm, Ar flowrate=10 liter/min, H₂ flowrate=1 liter/min, power input=20 kW.

Fig. 9 Temperature measurements of the single-color pyrometer for different plasma power input. Refer to Figure 8 for other conditions.

Fig. 10 Measured temperature profiles for the flat bottom and spherical bottom substrate holder with silver print bonding layer
Pressure=1 atm, Power input=20 kW, Argon flowrate=30 liter/min.

Fig. 11 Configuration of the substrate --- holder assembly.

Fig. 12 Measured substrate temperature for different types of bonding layer.
Refer to Fig.8 for operating conditions.

(a) Control

(c) 2.0 mg/ml

Figure 3. SEM images of the surface morphology of the polymer film.

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