C. R. Physique 20 (2019) 583–592

Contents lists available at ScienceDirect

Comptes Rendus Physique

www.sciencedirect.com

Improving the edge quality of single-crystal diamond growth by a substrate holder – An analysis

Amélioration de la qualité des diamants monocristallins obtenus par croissance à l'aide d'un porte-substrat – Analyse

Bo Yang [a], Qiao Shen [b], Zhiyin Gan [a,b,*], Sheng Liu [a,c,d,*]

[a] *School of Mechanical Science and Engineering, Huazhong University of Science and Technology, Wuhan 430074, China*
[b] *TrueOne Semiconductor Technology Company Ltd., Guangdong 528251, China*
[c] *School of Power and Mechanical Engineering, Wuhan University, Wuhan 430072, China*
[d] *Center of Electronic Manufacturing and Packaging Integration, Institute of Technological Sciences, Wuhan University, Wuhan 430072, China*

ARTICLE INFO

Article history:
Available online 3 October 2019

Keywords:
MPCVD
Single-crystal diamond
Substrate holder
Edge quality

Mots-clés :
MPCVD
Diamant monocristallin
Support de substrat
Qualité des bords

ABSTRACT

During the growth of a single-crystal diamond by MPCVD, polycrystalline diamonds are prone to grow in the edge regions. This substantially reduces the usable area of the grown diamond film. In addition, the inhomogeneous distribution of internal stress causes diamond to crack during continuous growth. In recent years, a series of experimental studies have been carried out to solve these problems and some achievements have been obtained. However, in order to understand fundamentally the growth mechanism of diamond, the relationship between growth quality and various influencing factors still needs to be quantitatively studied through integrated simulations and experiments. Electron number density and substrate temperature are important factors affecting diamond crystallization quality. In this paper, the growth conditions of the diamond were simulated and analyzed. Simulation results were compared with the experimental results. This evidences that the surface temperature distribution is relatively homogeneous, and that the significant electron number density gradient in the axial direction is the main reason for the formation of polycrystals in the edge regions. Therefore, substrate holders with different cavity depths were designed and the substrates grew in the same temperature range. The surface morphologies, crystalline qualities, and internal stress distributions of the grown diamonds were measured, and it was found that the quality of growth increased first and then decreased with the depth of the cavity, while the growth rate decreased with increasing the latter. These results are in good agreement with the simulation results. Finally, suggestions on the selection of the substrate holder for film growth with different thicknesses are proposed.

RÉSUMÉ

Lors de la croissance d'un monocristal de diamant par MPCVD, des diamants polycristallins ont tendance à pousser sur les bords. Ceci réduit considérablement la surface utilisable

* Corresponding author.
E-mail addresses: yb_hust@hust.edu.cn (B. Yang), ganzhiyin@126.com (Z. Gan), victor_liu63@vip.126.com (S. Liu).

https://doi.org/10.1016/j.crhy.2019.08.008
1631-0705/

du film de diamant obtenu. De plus, la distribution non homogène des contraintes internes provoque la fissuration du diamant au cours de sa croissance. Ces dernières années, plusieurs études expérimentales ont été menées pour résoudre ces problèmes, et des résultats ont été obtenus. Cependant, pour comprendre fondamentalement le mécanisme de croissance du diamant, la relation entre la qualité de la croissance et divers facteurs l'influençant doit encore être étudiée quantitativement au moyen de simulations et d'expériences intégrées. La densité du nombre d'électrons et la température du substrat sont des facteurs importants affectant la qualité de la cristallisation du diamant. Dans cet article, les conditions de croissance du diamant ont été simulées et analysées. Les résultats de la simulation ont été comparés aux résultats expérimentaux. Ceci montre que la distribution de la température de surface est relativement homogène et que le gradient significatif de densité numérique d'électrons dans la direction axiale est la raison principale de la formation de polycristaux sur les bords. Par conséquent, des supports de substrat avec des profondeurs de cavité différentes ont été conçus, et les substrats se sont développés dans la même plage de température. Les morphologies de surface, les qualités cristallines et la distribution des contraintes internes des diamants cultivés ont été mesurées, et on a constaté que la qualité de la croissance augmentait d'abord, puis diminuait avec la profondeur de la cavité, tandis que le taux de croissance diminuait avec l'augmentation de cette dernière. Ces résultats concordent bien avec les résultats de la simulation. Enfin, des suggestions quant au choix du support de substrat pour la croissance de films de différentes épaisseurs sont proposées.

1. Introduction

Single-crystal diamond has the advantages of wide bandgap, high mobility, and high thermal conductivity, which are the main issues of next-generation semiconductor materials [1–4]. At present, microwave plasma chemical vapor deposition (MPCVD) is an effective method for growing high-quality single-crystal diamond [5–7], because it could produce fewer impurities, relatively large area, and high-quality diamond.

In the semiconductor industry, Si wafers with a size of 450 mm in diameter have been achieved [8], while the fabrication of large-area and high-quality single-crystal diamond (SCD) is still an unsolved problem [9–11]. The problems of maintaining high growth quality and high growth rate in large-area diamond growth is still unsolved. Tallaire et al. studied in detail the effects of various deposition parameters on diamond growth and obtained high-quality diamonds in the central region. At the edge regions, however, polycrystal growth was not avoided [12]. In order to obtain high-quality diamond in the edge regions, Mokuno et al. proposed a method to improve the quality of diamond in the edge regions by using a substrate holder, which may avoid continuous reduction of the single-crystal diamond area during growth [13,14]. Subsequently, Nad et al. have proposed a distinct substrate holder design to obtain a large and thick diamond [15]. At present, all kinds of methods have some influence on the growth of high-quality diamond, but it is difficult to describe their specific effect quantitatively, and the trial-and-error method has mostly been used. In order to better understand the mechanism of diamond growth, it is necessary to quantitatively study these methods by modeling and simulations.

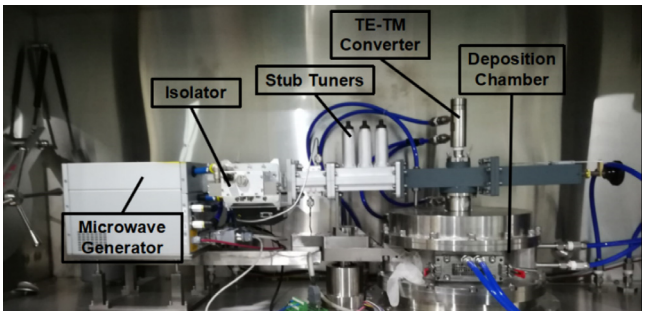
Over the past few years, several attempts have been made to establish a model for describing microwave-induced plasma characteristics [16–18]. However, the growth rate and quality of diamond mainly depend on the temperature and the ion number density in the deposition chamber. Lymberopoulos et al. established a model for the relationship between electron number density and electron energy, which provided a theoretical basis for subsequent simulation of gas temperature [19]. Lombardi et al. measured the gas temperatures of different gas components and obtained the gas temperature range under the corresponding conditions [20]. Yamada et al. discussed the hydrogen plasma models that could be used for the simulation of microwave chamber discharge. The plasma characteristic and gas temperature were illustrated by these models [21]. Hassouni et al. discussed the effect of chemical reaction species on gas temperature [22].

The present paper intends to quantitatively analyze the mechanism of the poor growth qualities in the edge regions of the substrate by combining simulation with experimental results, and proposes an improved method verified by experiments.

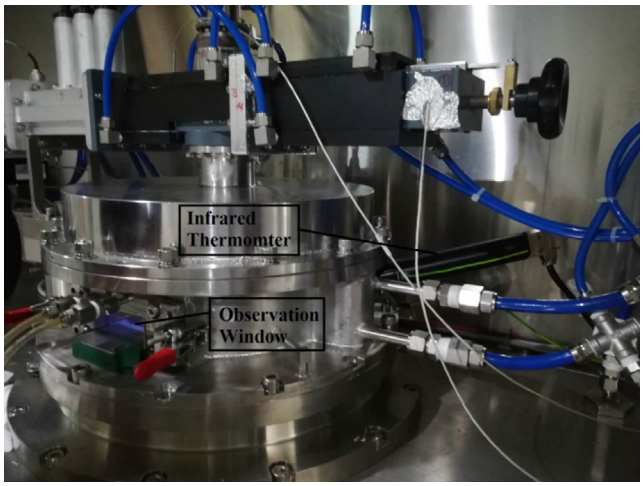
2. Experimental procedures

2.1. Experiment setup

Our homemade MPCVD system (SCMP150) was manufactured collaboratively by Wuhan University and Guangdong TrueOne Semiconductor company Ltd., as shown in Fig. 1. The microwave is generated by an AL20100 microwave generator (1–10 kW, 2.45 GHz) from MKS Instruments. The microwaves transmit through a rectangular waveguide, a TE-TM



(a) Microwave system of the MPCVD.



(b) Deposition chamber and the infrared thermometer.

Fig. 1. MPCVD system developed.

converter, then comes into the MPCVD deposition chamber. The waveguide includes three stub tuners, which are used to minimize the reflection loss of the incident power. The reflected microwave can be isolated by the microwave isolator to protect the microwave generator.

2.2. Diamond growth results

Our experiments were conducted on (100)-oriented 3.5–4 mm × 3.5–4 mm × ∼1 mm type Ib high-temperature–high-pressure (HTHP) synthetic single-crystal diamond. The quality of the substrates was quite good, with the characteristic peak of diamond at 1332.7–1332.9 cm^{-1}, a Full Width at Half Maximum (FWHM) in the Raman spectrum (inVia-Reflex) of 3.5–3.8 cm^{-1}, and an XRD rocking curve (PANalytical PW3040-60 MRD) FWHM in the range of 0.010–0.012°.

Before loading the substrates on the susceptor of the deposition chamber, they were washed with boiling concentrated sulfuric acid, then washed with pure water after acetone cleaning in an ultrasonic bath. Pure hydrogen was introduced into the deposition chamber and was ionized by the electric field generated by resonance between microwave and chamber. By adjusting the gas pressure and the input power, the substrate reached the growth temperature in hydrogen plasma, then was etched for 1 h. As the methane was introduced into the deposition chamber, the diamond started to grow. The deposited diamonds alter the substrate boundary layer and the behavior of the plasma drifts slightly versus deposition time. However, the substrate temperature can be held approximately constant by slightly adjusting the gas pressure versus time [15]. Therefore, the gas pressure of the deposition chamber during the growth was 180–210 mbar, and the input power was 3000–3500 W. The gas flow rate was 200 sccm (standard-state cubic centimeter per minute) for H_2, 5 sccm for CH_4. The growth temperature was controlled ranging from 1050–1100 °C.

Fig. 2 shows optical microscope (DSX 510) images of the grown diamond. Fig. 2(a) shows the whole optical image of the grown diamond. Figs. 2(b) and (c) show the enlarged images of the center and edge regions. Fig. 2(d) shows the FWHM of various Raman peaks measured by Raman spectrometry (inVia-Reflex), in which the Raman spectra were excited by a 532-nm laser source.

As shown in Fig. 2(b), the typical diamond growth steps were filled in the center region. As presented in Fig. 2(c), the edge region of the grown diamond was obviously higher than the inner region, which indicates that the growth rate in

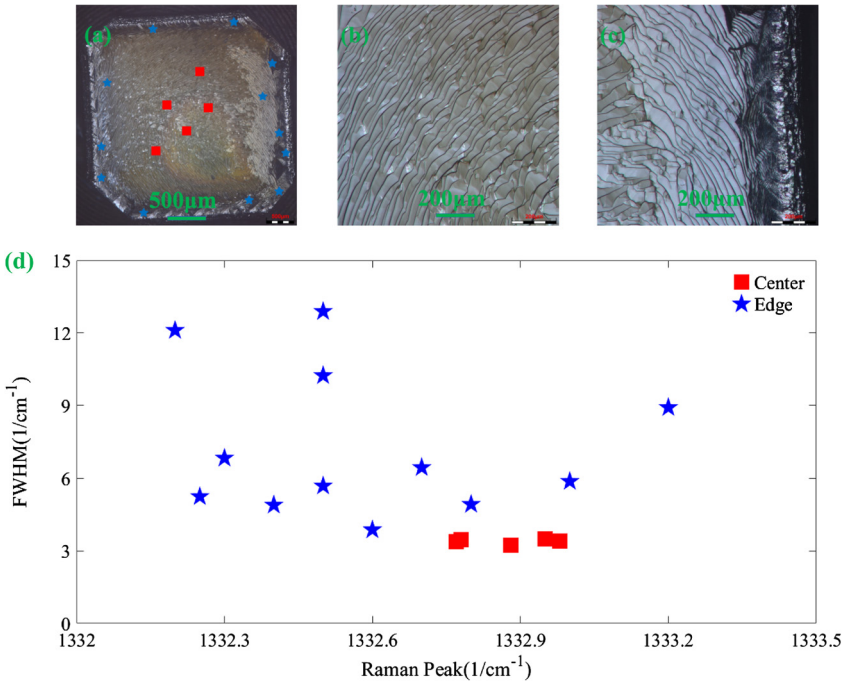


Fig. 2. **(a)** Optical microscope images of the grown diamond. **(b)** Center region. **(c)** Edge region. **(d)** Raman peak vs. FWHM results in the center and edge regions.

the edge region was faster than in the inner region. However, the high growth rate did not result in good quality and polycrystalline diamond appeared in the edge region.

Raman spectrometry was carried out on different regions of the grown diamond. The measured FWHM of the Raman peaks are shown in Fig. 2(d). The results are similar to those observed in Fig. 2(c), the characteristic peaks in the center regions (the red squares in the figure) are all between 1332.7 and 1333.1 cm^{-1}, and the corresponding FWHM of the Raman shifts are between 3.3 and 3.5 cm^{-1}. The Raman measurement in the edge regions are also compatible with the observed results (Fig. 2(c)). The Raman peaks in the edge regions (the blue stars in the figure) are between 1332.5 and 1333.2 cm^{-1} and the FWHM of the Raman shifts are between 4.5 and 12.8 cm^{-1}. Compared with the central region, the edge regions had a worse crystalline quality and serious growth inhomogeneous. Further growth in the presence of polycrystalline diamond in the edge region would inevitably lead to smaller and smaller high-quality areas in the center region [13].

3. Analysis of the poor quality of the edge region

3.1. Simulations

Both growth morphology and quality showed that the growth quality of the center regions was better than the edge regions. Therefore, it is necessary to simulate and analyze the microwave-induced hydrogen ionization in the deposition chamber. Through the previous simulation method [16–19], a simulation model suitable for our deposition chamber was established, and the correctness of the simulation was verified by comparing with the substrate temperature measurement results in the experimental process [20–27], in which the experimental temperature range is shown by the error bar in Fig. 3. The simulation was carried out under deposition conditions similar to those of the experiment, in which the gas pressure was 210 mbar and the input power was 3000 W. The axial temperature and the electron number density of the substrate surface were shown in Figs. 3–4. It should be noted that due to the fact that the surface of the substrate was the plasma boundary, which did not suit for observing the variation of the parameters. Therefore, 0.2 mm above the substrate surface was taken as the substrate surface in this paper.

As shown in Fig. 3, the variation of the substrate surface temperature in the axis direction is only 9 K, which means that the temperature homogeneity was good, that is to say, the temperature is not the main reason for the worse growth quality of the substrate edge. On the other hand, as seen from Fig. 4, electron number density decreased rapidly on a distance about 1 mm from the center of the substrate, and the difference between the center and the edge of the substrate reached 99.04%. The concentration of electrons determines the concentrations of CH_3 and H, which were the two most important species in diamond growth [28,29]. Therefore, an attempt was made to observe whether polycrystallinity in the edge regions will be improved by balancing the electron number density distribution along the axial direction of the substrate.

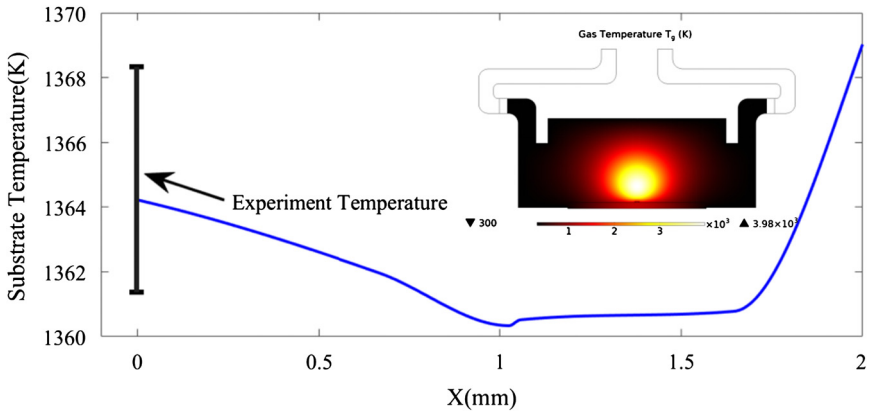


Fig. 3. Temperature (210 mbar, 3000 W) in axial direction on the substrate surface.

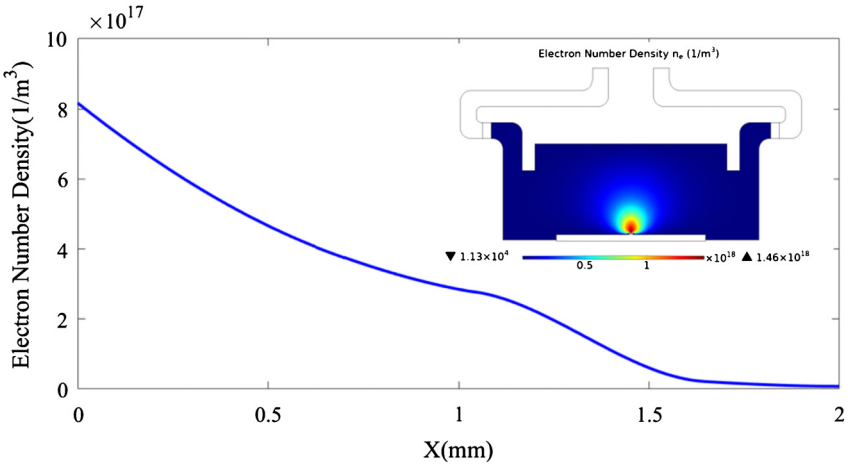


Fig. 4. Electron number density (210 mbar, 3000 W) in axial direction on the substrate surface.

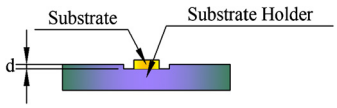


Fig. 5. Substrate holder with different cavity depths.

3.2. Simulation of employing the substrate holder with different cavity depths

The hydrogen in the MPCVD is ionized by the electric field produced by the resonance of microwave and deposition chamber to form the plasma, and electron number density is related to the electric field. Therefore, we can try to change the electric field on the substrate surface by introducing a new metal medium. However, the electrons and the ions will coexist in the plasma region, since the plasma generates both. The gas will become conductive, from which the electric field will be changed. Thus, it is reasonable to use the electron density rather than the electric field as a test to judge whether it is beneficial to improve the crystallization quality [30].

Inspired by previous studies [13–15,30], the cylindrical molybdenum substrate holders with four different cavity depths ($d = 0.5$ mm, 1 mm, 1.5 mm, and 2 mm) were designed to obtain the homogenization of the electron number density on the substrate surface, as shown in Fig. 5.

Due to that fact that the substrate holder is placed at the center of the susceptor, the morphology of the plasma had changed obviously, as shown in Fig. 6, in which the cavity depth of the substrate holder used in the simulation was $d = 1$, which indicated the characteristics of the plasma will be changed by the substrate holder indeed.

With the deepening of the cavity, the input powers and gas pressures need to be increased synchronously to make the substrate reach the growth temperature range. Therefore, the deposition conditions used as a function of the cavity depth were as follows: 160 mbar, 3000 W for $d = 0.5$ were, 160 mbar, 3500 W for $d = 1$, 180 mbar, 3800 W for $d = 1.5$, and 200 mbar, 3800 W for $d = 2$. Under these deposition conditions, the central temperature of the substrate surface

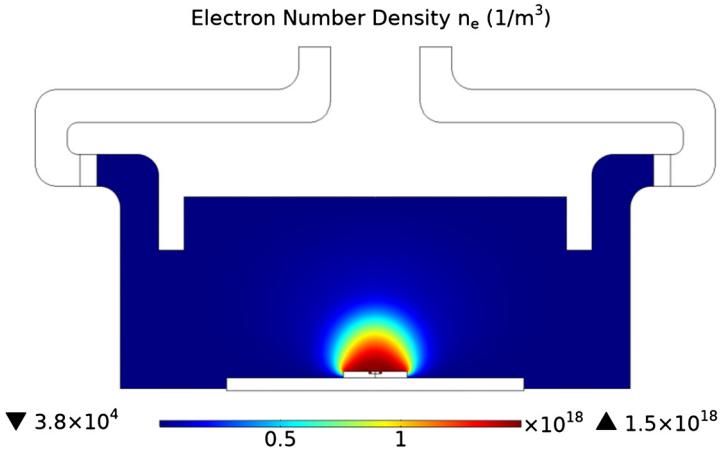


Fig. 6. Electron number density when using the substrate holder with cavity depth $d = 1$.

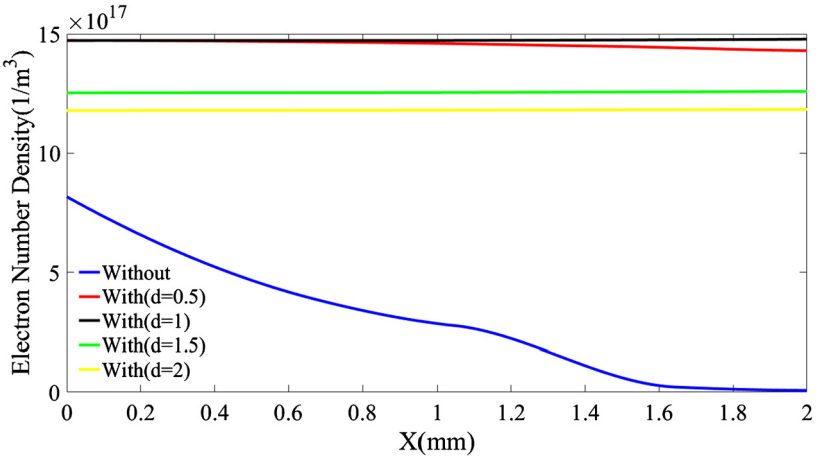


Fig. 7. Comparisons of electron number density between the situations without and with substrate holder.

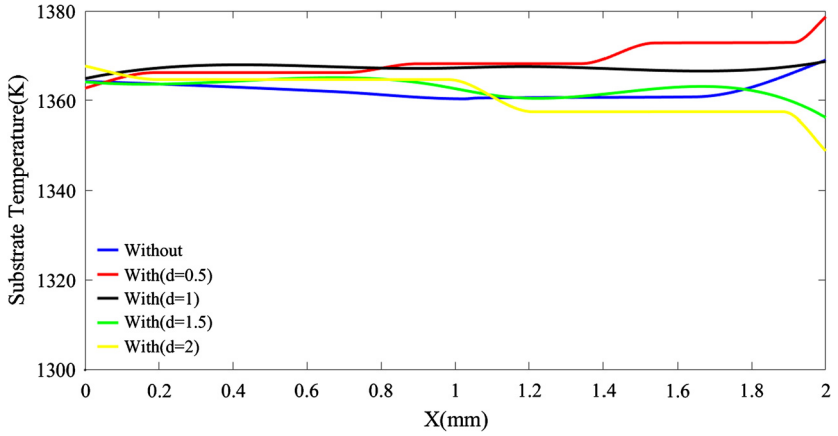


Fig. 8. Comparisons of the temperature of the substrate between the situations without and with substrate holder.

reached about 1360–1370 K; the changes of the electron number density and the temperature gradient along the axis of the substrate surface were compared with the situation that without employing the substrate holder.

When the center temperature of the substrate surface was approximately equal, without substrate holder, a 99.04% difference in electron number density between the center and the edge of the substrate was found, as described in Fig. 4. After the substrate holders were used in the simulation, the gradient of electron number density changed obviously in

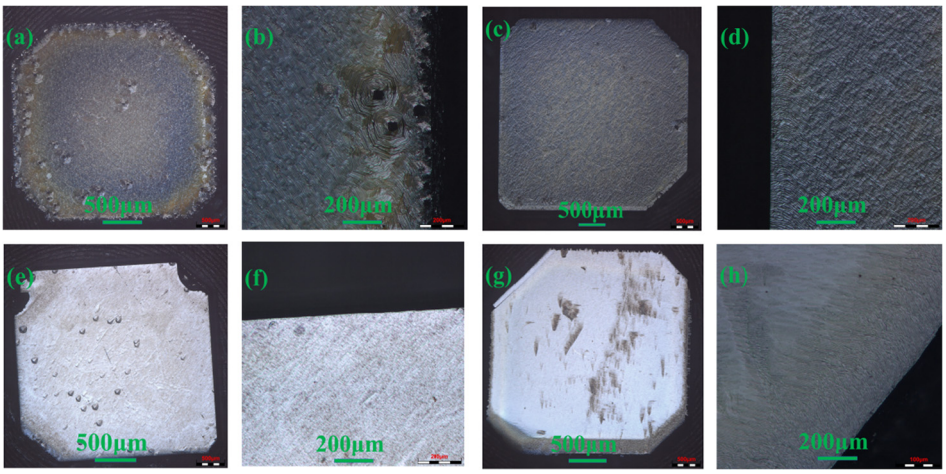


Fig. 9. Substrate grown by the substrate holder with a cavity depth of $d = 0.5$ **(a)** whole surface morphology, **(b)** edge region. $d = 1$, **(c)** whole surface morphology, **(d)** edge region. $d = 1.5$, **(e)** whole surface morphology, **(f)** edge region. $d = 2$, **(g)** whole surface morphology, and **(h)** edge region.

the axial direction, the differences between the center and the edge of the substrate were 3.48% ($d = 0.5$ mm), 0.47% ($d = 1$ mm), 0.45% ($d = 1.5$ mm), and 0.42% ($d = 2$ mm), respectively, as shown in Fig. 7. As shown in Fig. 8, due to the small size of the substrate, the overall temperature homogeneity was still good. The maximum temperature gradient occurred at the depth $d = 2$, reached about 25 K; the main reason for this was that the heat dissipation at the edge of the substrate increased with the deepening of the cavity depth. However, from the temperature range suitable for diamond growth, the substrate temperatures in the axial direction were all in the growth range. Therefore, the introduction of the substrate holder will indeed improve the homogeneity of electron number density on the surface of the substrates, while maintaining the homogeneity of substrate temperature simultaneously.

4. Results and discussion

Fig. 9 shows the grown diamond results with a substrate holder of difference cavity depths ($d = 0.5$ mm, $d = 1$ mm, $d = 1.5$ mm, and $d = 2$ mm), the growth temperatures were controlled between 1050 and 1100 °C and the CH_4/H_2 ratio was 2.5%. In a way similar to simulation analysis, the deposition conditions used as a function of the cavity depth were as follows: 155–165 mbar and 3000–3200 W for $d = 0.5$ were, 160–180 mbar, 3000–3500 W for $d = 1$ were, 180–210 mbar, 3500–3800 W for $d = 1.5$, 200–240 mbar, 3500–4000 W for $d = 2$. The XRD rocking curve of the films was measured after growth, the FWHM was 0.013–0.021°, compared with 0.010–0.012° for the HPHT synthetic diamond, which indicated the high crystalline quality of the grown diamond film.

Due to the introduction of the substrate holders, the formation of polycrystalline diamond in the edge regions was effectively improved, except for $d = 0.5$, a small amount of polycrystalline diamond still existing in the edge region. Raman spectrometry was carried out on the center and edge regions of the substrates grown by the substrate holders with different cavity depths. The measurement value of the Raman shift FWHM is shown in Fig. 11, in which $d = 0$ means the situation without substrate holder and the points in the figure are the average values of several measurement points.

As shown in Fig. 10, the Raman FWHM showed that the crystalline quality of the grown diamond in the center and edge regions showed a similar variation trend. When $d < 2$, the crystalline quality in the center regions remains mostly between 3.15 and 3.32 cm^{-1}, and it decreased with the increase of cavity depth. Meanwhile, in a way similar to situation in the center regions, with the increase of cavity depth, the crystallization quality in the edge regions will be also significantly improved.

However, when $d = 2$, the FWHM values in the center and edge regions will both increase, and the FWHM value of edge regions will increase more obviously, which should be related to the temperature of the substrate. As shown in Fig. 8, when $d = 2$, the large temperature difference between the center and the edge makes it difficult to control the temperature range during the growth process, but the overall crystallization quality was still good. The analysis in Fig. 7 showed that when $d = 0.5$ mm, the difference in electron number density between the center and the edge regions was significantly higher than that of the other three groups, which was also the main reason for the poor crystallization quality in the edge regions. Therefore, in combination with $d = 0.5$ and $d = 2$, electron number density has obviously a greater influence on the crystallization quality than temperature.

The characteristic peaks of the Raman shifts were shown in Fig. 11. The Raman peak can be used to evaluate the internal stress distribution of the grown diamond films, and the stress P (GPa) can be calculated according to Eq. (1).

$$P = 0.34\Delta\nu \tag{1}$$

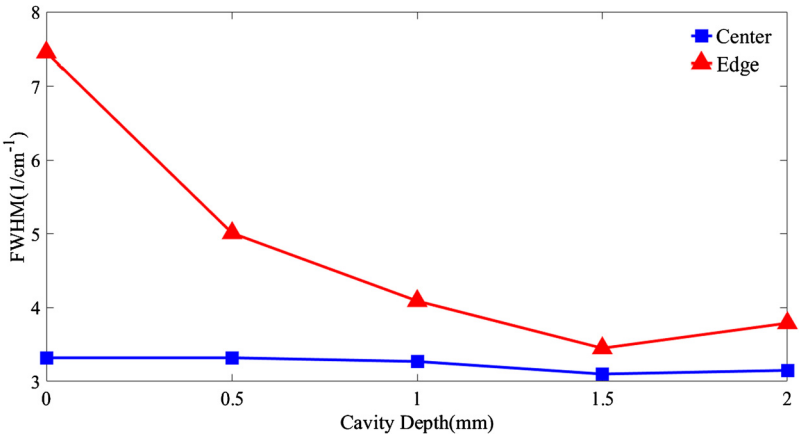


Fig. 10. FWHM of the center and edge regions vs. cavity depth.

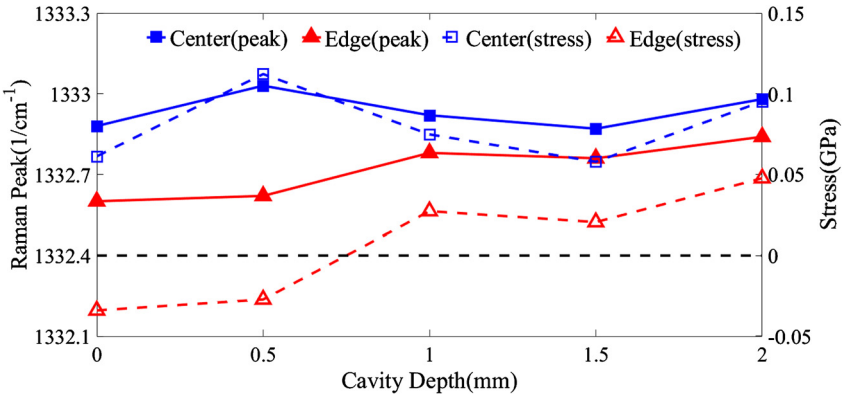


Fig. 11. Raman peak (left y-axis) and stress (right y-axis) vs. cavity depth.

where $\Delta\nu$ (cm^{-1}) is the peak shift. The mean values of the Raman peak (1332.7 cm^{-1}) of the substrate before growth were used as contrast values. $\Delta\nu > 0$ represents the compressive stress and $\Delta\nu < 0$ represents the tensile stress. Thus, the stress values were displayed on the right vertical coordinate axis, the black dotted line indicated unstressed, as shown in Fig. 11 [31,32].

Fig. 11 evidences changes in internal stress and crystalline quality with cavity depth similar to those that we can observe in Fig. 10. The maximum stress value was 0.1 GPa, occurring in the central region for $d = 0.5$, and the minimum stress was 0.03 GPa, occurring in the edge region for $d = 0$ mm. When $d = 0$ mm and 0.5 mm, there were two different stress characteristics at the center and the edge, and continuous growth may result in a decrease in crystal quality. By comparing internal stress and crystalline quality, it was found that higher internal stress distribution and higher crystallization quality was encountered in the central and edge regions for $d = 1$, 1.5 and 2 mm. Therefore, we intend to further compare the effects of different cavity depths on substrate growth through growth rate. The growth rate measurement results are displayed in Fig. 12.

As evidenced by Fig. 12, growth rate decreases with increasing cavity depth. As cavity depth increases, the contact between the plasma region and the substrate surface will be reduced, compared with Fig. 7; electron number density will also decrease with increasing cavity depth.

The densities of H and CH_3 are considered to be the most important species for diamond growth as they determine the growth rate and the growth quality [28,29]. There are many electron collision reactions in the chamber, so there is a relativity relationship between electron density and CH_3 and H density. However, electron density is not completely related to growth rate; so, in a forthcoming work, we will study the densities of CH_3 and H to describe the growth rate.

5. Conclusion

When the diamond substrate was directly placed on the susceptor of the MPCVD deposition chamber, the growth results showed that the edge regions of the grown diamond appeared to be made of a large number of polycrystals. The surface temperature and electron number density of the substrate were simulated and analyzed; it was found that the temperature homogeneity of the substrate surface was good, but that the electron number density difference between the center and

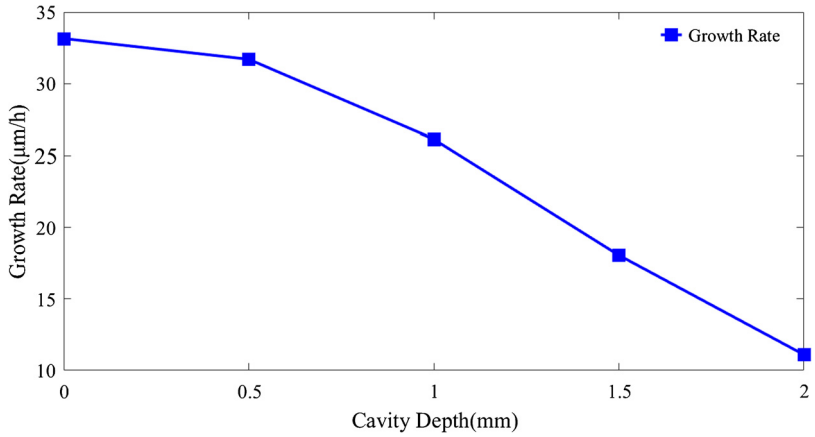


Fig. 12. Growth rate vs. cavity depth.

the edge regions reached up to 99.04%. The concentrations of H and CH_3 are considered to be the most important for diamond growth, as they determine the quality of the diamonds, and are affected by electron number density. Therefore, the significant electron number density gradient in the axial direction was the main reason for polycrystal growth in the edge regions.

The electron number density of plasma and the electric field in the chamber affect each other. A new method by balancing the electron number density distribution along the axial direction of the substrate was proposed. Substrate holders with different cavity depths were designed, the simulation results showed that the electron number densities of the substrates were effectively homogenized; meanwhile the substrate temperature remained homogeneous.

The substrates were grown on the substrate holders with different cavity depths, and the substrates were kept in the same temperature range during the growth process. The surface morphology and the Raman measurement results of the grown diamond showed that polycrystal formation in the edge regions could be effectively controlled by introducing substrate holders. With increasing cavity depth, the crystalline quality of the substrates increased first and then decreased. When $d = 2$ mm, the crystalline qualities of the substrates were slightly worse than those for $d = 1$ and 1.5, but the quality was still higher.

In order to further evaluate the effect of cavity depth on the quality of substrate growth, the growth rate was calculated by measuring the thickness of the substrate before and after growth. The results showed that the growth rate decreased with increasing cavity depth.

The crystalline quality, stress distribution, and growth rate of diamond were considered; substrate holders with cavity depths d of 1 mm and 1.5 mm can be used for high-quality diamond films. Finally, considering that the distance between the substrate surface and the substrate holder surface will decrease with increasing the thickness of the diamond during the growth process, the growth rate will increase gradually. Therefore, the substrate holder of $d = 1.5$ mm is more suitable for the growth of thick films, whereas the substrate holder with $d = 1$ mm is more suitable for the growth of thin diamond films.

Acknowledgements

This work was supported by the National Natural Science Foundation of China under grant number 51727901. The authors appreciated the kind help by our engineer, Mrs. Liting Hu, in the Center of Micro-Fabrication of WNLO for the support in XRD test, and we also appreciated the technical support from the Experiment Center for Advanced Manufacturing and Technology of the School of Mechanical Science & Engineering of HUST. Special thanks are addressed to Mrs. Wengjing Zhang for her assistance with Raman spectroscopy and optical microscopy.

References

[1] I. Aharonovich, J.C. Lee, A.P. Magyar, et al., Homoepitaxial growth of single crystal diamond membranes for quantum information processing, Adv. Mater. 24 (2012) 54–59.
[2] A. Faraon, C. Santori, Z. Huang, Quantum photonic devices in single-crystal diamond, New J. Phys. 15 (2013) 1.
[3] V.S. Bormashov, S.A. Tarelkin, S.G. Buga, Electrical properties of the high quality boron-doped synthetic single-crystal diamonds grown by the temperature gradient method, Diam. Relat. Mater. 35 (2013) 19–23.
[4] A. Mainwood, in: R.S. Sussmann (Ed.), CVD Diamond for Electronic Sensors and Devices, Wiley, Chichester, UK, 2009, Chapter 4.
[5] Y.F. Meng, C.S. Yan, S. Krasnicki, High optical quality multicarat single crystal diamond produced by chemical vapor deposition, Phys. Status Solidi A, Appl. Mat. Sci. 209 (1) (2012) 101–104.
[6] Y.A. Mankelevich, P.W. May, New insights into the mechanism of CVD diamond growth: single crystal diamond in MW PECVD reactors, Diam. Relat. Mater. 17 (2008) 1021–1028.
[7] M. Meyyappan, A review of plasma enhanced chemical vapour deposition of carbon nanotubes, J. Phys. D, Appl. Phys. 42 (21) (2009) 1–15.

[8] E. Tomzig, J. Virbulis, W. von Ammon, Y. Gelfgat, L. Gorbunov, Application of dynamic and combined magnetic fields in the 300 mm silicon single-crystal growth, Mater. Sci. Semicond. Process. 5 (2002) 347–351.
[9] A.B. Muchnikov, D.B. Radishev, A.L. Vikharev, A.M. Gorbachev, A.V. Mitenkin, M.N. Drozdov, Y.N. Drozdov, P.A. Yunin, Characterization of interfaces in mosaic CVD diamond crystal, J. Cryst. Growth 442 (2016) 62–67.
[10] G. Janssen, L.J. Giling, "Mosaic" growth of diamond, Diam. Relat. Mater. 4 (1995) 1025–1031.
[11] F. Silva, J. Achard, O. Brinza, X. Bonnin, K. Hassouni, A. Anthonis, K. De Corte, J. Barjon, High quality, large surface area, homoepitaxial MPACVD diamond growth, Diam. Relat. Mater. 18 (2009) 683–697.
[12] A. Tallaire, J. Achard, F. Silva, O. Brinza, A. Gicquel, Growth of large size diamond single crystals by plasma assisted chemical vapour deposition: recent achievements and remaining challenges, C. R. Phys. 14 (2013) 169–184.
[13] Y. Mokuno, A. Chayahara, Y. Soda, Y. Horino, N. Fujimori, Synthesizing single-crystal diamond by repetition of high rate homoepitaxial growth by microwave plasma CVD, Diam. Relat. Mater. 14 (2005) 1743–1746.
[14] A. Chayahara, Y. Mokuno, Y. Horino, Y. Takasu, H. Kato, H. Yoshikawa, N. Fujimori, The effect of nitrogen addition during high-rate homoepitaxial growth of diamond by microwave plasma CVD, Diam. Relat. Mater. 13 (2004) 1954–1958.
[15] S. Nad, Y. Gu, J. Asmussen, Growth strategies for large and high quality single crystal diamond substrates, Diam. Relat. Mater. 60 (2015) 26–34.
[16] M. Funer, C. Wild, P. Koidl, Simulation and development of optimized microwave plasma reactors for diamond deposition, Surf. Coat. Technol. 116–119 (1999) 853–862.
[17] A.M. Gorbachev, V.A. Koldanov, A.L. Vikharev, Numerical modeling of a microwave plasma CVD reactor, Diam. Relat. Mater. 10 (2001) 342–346.
[18] D. Herrebout, A. Bogaerts, M. Yan, R. Gijbels, W. Goedheer, A. Vanhulsel, Modeling of a capacitively coupled radio-frequency methane plasma: comparison between a one-dimensional and a two-dimensional fluid model, J. Appl. Phys. 92 (2002).
[19] D.P. Lymberopoulos, D.J. Economou, Spatiotemporal electron dynamics in radiofrequency glow discharges: fluid versus dynamic Monte Carlo simulations, J. Phys. D, Appl. Phys. 28 (1995) 727–737.
[20] G. Lombardi, K. Hassouni, G.-D. Stancu, L. Mechold, J. Röpcke, A. Gicquel, Modeling of microwave discharges of H_2 admixed with CH_4 for diamond deposition, J. Appl. Phys. 98 (2005) 053303.
[21] H. Yamada, A. Chayahara, Y. Mokuno, Y. Soda, Y. Horino, N. Fujimori, Modeling and numerical analyses of microwave plasmas for optimizations of a reactor design and its operating conditions, Diam. Relat. Mater. 14 (2005) 1776–1779.
[22] K. Hassouni, F. Silva, A. Gicquel, Modelling of diamond deposition microwave cavity generated plasmas, J. Phys. D, Appl. Phys. 43 (2010) 153001.
[23] H. Yamada, A. Chayahara, Y. Mokuno, Simplified description of microwave plasma discharge for chemical vapor deposition of diamond, J. Appl. Phys. 101 (2007) 063302.
[24] G. Lombardi, K. Hassouni, F. Bénédic, F. Mohasseb, Spectroscopic diagnostics and modeling of microwave discharges used for nanocrystalline diamond deposition, J. Appl. Phys. 96 (11) (2004).
[25] G. Shivkumar, S.S. Tholeti, M.A. Alrefae, T.S. Fisher, A.A. Alexeenko, Analysis of hydrogen plasma in a microwave plasma chemical vapor deposition reactor, J. Appl. Phys. 119 (11) (2016) 115.
[26] F. Silva, K. Hassouni, X. Bonnin, A. Gicquel, A.A. Alexeenko, Microwave engineering of plasma-assisted CVD reactors for diamond deposition, J. Phys. Condens. Matter 21 (36) (2009) 364202.
[27] R. Garg, T. Anderson, R. Lucht, T. Fisher, J. Gore, Gas temperature measurements in a microwave plasma by optical emission spectroscopy under single-wall carbon nanotube growth conditions, J. Phys. D, Appl. Phys. 41 (2008) 095206.
[28] H. Yamada, A. Chayahara, Y. Mokuno, Y. Kato, S. Shikata, A 2-in. mosaic wafer made of a single-crystal diamond, Appl. Phys. Lett. 104 (2014) 102110.
[29] Y.A. Mankelevich, A.T. Rakhimov, N.V. Suetin, Two-dimensional simulation of a hot-filament chemical vapor deposition reactor, Diam. Relat. Mater. 5 (1996) 888–894.
[30] H. Yamada, A. Chayahara, Y. Mokuno, Y. Horino, S. Shikata, Simulation of microwave plasmas concentrated on the top surface of a diamond substrate with finite thickness, Diam. Relat. Mater. 15 (2006) 1383–1388.
[31] N.G. Ferreira, E. Abramof, N.F. Leite, E.J. Corat, V.J. Trava-Airoldi, Analysis of residual stress in diamond films by x-ray diffraction and micro-Raman spectroscopy, J. Appl. Phys. 91 (4) (2002) 2466–2473.
[32] E.J. Di Liscia, F. Álvarez, E. Burgos, E.B. Halac, H. Huck, M. Reinoso, Stress analysis on single-crystal diamonds by Raman spectroscopy 3D mapping, Mater. Sci. Appl. 4 (2013) 191–197.