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Microwave plasma reactor with conical-reflector for diamond deposition

K. An [a], S.W. Yu [a,*], X.J. Li [b], Y.Y. Shen [a], B. Zhou [a], G.J. Zhang [c], X.P. Liu [a,*]

[a] Research Institute of Surface Engineering, Taiyuan University of Technology, Taiyuan 030024, China
[b] The Ningbo Branch of Ordnance Science Institute of China, Ningbo 315103, China
[c] Key Laboratory of Coal Science and Technology, Ministry of Education and Shanxi Province, Taiyuan University of Technology, Taiyuan 030024, China

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ABSTRACT

The modeling and design of a microwave plasma chemical vapor deposition (MPCVD) reactor with a conical-reflector cavity is presented. In the proposed reactor design, a mobilizable conical-reflector cavity, cylindrical reflector and mobilizable substrate were used to tune the system, which were different from the previous works. The electric field strength, plasma density, and tunability of the new MPCVD cavity were simulated using a finite element method (FEM). Simulations showed that this reactor possesses higher electron density than that of many other MPCVD reactors. When various frequencies microwaves were input, the tunability resulted in a minor reflection coefficient of 0.05. The good agreement of the plasma distribution between the simulation and experimental results validated the reliability of the simulation. Finally, diamond films have been successfully prepared using this new system. Experimental results indicated that the diamond films prepared using the new cavity were of high quality, at a deposition rate up to 12 μm/h.

1. Introduction

Since Deryagin et al. [1] synthesized diamond using chemical vapor deposition (CVD) under low pressure in the 1970s, a large number of methods to prepare diamond films with plasma have been developed all over the world [2–4]. Several examples include hot filament chemical vapor deposition (HFCVD), DC Arc Plasma Jet CVD, and MPCVD. MPCVD methods possess many distinct advantages when compared to the other two methods. Specifically, the MPCVD method can avoid metallic contamination from hot filaments since there is no electrode used, in contrast to HFCVD [5]. In addition, in contrast with the DC Arc Plasma Jet CVD method, MPCVD can achieve continuous and gradual modulation of input microwave power. This can stop diamond films from falling off substrates when thermal shock occurs due to the sudden cessation of an electric arc [6]. These advantages strongly motivate the use of the MPCVD method when preparing high quality diamond films.

Until now, the low growth rate of the MPCVD method has restricted wider adoption [7,8]. Enhancing the diamond film deposition rate has always been one of the primary goals of diamond research [9,10]. Some studies have indicated that high power density can be used to increase the growth rate significantly in MPCVD diamond deposition [11–14]. Samudrala et al. [13] prepared a minor sample (1 mm × 1 mm) under a microwave power of 1800 W. The result showed that under such a low microwave power, a significant increase in chamber pressure was able to compress the plasma to boost its power density. The plasma density contributes greatly to the diamond film growth rate (5 μm/h–6 μm/h), so this result stimulated studies to prepare a larger area of diamond films at higher growth rates. Studies showed that increasing the input microwave power with a corresponding raise in pressure of chamber could simultaneously improve the area of the diamond films and the power density [12]. Recently, Hemawan et al. [12] have successfully prepared a thick diamond plate with a high deposition rate of 6 μm/h–9 μm/h by increasing the input power to 4500 W. Despite this success, advances can still be made to raise the input microwave power and feed gas pressure to attain higher deposition rates with larger areas. However, currently two technical requirements limit this in MPCVD. First, microwave

* Corresponding authors. Tel.: +86 03516010540.
E-mail addresses: yushengwang@tyut.edu.cn (S.W. Yu), liuxiaoping@tyut.edu.cn (X.P. Liu).

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frequencies would change in the process of increasing the input microwave power, which demands favorable tuning of MPCVD devices [15]. Second, higher heat production from the higher input microwave power must dissipate the heat more quickly [16].

A MPCVD reactor model possessing a conical-reflector cavity for diamond film deposition is therefore proposed to satisfy these two constraints, and a prototype has been prepared. The simulated and optimized electric field strengths of the new reactor are thus presented, which employ finite element methods (FEM) for simulation. In addition, we will describe the results of the plasma and plasma electron densities which were modeled using a simple method used in Refs. [17–19]. The tunability of the MPCVD reactor as a function of the input microwave frequency is also presented. The simulation is validated using experimental results. It was observed that the reactor could perform satisfactorily in depositing diamond films with high quality at high deposition rate.

2. Proposed MPCVD reactor

Fig. 1 shows the cross-sectional view of the proposed reactor. The reactor consists mainly of three cylindrical cavities, which function not only as a microwave cavity but also as a deposition chamber. A coaxial inner conductor is located at the top part of the cavity. Microwave energy will be transmitted into the chamber through the ring-shaped quartz window that is located under the coaxial inner conductor. The quartz window can be isolated from the plasma by the second cylindrical cavity (marked as II). Such a design is employed to protect the window from overheating and plasma etching, so that the chamber can dissipate power sufficiently. The function of the window is to provide a vacuum for the diamond film deposition while providing means of allowing the microwave energy to enter the chamber.

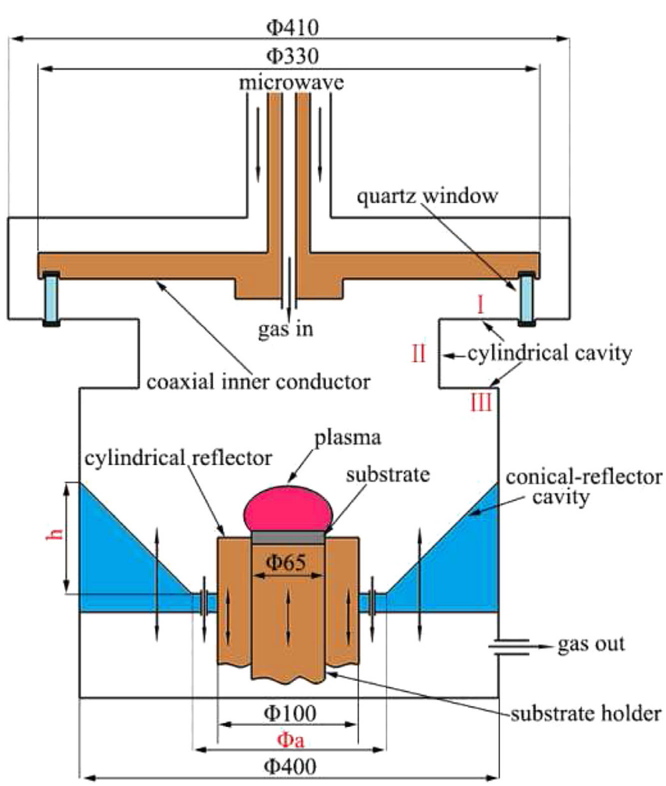

Fig. 1. Schematic diagram of proposed plasma reactor.

From Fig. 1, we could see that a substrate holder and a cylindrical reflector are mobilizable, which are located in the bottom of the chamber. The mobilizable substrate holder can elevate the substrate to various heights, which corresponds to using different thickness of substrates. The height of the chamber can also be tuned by moving the conical-reflector cavity, located at the third cavity (marked as III), so as to adjust to the volume of chamber. These mobilizable mechanisms are different from our previous works and other MPCVD reactors [10,11,14,17,20–22].

Microwaves will be coupled into the cavity from a rectangular waveguide via the coaxial antenna, which is inserted into the top end of the chamber, and a microwave resonance will be established if the size of the cavity is properly selected. When microwave energy is introduced into the chamber, it will be concentrated just above the substrate holder, where a hemispherically shaped plasma will be ignited by the energy from the microwave. Diamond films will be heated by the plasma and be deposited on substrates that are placed on top of the substrate holder. Silicon wafers with thicknesses of 3 mm and diameters of 63 mm and 40 mm were chosen as the substrates for the diamond deposition. Due to the uniform thickness of the silicon substrates, the substrate holder and cylindrical reflector are treated as a single unit throughout this paper.

The new plasma reactor was found to exhibit a variety of advantages over existing reactors.

(i) For input microwave frequency ranges between 2.40 GHz and 2.50 GHz, the new chamber enables tuning by moving the substrate holder, the cylindrical reflector and the conical-reflector cavity to each appropriate situation. Thus, this design provides the possibility to optimize the plasma distribution during the deposition process.
(ii) The quartz window is far away from the plasma, which can prevent contamination of Si and allow a large area of plasma to exist at high temperature. The walls of the cavity and the conical-reflector are made of 304 stainless steel. The substrate holder, the cylindrical reflector and the coaxial antenna are made of pure copper. All of these components are water-cooled. This mechanism ensures the input of high microwave power.
(iii) An electric field strength one order of magnitude higher than our previous works (max value of 6×10^4 V/m) was achieved [17]. The electric field strength of our reactor is shown in Fig. 2. It is well known that the stronger the electric field above the substrate, the more energy will be coupled into the cavity [17,23].
(iv) The quartz window under the coaxial inner conductor improves the vacuum degree with gravitational effects of the conductor and atmospheric pressure, which provides an advantage over the works reported in Refs. [17,22].

3. Simulation configuration

The configuration of the numerical simulation is as follows. For the calculation of Maxwell's equation, the walls of resonant cavity were assumed to be ideal conductors, and so the electric field vector parallel to the ideal conductor boundary was set to zero [17]. Under the gas pressure conditions between 0.01 Torr and 190 Torr, the recombination between ions and electrons was assumed to be the key mechanism of microwave energy loss, and the effect of spreading loss was ignored [18,23].

Following the findings of Li [17] and Füner [18], the effects of the plasma on the simulation of the electric field were ignored. In this stage, a quality factor was introduced, Q_f, as a criterion to measure the degree of optimization.