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Research Progress on Preparation Process Optimization and Porous Modification of Boron-Doped Diamond Electrodes

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Abstract: The refractory organic wastewater is difficult to be completely purified by the process, and the BDD electrode has become a high-efficiency electrocatalytic oxidation anode due to its excellent electrochemical performance. In this paper, the physicochemical and electrochemical characteristics of BDD electrodes are introduced, the high temperature and high pressure synthesis method and various chemical vapor deposition methods are summarized and compared, and the regulation effect of hot filament chemical vapor deposition process parameters on the film performance is analyzed, and two porous modification strategies, top-down etching and bottom-up porous substrate deposition, are classified and described, and their application effects in the degradation of organic pollutants are described. It is analyzed that the large-scale application of BDD electrodes has problems such as high cost, difficulty in large-area film formation, and disconnection between laboratory research and engineering implementation. It is proposed that the catalytic performance, preparation cost, and new composite porous structure need to be optimized in the future to improve the efficiency of wastewater treatment. Process improvement and industrialization provide theoretical support.

Keywords: Boron-doped diamond electrode; preparation process; parameter control; Porous design.

1. Introduction

Water resource pollution is the core problem that restricts the development of modern society. Organic wastewater discharged from pharmaceutical, printing and dyeing, chemical and other industries generally has the characteristics of complex components, strong biological toxicity, and poor biodegradability. Biological methods, flocculation sedimentation, and ordinary electrochemical oxidation It is difficult to achieve thorough mineralization of pollutants, easy to produce intermediate toxic by-products, and high treatment energy consumption. High-efficiency, stable, and non-secondary pollution advanced oxidized water treatment electrode materials have become the core of research in the field of electrochemistry.

As a typical inactive anode material, boron-doped diamond electrodes have shown irreplaceable application potential in the fields of electrocatalytic oxidation, electrochemical analysis, and electrosynthesis of refractory organic pollutants by virtue of their excellent electrochemical properties [1]. Different from electrodes such as platinum, glassy carbon, and titanium-based oxides, the OH produced on the surface of the BDD electrode has strong oxidation ability and non-selectivity, and can completely mineralize most organic pollutants into CO2 and H2O, avoiding the accumulation of toxic intermediate products, and at the same time withstand extreme working conditions such as strong acids, strong alkalis, and high current density. The service life of the electrode is much better than that of conventional anode materials. It is a functional electrode with great industrialization prospects in the field of advanced oxidation water treatment.

This paper systematically combs the core electrochemical characteristics of BDD electrodes, compares the advantages and disadvantages of HPHT and various CVD preparation technologies, deeply analyzes the control mechanism of HFCVD key process parameters on the microstructure and electrochemical performance of thin films, and classifies and summarizes the top-down and bottom-up The preparation strategy, micromorphology characteristics and water treatment application performance of the two types of porous BDD electrodes, analyze the defects of the existing preparation route, and finally look forward to the direction of high-performance, low-cost, and scalable BDD electrodes, aiming to provide new three-dimensional porous BDD electrodes The design, process optimization and industrial application of BDD electrodes provide theoretical reference and technical ideas.

2. BDD Electrode Characteristics

The electrochemical properties of BDD electrodes are related to their surface properties, the degree of B doping and the hybridization of C [2]. BDD electrode is a kind of inactive electrode, which exhibits excellent electrochemical stability and higher oxygen evolution potential in the electrochemical oxidation process, and its oxidation potential is much higher than that of most organic pollutants. The BDD electrode can effectively generate hydroxyl radicals (·OH), which can quickly and non-selectively mineralize organic pollutants to carbon dioxide and water, greatly improving the degradation efficiency. BDD electrodes have several excellent characteristics that make them stand out in electrochemical applications. First of all, the wide electrochemical potential window (2.8-3.5 V) is far higher than that of the electrode. The larger the sp3/sp2 ratio in the hybridization process, the larger the window is, which is conducive to the generation of more hydroxyl radicals and improves the degradation efficiency of organic pollutants. Secondly, due to the strong covalent bond structure between carbon atoms, BDD

electrodes show excellent mechanical stability and chemical tolerance, and can work stably even under harsh conditions. In addition, the low background current characteristics of BDD electrodes stem from their low double-layer capacitance and surface inert, making them excellent in trace substance detection. Finally, the hydrophobicity and self-cleaning power of the surface of BDD electrode greatly enhance the material adsorption, and can effectively remove surface contaminants through polarization treatment, maintaining stable performance.

3. Preparation and Optimization of BDD Electrode

3.1. Preparation of BDD electrode

The preparation method of BDD electrode has a decisive effect on its final performance. The preparation of boron-doped diamond electrode mainly includes chemical vapor deposition technology and high temperature and high pressure synthesis method.

High temperature and high pressure synthesis is a method to synthesize BDD by simulating the formation conditions of natural diamonds [3]. The high-purity graphite powder is fully mixed with the boron source, placed in a special high-pressure chamber, and treated under the ultra-high pressure of 5-6 GPa and high temperature conditions of 1300-1500 ℃. The high-temperature and high-pressure graphite structure is reorganized into Diamond structure, and boron incorporation is realized at the same time.

Chemical vapor deposition is the most common technique for preparing BDD electrodes. The advantage of this method is that it can accurately control the proportion of reactive gas, deposition temperature, pressure and plasma parameters, so as to realize the precise control of boron doping level and film structure, and can directly affect the conductivity, electrochemical window and oxygen evolution overpotential of the electrode. The most common CVD methods are: microwave plasma chemical vapor deposition, hot wire chemical vapor deposition, DC hot cathode plasma chemical vapor deposition, DC jet plasma chemical vapor deposition [4]. Different CVD methods have different advantages and disadvantages, as shown in Table 1, different CVD methods have their own characteristics. Microwave plasma CVD is famous for its high thin film and precise control, but the equipment is expensive and energy consumption is high. Although DC hot cathode plasma CVD and DC jet plasma CVD have excellent performance in low temperature deposition and high growth rate, they have great shortcomings in uniformity and stability. However, the flame deposition method is difficult to require in terms of film and controllability. Among these methods, HFCVD has obvious advantages in industrial production due to its simple equipment structure, relatively low cost, and good scalability, and has become the most widely used method for preparing BDD electrodes.

Table 1. Principles, advantages and disadvantages of various CVD methods

CVD method	Principle	Advantage	Disadvantages
Microwave plasma CVD	Microwave energy is used to excite the reaction gas mixture inside the reaction chamber, forming a high-energy plasma that deposits on the substrate surface.	Low operating temperature High film quality and purity 3. Good controllability and flexible parameter adjustment	1. High equipment cost 2. High energy consumption 3. Relatively low deposition rate
Hot-Filament CVD	A high-temperature heated metal filament (W, Ta) thermally decomposes and activates the reaction gas, producing active carbon atoms and hydrogen radicals that recombine and deposit on the substrate surface at relatively low temperature.	Simple equipment and low cost Good scalability, suitable for large-area deposition 3. Suitable for industrial production	1. Hot cathode lifetime and stability issues 2. Uniform large-area deposition remains challenging 3. Relatively complex equipment
DC Hot Cathode Plasma CVD	A DC power supply generates an arc discharge between the hot cathode and anode, forming a high-temperature plasma that excites and decomposes the reaction gas; active particles deposit on the substrate surface.	Low-temperature deposition, suitable for temperature sensitive substrates High-density plasma, conducive to fast growth 3. Low working pressure, reducing secondary reactions in the gas phase	1. Hot cathode lifetime and stability issues2. Uniform large-area deposition remains challenging3. Relatively complex equipment
DC Jet Plasma CVD	A DC power supply generates a high-speed, high-temperature plasma jet between the cathode and anode, rapidly decomposing and activating the reaction gas; the active particles are ejected onto the substrate surface.	High deposition rate High precursor utilization efficiency 3. Suitable for growing thick films	1. Poor large-area uniformity 2. Complex equipment design and control 3. Localized high temperature may affect certain substrates
Combustion Flame Deposition	Acetylene or other hydrocarbons are burned with oxygen to produce a high-temperature flame, in which the carbon-containing compounds are decomposed and activated, depositing on the substrate surface.	Simple equipment and low cost High deposition rate 3. Suitable for rapid deposition and in-situ doping	1. Difficult to control film quality 2. Poor uniformity and repeatability 3. Unsuitable for precise control of doping level

3.2. Control of process parameters

3.2.1. Composition of reactive gases

During the preparation of BDD electrodes by hot-filament chemical vapor deposition , the crystallinity and grain size of the films were affected by the concentration ratio of boron source and carbon source in the reactive gas composition. The low B/C ratio is usually favorable for the formation of BDD films with large grains and high crystallinity. However, high B/C ratio may lead to the decrease of grain size and grain boundary density. Excessive boron doping may lead to sp2 carbon content, affecting the structural integrity and electrochemical window of the films. For example, Gao et al.[5] adjusted the microstructure of BDD electrode such as boron doping concentration, sp3/sp2 ratio, and grain size by changing the reactive gas flow ratio. It was found that when the B2H6/total gas flow rate was constant, the grain size first increased and then decreased with the CH4 concentration. The electrochemical window and degradation rate also increased first and then decreased. The BDD electrode with B2H6/CH4/H2 flow ratio of 0.3: 3: 97 has the largest potential window and oxygen precipitation potential, the lowest degradation efficiency and the lowest energy consumption. Therefore, by accurately adjusting the ratio of boron source to carbon source, it is beneficial to form a stable BDD structure and improve the service life of the electrode.

3.2.2. Substrate temperature

During the growth of HFCVD, the substrate temperature can be controlled by adjusting the hot filament temperature finely. The change of hot filament temperature not only directly affects the decomposition efficiency of the vapor phase precursor, but also changes the temperature field of the substrate surface through radiation and convection heat transfer. Higher substrate temperature is usually beneficial to increase the crystallinity and sp3 content of films, but too high temperature may lead to the formation of non-diamond phase or internal stress. When titanium is used as the substrate material, the higher substrate temperature will not only affect the structure and properties of BDD films, but also promote the growth of titanium carbide transition layer between Ti substrate and BDD. The thickness of the TiC layer directly affects the adhesion strength between the BDD film and the Ti substrate. For example, Guo et al. [6]successfully prepared high boron-doped diamond films by two-stage temperature HFCVD method . Compared with the single-temperature method, the working life is increased by more than two times, and the multi-layer structure formed helps to improve the bond strength between diamond films and titanium substrates. Therefore, precise control of the substrate temperature can achieve high BDD film growth and good interfacial adhesion, thereby significantly improving the overall performance and durability of the electrode.

3.2.3. Sedimentation pressure

The deposition pressure is a key parameter in the process of preparing BDD electrode by HFCVD. It is shown that there is a nonlinear relationship between the deposition pressure and the nucleation density grain size growth rate and doping level of BDD thin films. Under low pressure, the nucleation density of diamond is higher and the growth rate is faster. The grain size of BDD increases first and then decreases with the increase of pressure. The reason for this change is the complex interaction between gas phase mass transfer and surface reaction kinetics. For example, Jia et al. [7] found that when the gas pressure is from 0.5 kPa to 1.5 kPa, the grain size increases slightly, and reaches the maximum value at 1.5 kPa, and the film shows a good crystal structure. However, when the pressure reaches 2 kPa and 3 kPa, the grain size becomes obviously smaller, and the grain presents incomplete shape and blurred boundaries. It is worth noting that although the grain size fluctuates with the pressure, the growth rate of BDD decreases with the increase of the pressure, which is related to factors such as the limited diffusion of reactants and the saturation of surface adsorption sites at high pressure.

3.2.4. Sedimentation time

Deposition time not only affects the thickness of the BDD film, but also affects the doping distribution and interface structure of the BDD electrode prepared by HFCVD. Prolonging the deposition time, the uniformity of the BDD electrode film and the grain size are improved. For example, Chang Weon Song et al. [8] found that the morphology of BDD films is not affected by the deposition time, but the thickness varies with the deposition time. At the same time, the deposition rate of BDD films is at a constant value of 100 nm/h, and the thickness leads to the expansion of the potential window. However, excessive deposition time will lead to the accumulation of internal stress, surface roughness, and even the formation of non-diamond phase.

The effect of HFCVD parameters on the properties of BDD electrode is essentially a fine adjustment process of microstructure. The synergistic effect of these parameters determines the microstructure, surface morphology, electrochemical activity and service life of BDD electrode, and then affects its performance in practical applications. The ratio of reactive gas directly affects the doping level of BDD films, the substrate temperature plays an important role in the adhesion and stability of BDD films, the deposition pressure has a great influence on the nucleation density, grain size and growth rate of BDD films, and the deposition time mainly affects the thickness and uniformity of BDD films. Based on the fine regulation of BDD electrode performance by HFCVD process parameters, researchers further explored how to use these parameters to prepare porous BDD electrode structures with higher surface area and electrochemical activity, so as to further improve the electrochemical performance of BDD electrodes.

3.3. Porous BDD electrode

Of BDD electrodes are usually deposited on flat substrates, and this two-dimensional structure limits its electrocatalytic performance and surface utilization. In order to break through this bottleneck, researchers have turned their attention to the design and preparation of porous electrodes. Compared with flat BDD, the porous structure can significantly increase the specific surface area of the electrode, providing more active sites and reaction interfaces for electrochemical reactions. This structure can not only improve the area of the reactant and electrode surface, but also improve the material transport efficiency. In recent years, the research and application of porous electrodes has become a hot spot in the field of electrode materials [9]. At present, many researchers have made research on porous BDD electrodes. According to the different deposition of BDD thin films, the main methods for preparing porous BDD electrodes are top-down method and bottom-up method.

3.3.1. Top-down etching

The top-down method is a method to etch BDD films into porous structures by regulating the microstructure of BDD electrodes, mainly using photolithography, chemical etching and plasma treatment. The Ohashi team [10] treated the BDD electrode by vapor activation and obtained a microscopic porous BDD electrode with a columnar structure (Fig. 1a), which has an electrochemical active surface area 20 times higher than that of the original BDD electrode (Fig. 1b). They were the first team to etch BDD electrodes, but this method can easily introduce unnecessary oxygen-containing functional groups through high-temperature steam treatment, thereby changing the chemical properties of the BDD surface. Shi et al. [11] formed dense pore structures and regular pore shapes by electrochemical deposition of Ni nanoparticles on the surface of BDD and catalytic etching with hydrogen-argon plasma (Fig. 1c), and the prepared porous electrodes have high specific capacitance, which is 22 times higher than that of ordinary BDD electrodes (Fig. 1d). However, it is difficult to precisely control the size and distribution of the pore size, as well as the depth of the pore, which limits the performance optimization of the electrode in some specific applications. Li et al. [12] used Ni nanoparticle-assisted plasma etching technology to form nano-holes of different shapes on different crystal planes by controlling the size of Ni particles and the etching time of BDD, including square and triangular (or hexagonal) holes (Fig. 1e), the electrochemical redox performance of the prepared porous BDD/Ta electrode is significantly improved (Fig. 1f) and can efficiently degrade methylene blue. Although this top-down method of preparing porous BDD electrodes has great advantages in accurately controlling the size and distribution of pores, especially for preparing porous structures with specific patterns or shapes, because the etching is carried out after the growth of the BDD film, it is easy to cause material waste, and the etching process may affect the overall structural integrity of the BDD film and its mechanical strength. At the same time, this post-processing method may require complex etching equipment and precise process control, reducing manufacturing costs and complexity.

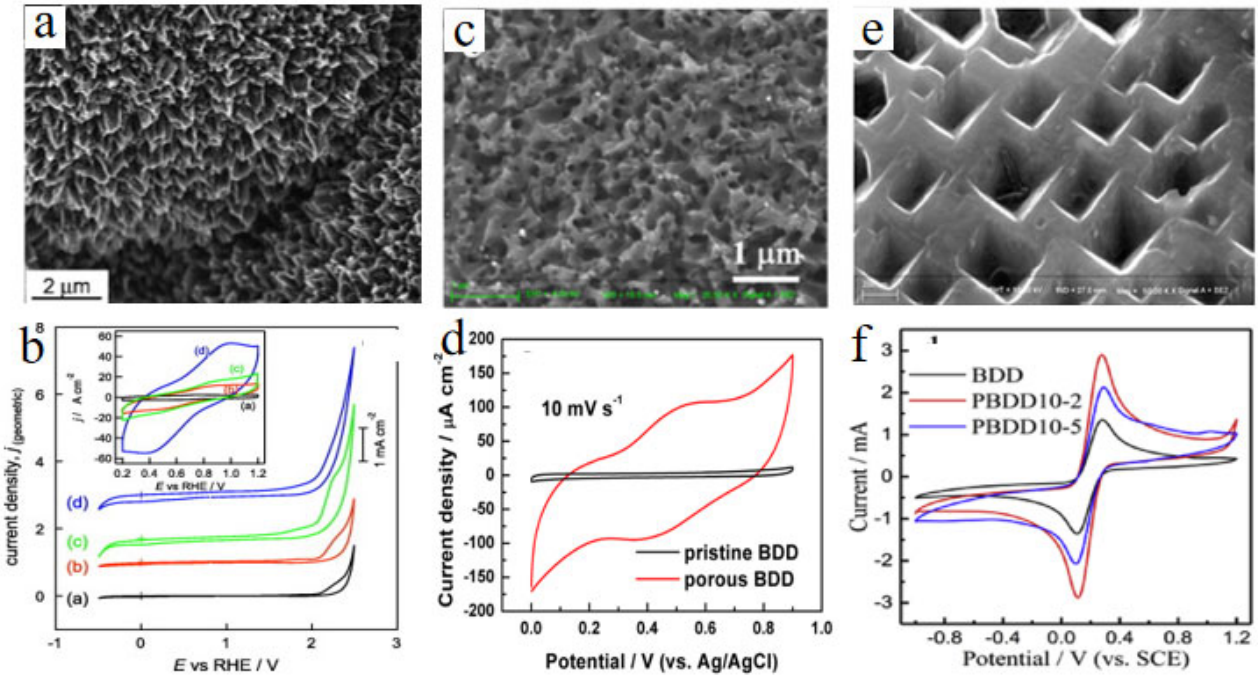


Figure 1. (a) SEM image of the BDD electrode after 2 hours of steam activation at 900◦C]; (b) Cyclic voltammograms of the BDD electrode at different activation temperatures in 0.5M H2SO4]; (c) SEM image of the porous BDD electrode after etching for 120 seconds; (d) CV curves of the BDD and porous BDD electrodes in 0.1 M Na2SO4 solution; (e) SEM image of the PBDD electrode; (f) CV curves of the BDD electrode at 0.1 mol L-1 and 5 mmol L-1 K3Fe(CN)6 solution at different etching times

3.3.2. Bottom-up sedimentation

BDD films are usually grown on substrates, and the most important part that determines the morphology and final performance of porous films is the substrate. Therefore, the research on porous substrate materials has become a hot spot, such as porous Si, nanotube, grid Ti and foam Ni. The bottom-up method is to use these porous substrates to directly deposit BDD films on them. Tang et al. [13] prepared a surface porous titanium substrate by electrodeposition-hot melt-alkali etching method (Fig. 2a), so that the EASA of the porous Ti/BDD electrode reached 11.39 cm2/cm2 (Fig. 2b), and the oxygen evolution potential and electrochemical window of the electrode were 2.99 V and 4.21 V, respectively (Fig. 2c). However, the porous substrate prepared by this method involves multiple steps, the complexity and time cost of the preparation process, and the characteristics of random shape, uneven pore distribution, and uneven pore size make it difficult to continuously and uniformly produce diamond films inside the substrate, nor can it form a channel for the free flow of organic wastewater. Therefore, it is not conducive to the improvement of liquid mass transfer, thus limiting the further improvement of electrochemical oxidation efficiency. Mei et al. [14] prepared a new three-dimensional macroporous BDD (3D-BDD) foam electrode using foamed Ni as a substrate (Fig. 2d), and the wastewater can flow freely

in the electrode pores. Compared with the 2D BDD electrode with the same geometry, the electroactive surface area of the 3D-BDD electrode is about 20 times larger (Fig. 2e), and the liquid phase mass transfer rate is significantly improved, which is more conducive to the degradation of organic matter (Fig. 2f). On the basis of previous research, Wei et al. [15] proposed a new idea, taking BDD with unique properties as the overall functional unit (FU), and assembling it into a three-dimensional macroporous ordered structure (OS), designed and prepared the "three-dimensional mutual penetration network" ordered structure 3D BDD electrode (Fig. 2g), the degradation efficiency of the electrode is increased by 4-5 times (Fig. 2h), and the energy consumption of mineralization is up to 1/15. And the turbulent kinetic energy of the fluid in the electrode with high porosity OS is higher through CFD simulation, indicating that the regulation of the organic removal performance by OS is effective (Fig. 2I). Due to the mismatch of thermal coefficients, it is difficult to etch the microstructure of foam BDD electrodes, which limits the ability of macroscopic and microscopic mixed structures. In order to break through this bottleneck, the team proposed a new idea: on the basis of the advantages of high mass transfer and high utilization rate of hydroxyl radicals in the foam structure, a top-down method is used to enhance the active area of the electrode, thereby improving The yield of hydroxyl radicals further optimizes the performance of the electrode. Miao et al. [16] prepared a W transition layer on the surface of foamed copper by hot wire evaporation technology, and formed a conical structure during high temperature heat treatment, and obtained a 3D-Cu/W/BDD electrode with a large specific surface area and "macro-micro" ultra-high mass transfer. The electrochemical active surface area is 7.9 times that of 2D-BDD electrode, and the removal rate of tetracycline hydrochloride TCH and TOC is 1.51 times and 5.31 times that of 2D-BDD, respectively (Fig. 3).

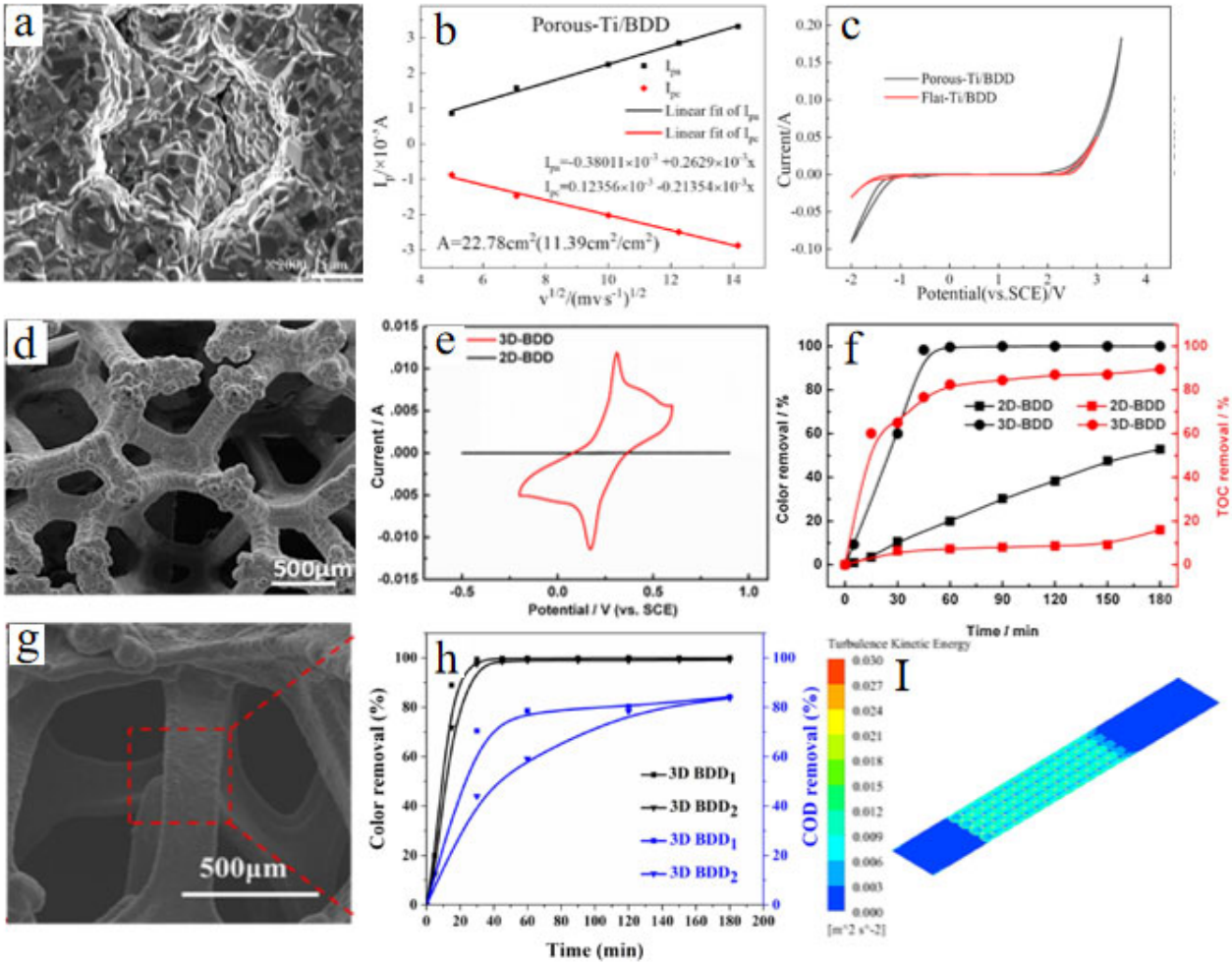


Figure 2. (a) SEM image of porous Ti/BDD electrode; (b) EASA of porous Ti/BDD electrode; (c) CV curves of BDD electrode and porous Ti/BDD electrode in 0.5 M H2SO4 solution; (d) SEM image of 3D macroporous 3D-BDD foam electrode; (e) comparison of CV curves of 2D-BDD and 3D-BDD electrodes; (f) comparison of decolorization rate and TOC removal rate of 2D-BDD and 3D-BDD electrodes for RB-19; (g) SEM image of "three-dimensional interconnected network" ordered structure of 3D BDD electrode; (h) comparison of color removal rate and COD removal rate of 3D BDD electrodes for ARS degradation; (I) simulated distribution map of kinetic energy in turbulent flow on 3D BDD electrode

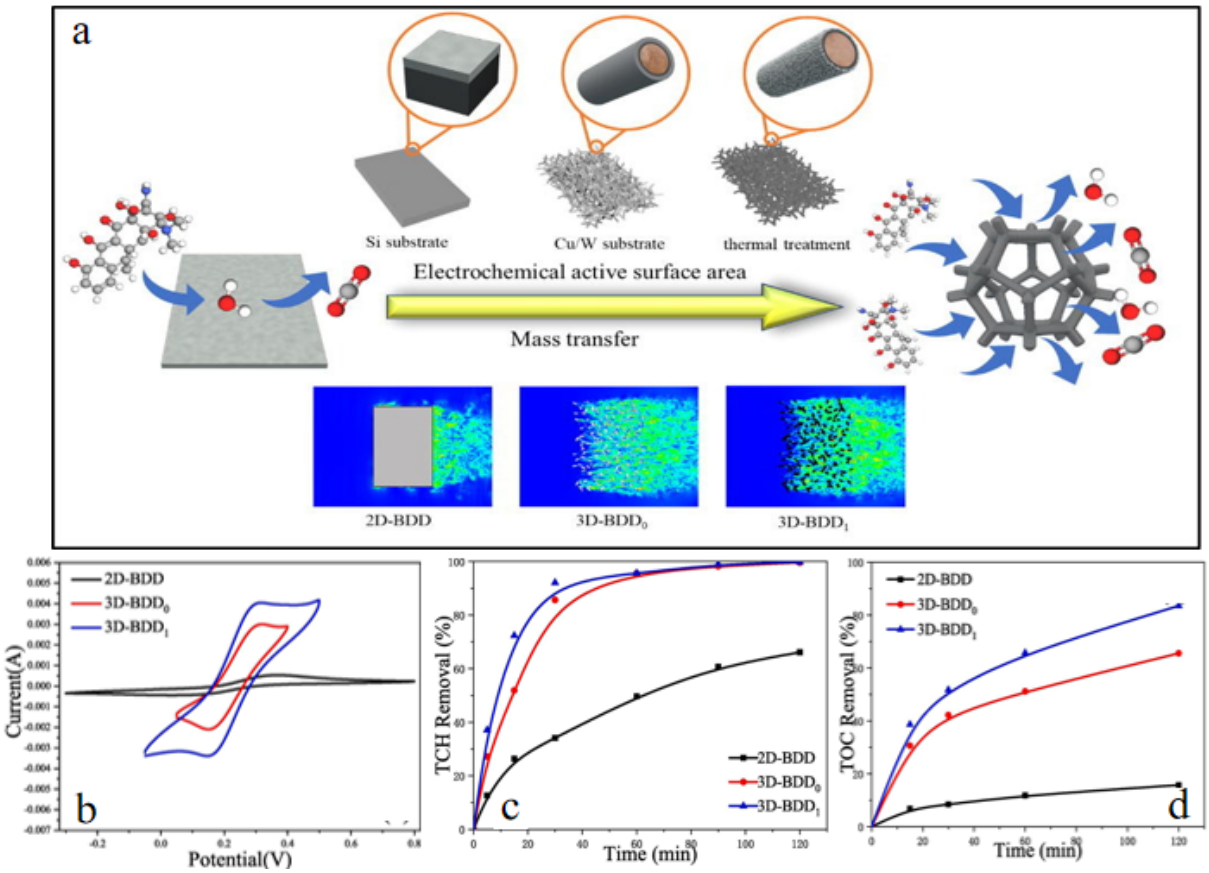


Figure 3. Schematic diagram of 3D-Cu/W/BDD electrode preparation and electrochemical performance and degradation performance test

The ingenious combination of top-down and bottom-up methods successfully broke through the structural limitations of foam BDD electrodes, realized the organic combination of macro-foam structure and microstructure, and significantly improved the specific surface area and mass transfer efficiency of the electrode. This composite strategy has opened up a new way for the design and preparation of high-performance BDD electrodes. In the future, breakthroughs are expected to be made in further optimizing microstructure morphology, exploring new transition layer materials, and more efficient surface treatment technologies, which is expected to promote BDD electrodes. Wide application in the field of commercial synthesis.

4. Conclusion and Prospect

BDD electrode is a potential anode for electrochemical oxidation. BDD electrochemical oxidation technology can efficiently treat high concentration refractory organic wastewater. In this paper, various preparation methods of BDD electrodes are sorted out and compared, and the internal relationship between preparation process regulation, macro and micro porous modification and electrode catalytic activity is summarized. The role of process parameters and porous structure on the micromorphology, interface bonding and degradation performance of the film is analyzed:

(1) The preparation of BDD electrodes mainly includes two types: high-temperature and high-pressure HPHT method and various CVD chemical vapor deposition methods. Among them, hot-filament chemical vapor deposition has become the mainstream preparation method due to its comprehensive advantages of simple equipment, large-area preparation, and easy industrial scale-up; By accurately adjusting key process parameters such as reaction gas composition, substrate temperature, deposition pressure, and deposition time, the BDD film grain size, boron doping level, sp3/sp2 carbon ratio, and the interface bond strength between the film and the substrate can be adjusted in a directional manner. Improve the electrode electrochemical window, oxygen evolution potential and catalytic stability.

(2) The performance improvement of BDD electrode is divided into two core paths: process parameter regulation and porous structure modification. In terms of preparation, HFCVD has become the mainstream preparation technology due to its advantages of easy amplification and low cost. It can accurately optimize the film doping concentration, grain structure and substrate interface bonding strength by regulating the boron-carbon gas ratio, substrate temperature, deposition pressure and duration; Porous modification is divided into the top-down method of post-etching of thin films and the bottom-up method of in-situ deposition of porous substrates. Composite two modification ideas can simultaneously build macro-fluid channels and micro-porous active interfaces, breaking through flat BDD electrodes. The shortcomings of insufficient specific surface area and low mass transfer efficiency.

Generally speaking, BDD electrodes are anode materials for the treatment of industrial refractory organic wastewater, but there are still many key problems that need to be broken through in the large-scale implementation of BDD electric oxidation water treatment technology:

(1) Electrode preparation cost and large-area preparation problems. The high price of CVD deposition supporting

equipment and high-purity boron-carbon precursor raw materials increases the production cost of electrodes; The existing deposition system and suitable substrate materials are limited, and it is difficult to prepare continuous BDD films with large areas, uniform thickness and doping, which restricts industrial mass production.

(2) The highly reactive porous BDD system is out of touch with engineering applications. The doping, pore structure, and interface matching mechanism of macrocomposite porous BDD with high catalytic activity still need to be systematically explored; At present, most of the relevant research is limited to the laboratory small test system, and there are few actual pilot tests and engineering cases for printing and dyeing, leachate, and chemical wastewater. Multidisciplinary innovation is required to promote technology implementation.

References

[1] Zhang, L., Peng, W., Wang, W., et al. (2024). A comprehensive review of the electrochemical advanced oxidation processes: Detection of free radical, electrode materials and application. Journal of Environmental Chemical Engineering, 113778.

[2] Yamaguchi, C., Natsui, K., Iizuka, S., et al. (2019). Electrochemical properties of fluorinated boron-doped diamond electrodes via fluorine-containing plasma treatment. Physical Chemistry Chemical Physics, 21(25), 13788-13794.

[3] Lin, Y., Shen, W., Fang, C., et al. (2024). High pressure and high temperature synthesized boron-doped diamond electrodes for effective waste water treatment. Journal of the European Ceramic Society, 44(7), 4570-4579.

[4] An, K., Chen, L., Yan, X., et al. (2018). Fracture behavior of diamond films deposited by DC arc plasma jet CVD. Ceramics International, 44(11), 13402-13408.

[5] Gao, X., Li, W., Mei, R., et al. (2019). Effect of the $B_2H_6/CH_4/H_2$ ratios on the structure and electrochemical properties of boron-doped diamond electrode in the electrochemical oxidation process of azo dye. Journal of Electroanalytical Chemistry, 832, 247-253.

[6] Guo, L., & Chen, G. (2007). Long-term stable Ti/BDD electrode fabricated with HFCVD method using two-stage substrate temperature. Journal of the Electrochemical Society, 154(12), D657.

[7] Jia, F., Bai, Y., Fang, Q., et al. (2010). The influence of gas pressure and bias current on the crystallinity of highly boron-doped diamond films. New Carbon Materials, 25(5), 357-362.

[8] Song, C. W., You, M. Y., Lee, J. M., et al. (2020). Electrochemical properties and chemical oxygen demand depending on the thickness of boron-doped diamond. Coatings, 10(11), 1097.

[9] Li, D., Li, J., Yu, X., et al. (2023). Combination of porous structure and MnO_2 modification for improving capacitance of planar BDD electrode. Journal of Electroanalytical Chemistry, 944, 117647.

[10] Ohashi, T., Zhang, J., Takasu, Y., et al. (2011). Steam activation of boron doped diamond electrodes. Electrochimica Acta, 56(16), 5599-5604.

[11] Shi, C., Li, C., Li, M., et al. (2016). Fabrication of porous boron-doped diamond electrodes by catalytic etching under hydrogen–argon plasma. Applied Surface Science, 360, 315-322.

[12] Li, X., Li, H., Li, M., et al. (2018). Preparation of a porous boron-doped diamond/Ta electrode for the electrocatalytic degradation of organic pollutants. Carbon, 129, 543-551.

[13] Tang, Y., Liu, M., He, D., et al. (2022). Efficient electrochemical degradation of X-GN dye wastewater using porous boron-doped diamond electrode. Chemosphere, 307, 135912.

[14] Mei, R., Wei, Q., Zhu, C., et al. (2019). 3D macroporous boron-doped diamond electrode with interconnected liquid flow channels: A high-efficiency electrochemical degradation of RB-19 dye wastewater under low current. Applied Catalysis B: Environmental, 245, 420-427.

[15] Wei, Q., Liu, G., Zhu, C., et al. (2020). Ordered structures with functional units (OSFU) enabled highly robust diamond anode for electrochemical decomposing of organic pollutants. Chemical Engineering Journal, 397, 125465.

[16] Miao, D., Liu, T., Yu, Y., et al. (2020). Study on degradation performance and stability of high temperature etching boron-doped diamond electrode. Applied Surface Science, 514, 146091.