

Analysis of the Characteristics of Bipolar Electrode-electrochemiluminescence Sensor and Comparative Study with Traditional Sensors

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Abstract. Electrochemiluminescence (ECL) technology, as a product of the integration of electrochemistry and chemiluminescence, has attracted much attention since its inception. Also, compared with traditional bipolar electrodes (BPEs) do not require ohmic contacts and provide high structural freedom, which enhances reaction efficiency and detection sensitivity. Therefore, bipolar electrode-electrochemiluminescence sensors (BPE-ECL sensors) combine BPEs and ECL ingeniously, opening up a new path for analysis and detection. In the current era of continuous innovation in analytical detection technologies, with the growth of requirements for detection accuracy and speed in various fields, scientific researchers have met an important task about how to develop sensors with superior performance. So this essay will explore BPEs, a crucial component of BPE-ECL sensors, then compare it with other sensors to evaluate its value in some fields like medical care, food industry, and environmental monitoring.

Keywords: food security, medical treatment and health, sensors, BPE-ECL

1. Introduction

BPE-ECL sensors are an ideal combination of closed bipolar electrodes and electrochemical luminescence technology, and this integration has facilitated the rapid development of biological analysis applications. Nowadays, these sensors are successfully used for the detection of biomolecules, cancer cells, and other analytes. As public awareness of food safety, medical health, and environmental protection continues to grow, the field of detection has witnessed significant technological upgrades and rapid development. What's more, electrochemical sensors hold a central position in this field due to their wide range of application scenarios. For instance, in the medical field, they can be used for disease diagnosis, treatment and monitoring, such as electrochemical glucose sensors [1] and dopamine electrochemical sensors [2]. Meanwhile, in the ecological domain, they can assist in ensuring the emissions of industrial pollutants to meet standards and promote sustainable environmental development. In the food sector, they are also able to make sure product quality by detecting the content of food components and additives. At present, Electrochemical sensors mainly include amperometric sensors (which detect analyte concentrations by measuring

current changes caused by redox reactions under an applied potential) and potentiometric sensors (which are based on the Nernst equation and detect analyte concentrations by measuring the voltage of an electrochemical cell). What's more, these sensors have many advantages. For example, amperometric sensors offer high sensitivity and can operate without a reference atmosphere [3]. Moreover, potentiometric sensors feature small size, short response time, ease of operation, cost-effectiveness, and resistance to sample color and turbidity [4].

However, traditional electrochemical sensors have some limitations in terms of slow response and low sensitivity. Therefore, BPE-ECL sensors, as a more efficient and convenient electrochemical sensor currently, can overcome these problems of slow response and low sensitivity of some existing sensors, providing a more accurate and rapid method for the detection field. Also, BPE-ECL sensors not only possess the advantages of other electrochemical sensors in terms of sensitive signal response and rapid detection, but also have characteristics like no requirement for direct electrical contact and strong anti-interference capability [5].

2. BPE-ECL sensors

BPE-ECL sensors operate by applying a sufficient voltage through the driving electrodes, forming an electric field within the channel. This electric field then induces redox reactions at the two poles of BPEs, thereby generating an ECL signal [6].

2.1. The characteristic analysis of BPEs

BPEs have prominent advantages such as high flexibility, excellent reaction efficiency and outstanding sensitivity. BPE-ECL sensors developed based on BPEs overcome the shortcomings of amperometric sensors (slow response) and potentiometric sensors (poor sensitivity) effectively. They exhibit performance advantages surpassing those of traditional sensors in fields such as medical testing, food safety, and environmental monitoring, and thus have been widely applied. Table 1: Comparison of the advantages and disadvantages between traditional electrodes and BPEs [5,7]

Table 1. Comparison of the advantages and disadvantages between traditional electrodes and BPEs

Electrode type	advantages	disadvantages
traditional electrodes	low cost high chemical stability and wide application range stable chemical properties and good signal reproducibility	need to connect wires, large in size, a risk of electrical leakage reaction products are prone to mix and cause interference
BPEs	no separate wiring required, high degree of freedom high reaction efficiency and good sensitivity	impossible to directly measure the current and potential at the two poles impossible to control the growth direction of the synthetic polymer materials impossible to supply the overpotential generated due to the change in BPEs length in a timely manner may result in a branch

2.2. Application

The BPE-ECL sensors have now been widely applied in the detection field. Moreover, they have demonstrated remarkable strengths in core fields such as medical diagnosis, food safety monitoring, and environmental detection due to their characteristics such as no direct electrical contact, sensitive signal response, and strong anti-interference ability.

In medical fields, they enable screening for nucleic acids, proteins, viruses and cells rapidly. For example, a biosensor based on BPE-ECL and combining electrocatalysis and enzymatic catalysis was constructed to monitor the ALP activity during osteoblast differentiation. Because the dual signal amplification strategy employs a combination of electrocatalysis and enzymatic catalysis, the electrochemical luminescence of intensity was increased by 10 times. Therefore, this platform has great potential in the field of clinical diagnosis [5]. They have also achieved significant breakthroughs that drive progress in the medical field. Current bacterial detection methods, including electrochemical impedance spectroscopy (EIS) biosensors (which detect bacteria through impedance changes caused by bacterial adsorption on the electrode surface, with signals dependent on the number of surface-bound bacteria and interface status) and conductivity biosensors (which alter the electrical conductivity of solutions via ions released during bacterial growth, metabolism, or lysis, with signals dependent on ion exchange between bacteria and the surrounding environment). These approaches primarily rely on surface responses, and whether the bacteria are alive or not, as long as their physical structures (such as cell membranes or surface proteins) remain intact, they can produce similar responses on the sensor surface, as long as their physical structures (such as cell membranes, surface proteins, etc.) are not completely destroyed, they can all produce similar responses on the sensor surface, which means none of these methods can distinguish between them. Furthermore, the actual samples contain complex matrices, and these substances will have non-specific interactions with the sensors' surfaces, thereby interfering with the signals generated by the bacteria. In contrast, in the BPE-ECL sensor system, the two poles of the closed BPEs are physically separated. Consequently, complex food matrices do not interfere with the electrochemiluminescence reaction or signal reading, which improves the accuracy of signal acquisition. Additionally, this system requires no additional wire connection, enabling easy operation and rapid detection. In addition, the BPE surface in this system does not require chemical modification and can operate directly by utilizing the inherent electrochemical properties of the electrode itself, thereby reducing the preparation cost and time [8].

In the food industry, they can detect contaminants such as mycotoxins efficiently. For example, in the detection of food samples, BPE Array-Based Electrochemiluminescence Biosensor exhibits good accuracy for fumonisin B (a class of mycotoxins produced by fungi of the genus *Fusarium*, which widely contaminates food crops such as corn, sorghum, and wheat, as well as their processed products) and enables the visual detection of FB1 within the range of 5. In addition, it is also used to monitor the concentration of FB1 in corn and peanut samples, with the recovery rate reaching over 99% [9].

In environmental monitoring, it can identify key indicators accurately in water bodies, such as heavy metal ions and dissolved oxygen. For instance, water, as an indispensable natural resource in human daily life, is facing serious environmental problems such as pollution, which is seriously threatening human health. Thus, a rapid and label-free paper-based open BPE-ECL sensor was developed for detecting in water, thereby preventing Hg from harming human health. Compared with other reported sensing devices, this method demonstrates higher sensitivity and a lower detection limit. Also, the open BPE-ECL sensors have more accurate results and a shorter detection time than most traditional detection devices [6].

2.3. Compare the technical advantage with traditional sensors

Traditional electrochemical sensors have some limitations. The response time of amperometric sensors is relatively long. For example, a type of amperometric sensor based on yttria-stabilized zirconia (YSZ) material is equipped with a symmetrical platinum electrode pair for detecting the concentrations of CO and in inert gases. When the concentration of undergoes a step change within the range of 4.6-13.7 vol.%, due to insufficient proton conductivity of the electrolyte or poor performance of the electrodes, the response time of this sensor exceeds 30 minutes, resulting in a delay in the response. So now it is still difficult to achieve simultaneous detection of and CO in inert gases [3]. In addition, there are several solutions addressing the issue of improving the sensitivity of the ion-selective electrode (ISE) in potentiometric sensors so far like using the electropolymerization method to incorporate g-C₃N₄ nanoparticles into the ion-electron sensors for analyzing sweat. Although this approach has a wider detection range and high selectivity, this problem remains a key and challenging area of current researches [10]. To better illustrate the comparative performance of different electrochemical sensor types, Table 2 summarizes the advantages and disadvantages of amperometric and potentiometric sensors [11, 12].

Table 2. Advantages and disadvantages of amperometric sensors and potentiometric sensors

Sensor type	Advantages	disadvantages
amperometric sensors	high sensitivity easy for miniaturization and integration diverse and flexible analytical methods easy to carry provide appropriate detection strategies for different target analytes	Interfere with the target signal limited linear range poor adaptability to complex substrates
potentiometric sensors	respond promptly low-power dissipation efficient high cost-effectiveness easy to miniaturize low sample consumption	low sensitivity of the ion-selective electrode

2.4. Limitation

However, BPE-ECL sensors still have certain limitations at present. Most BPE-ECL sensors can detect electroactive substances directly, reaching the level of single molecules and single cells. While the μM level is far from meeting the detection requirements. Thus, When detecting ultra-trace target analytes (such as pg-level or fg-level biomarkers), the μM concentration level is far from catering for the detection requirements. So, researchers need to explore continuously in the field of signal amplification in order to enhance the sensitivity of the detection [13]. Meanwhile, BPE-ECL sensors still have significant limitations. On the one hand, the consumption of samples and reagents is relatively high, because the electrode reaction relies on a certain volume of solution environment to ensure sufficient ion conduction and reaction. Therefore, this may directly lead to excessively high costs and is not conducive to the application in scenarios requiring micro-detection. On the other hand, the operation process is rather complicated, as they entail sample pretreatment, modification of the electrode surface, optimization of electrochemiluminescence reaction conditions, and other processes. It not only prolongs the testing period but also increases the risk of human error. These issues have restricted the expansion of this type of sensor towards high-throughput and

automated detection. Therefore, it is necessary to develop new solutions to achieve technological breakthroughs [14].

2.5. Current solutions

First, To address the issues of cumbersome procedures and high reagent consumption, the flow direction of fluids can be controlled through special channel structures and the differences in fluid resistance among channels of varying sizes. For instance, multiple parallel detection units integrated on a chip enable rapid and automatic multi-sampling. This design not only significantly improves sensing efficiency but also helps reduce reagent consumption. One example is an antibody ordered assembly functional BPE-ECL platform for aflatoxin B1 Detection [13]. Second, regarding signal amplification strategies, there are two main categories. The first one is nanomaterial-based modification of the surface of BPEs, which helps construct an efficient electron transfer channel by leveraging the extremely large specific surface area and unique electron conduction properties of nanomaterials. Also, this modification not only increases the contact sites between the electrode and the reaction system, but also effectively reduces the energy barrier during electron transfer, significantly improving the rate and efficiency of electron transfer on the electrode surface, which promotes the optimization of the response performance of biosensors. Another one is enzyme catalysis, which amplifies the detection signal through the catalytic amplification effect of enzymes on substrates. Furthermore, these signal amplification strategies have enabled the detection level of the system to reach the fM range, significantly improving its sensitivity and providing the possibility for the detection of single molecules and single cells [13].

3. Conclusion

The integration of bipolar electrodes (BPEs) with electrochemiluminescence (ECL) has enabled the development of simple, portable, and multifunctional sensors that are now widely applied across diverse detection fields. Current BPE-ECL sensors have achieved a relatively mature stage of development, and several effective strategies for performance enhancement have already been identified, such as integrating multiple parallel detection units, applying nanomaterials to facilitate electron transfer, and employing enzyme catalysis to amplify signals.

Nonetheless, existing improvements remain insufficient for addressing the broader challenges of stability, sensitivity, and cost-effectiveness. Future research should therefore not only refine these established approaches but also explore new directions. For instance, the stability of electrode materials may be improved through the introduction of nanocomposite coatings on BPE surfaces, while the detection limits could be further reduced by advancing signal amplification strategies, including the development of miniaturized BPE-ECL platforms and the utilization of low-cost, sustainable electrode materials.

Continuous innovation in these areas will significantly enhance the practicality and competitiveness of BPE-ECL sensors, particularly in challenging scenarios such as complex food matrix analysis and on-site rapid screening. Such technological breakthroughs are expected to expand the application boundaries of BPE-ECL sensors in point-of-care testing (POCT), clinical diagnostics, and food safety monitoring, while also improving the overall efficiency and accuracy of detection. Ultimately, these advancements will provide stronger technical support for addressing urgent public health needs and ensuring the protection of human well-being.

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