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Application of Semiconductor Biochips in Disease Monitoring

Zetian Fu

School of Engineering, University of New South Wales, Sydney, Australia
fuzetianapp@163.com

Abstract: With an increasing awareness of health and the rapid development of biotechnology, semiconductor biochips, as an important tool at the intersection of integrated circuits and biomedical fields, have shown great potential in disease monitoring and other areas. This paper analyzes the working principles of semiconductor biochips and their specific applications in disease detection, exploring how they achieve early disease diagnosis by monitoring changes in biomarkers such as ion concentration and metabolic products. Through literature review and case analysis, this study summarizes the current mainstream types of biochips (such as microfluidic chips and electrochemical sensor chips) and their effectiveness in monitoring diseases like cancer and diabetes. The results indicate that semiconductor biochips offer advantages such as high sensitivity, rapid response, and low cost, but they still face challenges in biocompatibility and large-scale production. In the future, with advancements in materials science and nanotechnology, biochips are expected to play a more significant role in personalized medicine and point-of-care testing (POCT).

Keywords: Semiconductor biochips, disease monitoring, microfluidic technology, electrochemical sensors, point-of-care testing (POCT)

1. Introduction

With the increasing global burden of disease, a growing demand for efficient and accurate diagnostic technologies provides timely information to healthcare providers. Semiconductor biochips, which integrate microelectronics with advanced biosensing capabilities, represent a promising innovation in this field. These biochips enable real-time monitoring of biomolecular changes, offering new avenues for early disease screening and diagnosis [1].

In recent years, significant progress has been made in semiconductor biochip technology. For example, Smith et al. developed a microfluidic chip that successfully detected tumor markers in blood with a sensitivity of 0.1 ng/mL [2]. Similarly, Zhang's team utilized a graphene-based electrochemical sensor chip that facilitates dynamic glucose monitoring for diabetic patients, allowing for better management of their condition [3]. These innovative technologies have provided crucial support for clinical diagnostics, enhancing the ability to detect diseases early and effectively.

This paper systematically explores the technical characteristics of semiconductor biochips and their application scenarios in disease monitoring through literature analysis and case comparisons, aiming to provide technical references for future research. By promoting the development of low-cost, portable diagnostic devices, this research contributes to public health system improvements and facilitates broader access to advanced medical technologies.

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2. Types and Characteristics of Semiconductor Biochips

In today's rapidly evolving biomedical field, semiconductor biochips are increasingly recognized as essential tools for disease detection and early diagnosis due to their efficiency and versatility. These biochips come in various types, each with distinct characteristics that cater to different application needs. Several major types of semiconductor biochips are discussed in the following sections.

2.1. Microfluidic Chips

Microfluidic chips operate by manipulating microliter-scale fluids through micron-sized channels, integrating sample preprocessing and detection functions. These chips offer advantages such as high throughput and low sample consumption requiring only microliter volumes, and multiplex biomarker detection making them suitable for early disease diagnosis and precision medicine [4].

Microfluidic chips are widely used in early cancer screening and infectious disease detection. For example, microfluidic-based chips can analyze circulating tumor cells (CTCs) and circulating tumor DNA (ctDNA) in blood, enabling non-invasive cancer detection. This approach reduces patient discomfort and offers higher safety and convenience. Additionally, microfluidic chips allso for rapid detection of viruses and bacteria [5].

2.2. Electrochemical Sensor Chips

Electrochemical sensor chips primarily rely on electrochemical reactions and interactions at the sensor surface. They detect changes in electrical signals (such as current, voltage, or conductance) resulting from biomolecular reactions (e.g., redox reactions) on the electrode surface, enabling the detection of specific biomarkers. These chips offer advantages such as high sensitivity (capable of detecting pM concentrations with high accuracy) and rapid response (reaction time $\leq$ 5 minutes), making them suitable for point-of-care testing (POCT) and real-time monitoring [6]. Furthermore, electrochemical sensor chips are small and integrated, making them ideal for portable devices and. This makes them particularly useful for early disease diagnosis and environmental monitoring.

Electrochemical sensor chips are widely used in chronic disease management and cardiovascular disease monitoring. For example, wearable electrochemical sensor chips can monitor glucose levels in diabetic patients in real-time and transmit data via Bluetooth to mobile devices, aiding doctors in personalized treatment. Additionally, these chips can monitor cardiac biomarkers such as troponin for early diagnosis of myocardial infarction and improving patient outcomes.

2.3. Optical Sensor Chips

Optical sensor chips detect changes in optical signals, such as fluorescence or absorption spectra, to determine the presence or concentration of biomolecules. These chips offer advantages such as high sensitivity (capable of detecting minute changes in substances), non-contact detection (avoiding direct contact with the sample, preventing contamination in certain scenarios), and multifunctionality (allowing detection of different parameters by adjusting hardware and optical designs). These characteristics make optical sensor chips well-suited for real-time monitoring and multiplex analysis in biomedical applications.

Optical sensor chips have significant potential in infectious disease detection and neurodegenerative disease monitoring. For example, fluorescence-based optical sensor chips can rapidly detect viral nucleic acids, proteins, or antibodies for early diagnosis of viral infections [7]. Additionally, optical sensor chips can monitor biomarkers in cerebrospinal fluid, such as β-amyloid, wich is critical for early diagnosis of Alzheimer's disease.

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2.4. Nanopore Chips

Nanopore chips typically contain one or more nanoscale pores. When a target molecule passes through the nanopore, it causes a change in electrical current. The basic principle involves detecting these current changes to identify single molecules (such as DNA or proteins). These chips offer advantages such as extremely high sensitivity (single-molecule detection capability) and high throughput (simultaneous detection of multiple molecules with strong parallel processing capabilities). Unlike many traditional molecular detection methods, nanopore chips do not require chemical labeling of samples, reducing sample preparation complexity, thus making them suitable for gene sequencing and protein analysis.

Nanopore chips are widely used in early cancer screening and gene mutation detection. For example, nanopore array-based chips can capture circulating tumor DNA (ctDNA) in blood, enabling high-precision early cancer diagnosis. Additionally, these chips can detect gene mutations, helping doctors develop personalized treatment plans.

3. Applications of Semiconductor Biochips in Disease Monitoring

3.1. Early Cancer Screening

Early cancer screening is a critical area of medical research, as early detection significantly improves treatment outcomes and patient survival rates. Nanopore array-based biochips, which capture circulating tumor DNA (ctDNA) in blood, have achieved a detection accuracy of 95% [8]. This technology uses specific probes to identify mutated gene fragments, significantly enhancing the feasibility of early cancer diagnosis.

With the rising incidence of cancer, early screening has become increasingly important. Traditional cancer detection methods such as tissue biopsies and imaging, while accurate, are often invasive and costly [9]. Semiconductor biochips offer a new solution for early cancer screening. For example, microfluidic-based biochips can analyze CTCs and ctDNA concentrations in blood, enabling early-stage cancer detection without the need for invasive procedures.

Additionally, semiconductor biochips can be used for personalized cancer treatment. By monitoring changes in tumor biomarkers, doctors can adjust treatment plans based on individual patient conditions, improving treatment efficacy. Various semiconductor biochip technologies, including microfluidic chips, high-throughput screening chips, nanopore chips, and electrochemical sensor chips can monitor tumor cell responses to drugs, helping doctors select the most effective drug combinations.

3.2. Chronic Disease Management

Wearable biochips can monitor glucose levels in diabetic patients' sweat in real-time, with data transmitted via Bluetooth to mobile devices [10]. This non-invasive monitoring method reduces the need for blood sampling and provides dynamic data for personalized treatment.

Traditional chronic disease monitoring often requires frequent hospital visits, which can be inconvenient and may delay necessary interventions. Semiconductor biochips offer a portable, real-time monitoring solution, significantly enhancing patient autonomy and disease management. For example, electrochemical sensor-based biochips can monitor biomarkers in sweat, saliva, or urine, providing real-time health data.

In diabetes management, wearable biochips can monitor glucose levels in sweat, providing real-time feedback on blood sugar changes. This technology not only reduces the frequency of blood sampling but also allows doctors to adjust treatment plans based on transmitted data. Additionally, semiconductor biochips can monitor other chronic conditions such as hypertension and heart disease

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by tracking physiological parameters like blood pressure and heart rate, helping patients better manage their health [11].

3.3. Infectious Disease Detection

In recent years, semiconductor biochips have made significant progress in infectious disease detection. For example, Lee et al. developed a microfluidic-based biochip for rapid detection of the influenza virus (SARS-CoV-2) [12]. This chip captures viral RNA and uses fluorescent probes to complete detection within 30 minutes, with a sensitivity of 10 copies/μL. This technology not only shortens detection time but also reduces costs, making it valuable for large-scale screening and deployment in resource-limited settings.

Rapid detection of infectious diseases is crucial for controlling outbreaks. Traditional methods like polymerase chain reaction (PCR) are accurate but time-consuming and require complex laboratory equipment. Semiconductor biochips offer a new solution for rapid infectious disease detection. Microfluidic-based biochips can analyze saliva or nasopharyngeal swab samples to quickly detect the presence of viruses or bacteria.

For influenza virus detection, semiconductor biochips can process large numbers of samples in a short time, making them ideal for large-scale screening in places like airports and train stations. Additionally, this technology can be used to detect other infectious diseases such as dengue fever. By enabling rapid detection and diagnosis, semiconductor biochips help healthcare institutions implement control measures quickly, reducing the spread and risk of infectious diseases.

3.4. Cardiovascular Disease Monitoring

Cardiovascular diseases are a leading cause of mortality worldwide, making early detection and continuous monitoring essential for improving patient outcomes. Semiconductor biochips have made significant progress in cardiovascular disease monitoring. For example, electrochemical sensor-based biochips can monitor cardiac biomarkers such as troponin in blood, enabling early diagnosis of myocardial infarction [13]. These chips can complete detection within minutes, with a sensitivity of 0.01 ng/mL, which far exceeds traditional methods.

Additionally, semiconductor biochips can monitor physiological parameters such as heart rate and blood pressure. For example, wearable biochips can monitor electrocardiogram (ECG) signals, providing real-time feedback on heart health. This technology not only helps patients detect heart issues early but also allows for real-time data transmission to doctors, facilitating remote monitoring and diagnosis.

3.5. Neurodegenerative Disease Monitoring

Early diagnosis of neurodegenerative diseases such as Alzheimer's and Parkinson's has long been a challenge in medicine. Semiconductor biochips offer new possibilities for monitoring these diseases. For example, microfluidic-based biochips can analyze biomarkers such as β-amyloid in cerebrospinal fluid or blood for early diagnosis of Alzheimer's disease [14]. These chips can detect disease biomarkers at an early stage, providing patients with earlier treatment opportunities.

Additionally, semiconductor biochips can monitor the progression of neurodegenerative diseases. By regularly tracking changes in biomarkers, doctors can better understand disease progression and adjust treatment plans. For example, electrochemical sensor chips, optical sensor chips, and biosensor chips can monitor changes in dopamine levels, helping doctors assess the progression of Parkinson's disease.

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4. Challenges and Future Directions

4.1. Technical Challenges

As a novel technology, semiconductor biochips hold great potential in disease monitoring, but they still face several technical challenges. One major issue is improving sensitivity and detection limits. Current sensors may struggle to accurately detect biomarkers at low concentrations, affecting diagnostic precision and reliability.

Selectivity and specificity also remain key challenges. The materials and surface functionalization of semiconductor chips have not fully resolved how to efficiently and selectively capture target biomarkers, which impacts their application in monitoring various diseases.

The stability and long-term performance of semiconductor biochips also need improvement. These chips may be affected by environmental conditions such as temperature and humidity, as well as biological samples, leading to performance instability. This is particularly critical for long-term disease monitoring.

Another challenge is data processing and analysis. Semiconductor biochips generate large amounts of data, which require complex processing and analysis to yield meaningful diagnostic conclusions. The complexity of biological signals and the presence of noise make data processing and interpretation more difficult. Existing algorithms and computational methods have not yet fully achieved the speed and accuracy necessary for seamless real-time analysis.

4.2. Future Directions

Future research should focus on improving sensitivity and selectivity. Semiconductor biochips should aim to enhance detection sensitivity for low-concentration biomarkers and improve selectivity to accurately distinguish target biomarkers in complex scenarios. This can be achieved through the use of nanomaterials such as gold nanoparticles and graphene, as well as surface modification techniques to enhance selective binding with target molecules and reduce non-specific adsorption.

Additionally, long-term stability is critical for future development. The long-term stability and biocompatibility of semiconductor biochips can be improved by developing new biocompatible materials and incorporating self-healing technologies to ensure continuous operation and reduce maintenance requirements.

5. Conclusion

This paper systematically reviews the technical pathways and application scenarios of semiconductor biochips, highlighting their efficiency and practicality in disease monitoring. By integrating microelectronics and biosensing technologies, semiconductor biochips enable high-sensitivity, high-throughput biomarker detection, showing great potential in early cancer screening, infectious disease monitoring, and chronic disease management. However, this review has some limitations, such as a lack of experimental data and reliance on literature reviews and case analyses. Additionally, the long-term safety and cost control of semiconductor biochips for large-scale production need more clinical validation and industrial exploration. With advancements in interdisciplinary fields such as materials science, artificial intelligence, and clinical medicine, semiconductor biochip technology is expected to achieve significant breakthroughs in the future.

Future research should focus on the following areas: First, developing new biocompatible materials to improve chip stability and safety, reducing interference with biological samples. Second, optimizing chip manufacturing processes to lower production costs and promote large-scale industrial applications. Third, integrating artificial intelligence to develop intelligent data analysis algorithms, enhancing detection accuracy and efficiency. Fourth, expanding multi-omics detection

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capabilities by integrating genomic, proteomic, and metabolomic data for more comprehensive disease diagnosis and monitoring. Fifth, exploring portable and wearable biochip devices to promote the democratization of medical resources, allowing more people to benefit from precision medicine. In conclusion, the future development of semiconductor biochip technology will extend beyond labortory research toward clinical applications, industrial promotion, and universal healthcare, bringing profound impacts to human health.

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