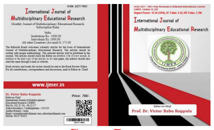
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IMPACT OF DIFFERENT SEMICONDUCTORS IN BIOSENSORS FOR THE DIAGNOSIS OF VARIOUS DISEASES: RECENT ADVANCES, CHALLENGES, AND FUTURE PERSPECTIVES

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Abstract

The rapid advancement of biosensor technology has revolutionized disease diagnosis by enabling sensitive, selective, rapid, and cost-effective detection of biomarkers. Semiconductor-based biosensors have emerged as a promising class of diagnostic devices owing to their unique electrical, optical, and physicochemical properties. Various semiconductor materials, including silicon (Si), germanium (Ge), zinc oxide (ZnO), titanium dioxide (TiO_2), gallium nitride (GaN), indium oxide (In_2O_3), cadmium sulfide (CdS), and two-dimensional semiconductors such as molybdenum disulfide (MoS_2), have demonstrated remarkable performance in biosensing applications. These materials facilitate high sensitivity, low detection limits, and real-time monitoring of disease biomarkers associated with diabetes, cancer, cardiovascular disorders, infectious diseases, neurological disorders, and genetic abnormalities.

This review comprehensively examines the role of different semiconductor materials in biosensor development and their impact on disease diagnosis. The sensing mechanisms, fabrication techniques, advantages, limitations, and clinical applications are discussed in detail. Furthermore, recent developments in nanostructured semiconductor biosensors, wearable diagnostic systems, and artificial intelligence-integrated biosensing platforms are highlighted. The paper concludes by addressing current challenges and future opportunities for semiconductor-based biosensors in personalized healthcare and point-of-care diagnostics.

Keywords: Semiconductor Biosensors, Disease Diagnosis, Silicon Nanowires, Zinc Oxide Nanostructures, Cancer Detection, Diabetes Monitoring, Point-of-Care Diagnostics, Nanotechnology.

1. Introduction

The increasing prevalence of chronic and infectious diseases worldwide necessitates the development of advanced diagnostic tools capable of early detection and continuous monitoring. Conventional laboratory diagnostic techniques, including ELISA, PCR, chromatography, and spectroscopy, often require sophisticated instrumentation, trained personnel, and prolonged analysis time.

Biosensors have emerged as transformative diagnostic tools by integrating biological recognition elements with transducers that convert biological interactions into measurable signals. Semiconductor materials play a pivotal role in enhancing biosensor performance due to their tunable electronic properties, miniaturization capability, and compatibility with microfabrication technologies.

Recent advancements in nanotechnology have significantly improved semiconductor biosensors by increasing surface area, enhancing charge transfer mechanisms, and facilitating label-free detection. Consequently, semiconductor biosensors have found widespread applications in diagnosing diseases such as:

- Diabetes Mellitus
- Breast Cancer
- Prostate Cancer
- Lung Cancer

- Cardiovascular Diseases
- Alzheimer's Disease
- Parkinson's Disease
- COVID-19
- Tuberculosis
- Hepatitis
- HIV/AIDS

2. Fundamentals of Semiconductor Biosensors
2.1 Definition

A semiconductor biosensor is an analytical device that combines:

1. Biological Recognition Element
    - Enzymes
    - Antibodies
    - DNA/RNA probes
    - Aptamers
    - Cells
2. Semiconductor Transducer
    - Silicon
    - ZnO
    - TiO_2
    - GaN
    - MoS_2
3. Signal Processing Unit

The interaction between analyte and bioreceptor generates an electrical or optical signal that is processed and quantified.

2.2 Working Principle

The biosensing mechanism generally involves:

Biomarker + Bioreceptor → Biochemical Interaction → Semiconductor Response → Electrical Signal
Changes observed include:

- Current variation
- Voltage variation
- Resistance change
- Capacitance change
- Optical emission variation

3. Classification of Semiconductor Materials Used in Biosensors
3.1 Silicon-Based Biosensors
Properties

- Excellent electrical conductivity
- CMOS compatibility
- High stability
- Established fabrication technology

Applications

Diabetes Detection

Silicon nanowire FET biosensors detect glucose with high sensitivity.

Cancer Diagnosis

Detection of:

- PSA (Prostate-Specific Antigen)
- CEA (Carcinoembryonic Antigen)

COVID-19 Detection

Rapid viral protein identification.

Advantages

- High sensitivity
- Miniaturization
- Integration with electronics

Limitations

- Surface oxidation
- Complex fabrication

3.2 Zinc Oxide (ZnO) Biosensors
Properties

- Wide bandgap (3.37 eV)
- High electron mobility
- Biocompatibility

Nanostructures

- Nanorods
- Nanowires
- Nanoflowers

Disease Applications

Glucose Monitoring

ZnO nanorods provide efficient enzyme immobilization.

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Cholesterol Detection

Sensitive monitoring in blood samples.

Cancer Biomarkers

Detection of:

- AFP
- CA-125
- HER2

Advantages

- Low cost
- High surface area
- Excellent sensitivity

3.3 Titanium Dioxide (TiO_2) Biosensors

Characteristics

- Photocatalytic activity
- Chemical stability
- Biocompatibility

Medical Applications

DNA Detection

Identification of genetic mutations.

Tuberculosis Diagnosis

Rapid bacterial detection.

Cancer Cell Recognition

Enhanced signal amplification.

3.4 Gallium Nitride (GaN) Biosensors

Features

- High thermal stability
- High electron mobility
- Radiation resistance

Disease Diagnosis

Breast Cancer

Detection of HER2 biomarkers.

Neurological Disorders

Monitoring neurotransmitters.

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Infectious Diseases

Rapid pathogen sensing.

3.5 Germanium (Ge) Biosensors
Advantages

- High carrier mobility
- Excellent optical response

Applications

- Protein detection
- DNA hybridization
- Viral diagnostics

3.6 Indium Oxide (In_2O_3) Biosensors
Applications

Cardiac Disease Detection

Monitoring Troponin-I.

Kidney Disease

Detection of creatinine biomarkers.

Cancer Diagnostics

Detection of tumor markers.

3.7 Molybdenum Disulfide (MoS_2) Biosensors
Importance

MoS_2 is a two-dimensional semiconductor with exceptional sensing capabilities.

Disease Applications

COVID-19 Detection

Ultra-low viral concentration detection.

Alzheimer's Disease

Amyloid-beta protein sensing.

Cancer Biomarkers

High sensitivity diagnosis.

Advantages

- Atomically thin structure
- Excellent charge transport
- Flexible device fabrication

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4. Disease Diagnosis Using Semiconductor Biosensors

4.1 Diabetes Mellitus

Biomarkers

- Glucose
- HbA1c

Semiconductor Materials

- Silicon nanowires
- ZnO nanorods
- TiO_2 nanoparticles

Impact

- Continuous glucose monitoring
- Non-invasive testing
- Improved patient management

4.2 Cancer Diagnosis

Biomarkers

- PSA
- CEA
- AFP
- CA-125
- HER2

Semiconductor Platforms

- Silicon FET sensors
- MoS_2 nanosensors
- GaN sensors

Impact

- Early-stage cancer detection
- Reduced mortality
- Personalized treatment planning

4.3 Cardiovascular Diseases

Biomarkers

- Troponin-I
- CRP
- BNP

Semiconductor Materials

- In_2O_3
- Silicon nanowires

Impact

Rapid diagnosis of heart attacks within minutes.

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4.4 Infectious Diseases

Diseases

- COVID-19
- HIV
- Hepatitis
- Tuberculosis

Semiconductor Sensors

- MoS_2
- ZnO
- TiO_2

Impact

Rapid point-of-care testing.

4.5 Neurological Disorders

Biomarkers

- Dopamine
- Amyloid-beta
- Tau proteins

Semiconductor Platforms

- GaN
- MoS_2
- Graphene-semiconductor hybrids

Impact

Early detection of Alzheimer's disease.

5. Comparative Analysis of Different Semiconductor Biosensors

Semiconductor	Sensitivity	Biocompatibility	Cost	Major Applications
Silicon	Very High	High	Moderate	Cancer, Diabetes
ZnO	High	Excellent	Low	Glucose, Cholesterol
TiO_2	High	Excellent	Low	DNA Detection
GaN	Very High	High	High	Neurological Disorders
Ge	High	Moderate	High	Viral Detection
In_2O_3	High	High	Moderate	Cardiac Diseases
MoS_2	Extremely High	Excellent	Moderate	COVID-19, Cancer

6. Challenges

Major challenges include:

- Long-term stability
- Reproducibility
- Biofouling
- Fabrication costs
- Regulatory approval
- Clinical validation

7. Future Perspectives

Future research directions include:

- AI-assisted biosensing
- Wearable biosensors
- Flexible electronics
- Internet of Medical Things (IoMT)
- Quantum semiconductor sensors
- Multiplex biomarker detection
- Smartphone-integrated diagnostics

8. Conclusion

Semiconductor-based biosensors have significantly transformed disease diagnosis by enabling highly sensitive, selective, and rapid detection of biomarkers. Silicon, ZnO, TiO_2, GaN, Ge, In_2O_3, and MoS_2 each offer unique advantages for specific diagnostic applications. Among these, nanostructured and two-dimensional semiconductors have demonstrated exceptional potential in detecting cancer, diabetes, cardiovascular diseases, infectious diseases, and neurological disorders at very low concentrations. Continued advancements in nanotechnology, artificial intelligence, and wearable electronics are expected to further enhance the capabilities of semiconductor biosensors, making them indispensable tools in future personalized healthcare systems.

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