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A Review of sensor Devices Applied Using Gallium Nitride and Its Properties

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ABSTRACT

Devices made of gallium nitride (GaN) have high electron mobilities, large band gaps 3.4 ev, and low dielectric constants. because it uses less energy overall than normal Si devices and decreases the volume, weight and power consumption of power electronic systems., it is a good replacement material for sensors, radar, and other silicon-based applications. In this article, we review the features and advancement of cutting-edge GaN power device architectures, assess the condition of the research, and project the future of GaN device applications. The difficulties of GaN devices were also fully examined with regard to the sensitivity and effectiveness of the sensor systems.

Keywords: *Bio-sensors, Electrochemical sensors, Gallium nitride, Porous silicon, GaN heterostructure*

1. INTRODUCTION

III-nitride semiconductor materials with a hexagonal wurtzite structure and may be found in many forms, including nanoparticles, powder, and films, as shown in Figure 1 [1-4].

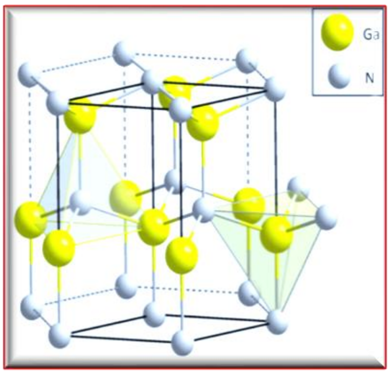

Figure 1. Appear the wurtzite structure of Gallium Nitride material [1].

GaN has acquired its popularity in the past decade due to its distinctive characteristics like high thermal conductivity values, up to 500 W/mK, particularly for high-quality, single-crystal GaN samples. high electron mobility in GaN is around 1000-2000 $cm^2/V{\cdot}s$ at room temperature, chemical inertness, high carrier saturation velocity, wide band gap of 3.4 eV, radiation hardness, a high optical absorption coefficient, low sensitivity to ionizing radiation outstanding and thermal stability [5-8].

A semiconductor called gallium nitride (GaN) displays high electron mobility that is comparable to silicon's., but with a wider band gap that is three times larger [9-11]. Due to this unique combination of properties, gallium nitritde is considered a highly promising material for use in high-power applications and for operation at high temperatures [12-15].

In other words, GaN high electron mobility and wide band gap make it an excellent choice for applications that require high power and can withstand high temperatures [16-19]

GaN nanostructures have been created utilizing various growth processes in several successful trials, including organic chemical vapor deposition of the metal [20-23], Sol-gel Chemistry [24-26], Thermal Ammonia [27, 28], Reactive Epitaxial of Molecular Beam [29, 30], Chemical Vapor Deposition (CVD) [31, 32], Electrochemical Deposits [33, 34], Thermal Vapor Deposition, combustion method [35, 36], Physical Vapor Deposition [37, 38], Pulsed Laser Deposition(PLD) [39, 40] and Pulsed Laser Ablation in Liquid (PLAL) [41, 42]. The (PLAL) technique is a technology extensively researched over the last decade, it creates nanoparticles by laser ablation in liquids [43-46].

However, PLD, which is a rapid deposition technique, and not so expensive method [47, 48]. This technology can be used to form III-nitride semiconductor materials of much importance because of its simple method, diversity, and speedy thin film production. The electrical, thermal and optical properties of gallium depend on the precipitation method [49, 52].

GaN Because of its unique property, which made it suitable for many optoelectronic devices such as photodiodes, LDs and UV detectors [53-56], solar cells [57, 58], pH sensors [59, 60], light-emitting diode (LED) [61, 62], shorter wavelength optical devices [63, 64], high-power transistor devices [65, 66], Gas sensor and biosensor.

In this research, the results of previous research on the applications of gallium nitride were presented. This review paper is a base for manufacturing a biosensor that is less expensive, more sensitive, and more efficient than what is found in these studies.

Table 1 Previous studies for GaN

Year	Type of analysis	Type of substrate	Result
2011 [67]	DNA sensor	High electron mobility ALGaN/GaN transistor	With an increase in concentration, the current decreases
2011 [68]		Undoped AlGaN/GaN HEMTs	A high sensitivity of 3.88 mA/mm/pH or 1.9 mA/pH
2014 [69]		A C-level Al2O3 substrate	The response increases with the increase in the operating temperature.
2014 [70]	PH sensor	AlGaN/GaN hetero Structure	They found that as the temperature increased, the sensitivity of the hydrogen ace increased
2015 [71]	glucose biosensors	AlGaN/GaN heterostructure and the ZnO-based nanorod array	The photoelectrochemical (PEC)
2015 [72]	CRP	Biosensor based on AlGaN/GaN high electron mobility transistor	Good selectivity from 10 ng/ml to 1000 ng/ ml
2016 [73]	urea biosensors	AlGaN/GaN ISFET	Sensitivity 18.15 mA/pCurea within the urea concentration from 25 μM to 50 mM which was much better than the 12.95 mA/pCurea within the concentration from 50 μM to 50 mM
2017 [74]		Nanostructured Cu2Zn1xCdxSnS4 quinternary alloy films at various Cd concentrations	Incorporation of Cd into CZTS reduced the gap value from 1.81 to 1.72 ev
2018 [75]		Ion-sensitive field-effect transistor (ISFET) made of AlGaN/GaN and coated with an Al2O3 layer	The Al2O3-ISFET's sensitivity, asinferred from transfer characteristics, is around 57.8 mV/pH, as opposed to the reference one's approximately 48.4 mV/pH.
2018 [76]		AlGaN/AlN/GaN MOS-HEMT's	Has exceptional sensitivities for prostate cancer (from serum) and breast cancer of 0.91 mA/ngml-1 and 0.054 mA/gml-1, respectively.

2018 [77]	pH sensors	AlGaN/GaN heterostructure	Comparing the sensor to traditional AlGaN/GaN pH sensors with a single detecting region, it shows a much greater pH sensitivity of 1.35 mA/pH.
2019 [78]	prostate cancer breast cancer	AlGaN/AlN/GaN MOS-HEMT	Manufactured device, that it gives an excellent sensitivity of 0.91mA/ngml-1 and 0.054mA/μgml-1
2019 [79]		EA for surface amination on GaN	EA on GaN can actually improve AlGaN/GaN HEMT performance when exposed to high temperatures and intense irradiation.
2019 [80]		AlGaN/GaN- based sensors on gallium	Linear response towards pH but without the use of ionic strength, the response is reflected in the pH in the form of the letter
2020 [81]	glucose Sensor	AlGaN/GaN high electron mobility transistor (HEMT)	Excellent response to glucose current with linear ranges from 0.1 to 10 mM and from 10 to 100 mM at a gate voltage of 1.5V and high sensitivity of 9.4 * 10^5 and 3.15 * 10^4 UA
2020 [82]		GaN thin films as mmonia (NH3) gas sensor	The concentration of NH3 gas increased the sensitivity of the GaN-Si gas sensor.
2021 [83]		An open gate AlGaN/GaN	A successful HEMT-based biosensor has been produced, and a physics-based analytical model has been constructed to evaluate the device's threshold voltage and drain current sensitivity. It has been found that the drain current sensitivity falls off as Al composition and barrier thickness increase.
2021 [84]		Pd- AlGaN/GaN	The sensor showed high sensitivity (8.1%), fast response (6 s) and recovery times (7 s) under 1 ppm NO2
2021[85]		Pd-AlGaN/GaN HEMTs	When the sensor was biased near the threshold voltage, the electron density in the channel showed a relatively larger change with a response to the gas exposure and demonstrated a significant improvement in the sensitivity. At 300 ◦ C under 100 ppm concentration, the sensor's sensitivities were 26.7% and 91.6%, while the response times were 32 and 9 s
2022 [86]		A split-gate AlGaN/GaN heterostructure field-effect transistor with an auxiliary gate was created.	It has been noted that the saturation characteristics are improved with lower voltages and lower channel current, which makes the split gate device more suitable for power consumption applications.
2022 [87]		Ion-sensitive heterostructure field effect transistor (ISHFET) pH sensor based on solid-state AlGaN/GaN	A pH range of 4-9.18 was used to assess the performance of the integrated pH sensor microprobe. The pH sensor microprobe has a width to length ratio of 4.2, and at a drain-source voltage of 0.5 V, it can measure pH with a sensitivity of 143.57 A/pH.
2023 [88]		Using WO3/Pd-AlGaN/GaN HEMTs as a gas sensor	The sensor showed a high sensitivity of 658% to 4%-H2, whereas interacting with NO2, CH4, CO2, NH3, and H2S was little. The sensor's response to 10 ppm hydrogen between 150 and 250 °C was at least eight times greater than that of other target gases.
2023 [89]		AlGaN/GaN heterojunction field effect transistors	According to the experimental findings, this biosensor has a good detection limit of 1.81 fM, a high sensitivity of 77 μA/log concentration, and a linear range of 2 fM to 2nM.

1.1 Physical Properties Developments

The physical characteristics of Gallium nitrite (GaN) compelled many scientists to select it as the ideal thin film Because of its excellent cracking resistance. the cracking resistivity of GaN can vary depending on the specific growth method and device application. Generally, high-quality GaN films grown by epitaxial techniques have cracking resistivities in the range of 1-3 GPa, while bulk GaN crystals can have cracking resistivities as high as 10 GPa. This substance has a hardness characteristic of 12 GPa and generally contains 10^{10}-10^{12} dislocations per square millimeter. Notably, because to its outstanding thermal stability, conductivity, and heat capacity, it is particularly well suited for long-lasting applications like surface Plasmon resonance-based sensors and diode lasers, which depend on the deposition of a sensing layer [90, 91]

Gallium nitride (GaN) holds promise for the development of high-frequency and high-power devices because of its superior material properties including, high mobility in heterojunction 2-D electron gas (2DEG) channels, thermal stability, electron-saturation velocity, and high critical electric field.

1.2 Preparing Technique of GaN

The preparation of GaN involves several steps, including substrate preparation, buffer layer deposition, GaN layer deposition, annealing, and post-treatment. The choice of substrate material, such as sapphire or silicon carbide, can affect the quality and properties of the GaN film [92, 93].

The buffer layer, typically made of GaN or AlN, helps reduce defects and strain in the GaN film [94, 95].Various techniques can be used for GaN layer deposition, such as molecular beam epitaxy or hydride vapor phase epitaxy, metal-organic chemical vapor deposition [96, 97]. Annealing is performed to improve the crystallinity and reduce defects in the GaN film, and post-treatment processes, such as etching or ion implantation, may also be employed to change the GaN layer's surface characteristics [98, 99].

1.3 Sensitivity of GaN

GaN (gallium nitride) is a semiconductor material that is used in various electronic and optoelectronic devices, including LEDs, power electronics, and high-frequency applications. GaN exhibits high sensitivity to temperature and light.

Temperature Sensitivity: GaN has a negative temperature coefficient of resistance, which means that its electrical resistance decreases as temperature increases. This property makes GaN suitable for high-temperature applications, as it can operate at temperatures up to 600°C without significant performance degradation. However, this also means that GaN devices must be carefully designed to handle the heat generated during operation.

Light Sensitivity: GaN exhibits high sensitivity to light in the ultraviolet (UV) and blue regions of the spectrum. This property makes GaN well-suited for use in optoelectronic devices such as LEDs and laser diodes.

However, GaN is also sensitive to radiation damage from sources such as cosmic rays, which can degrade device performance over time.

Overall, GaN is a highly sensitive material that must be carefully designed and optimized for specific applications to achieve optimal performance and reliability [100, 101].

1.4 Heterostructures Sensor of GaN

Gallium nitride (GaN) heterostructures have shown great potential as high-performance sensors because of their distinct electrical and optical characteristics. GaN-based heterostructures can be designed to have different band gap energies, allowing for selective sensing of different gases or chemicals based on their energy levels [102, 103].
The AlGaN/GaN high electron mobility transistor (HEMT) sensor is one type of GaN-based heterostructure sensor. The two-dimensional electron gas (2DEG) generated at the AlGaN/GaN interface serves as the detecting area for the AlGaN/GaN HEMT sensor. When gas molecules adsorb onto the 2DEG surface, the surface potential changes, leading to a change in the HEMT current [104, 105].

Another type of GaN-based heterostructure sensor is the metal/insulator/GaN (MIG) diode. The MIG diode consists of a metal contact, an insulating layer, and a GaN layer.The surface chemistry of the GaN layer varies when the device is subjected to a gas or chemical, changing the Schottky barrier height and the device capacitance [106, 107]. GaN-based heterostructure sensors have several advantages over traditional sensors, including high sensitivity, selectivity, and fast response time.

In addition,GaN-based sensors can function in hostile environments and at high temperatures, making them ideal for applications in aerospace, automotive, and industrial settings [89]. GaN-based heterostructure sensors have several advantages over traditional sensors, including high sensitivity, selectivity, and fast response time. In addition, GaN-based sensors can function in hostile environments and at high temperatures, making them [108, 109].

1.5 Deposition Technique of GaN

There are various methods for depositing thin-film GaN, and these include physical vapor deposition (PVD) techniques and chemical vapor deposition but the physical vapor deposition (PVD) techniques such as pulsed laser deposition (PLD). PLD has several advantages over other methods, such as its simplicity, flexibility, and ability to rapidly produce films with a highly directional plume of material 110-12]. This process is also advantageous because it allows for low levels of contamination and precise control over the stoichiometry of the deposited material. Overall, PLD is a powerful technique for depositing III-nitride semiconductor materials that offers a range of benefits for researchers and manufacturers alike [113-115]. Furthermore, altering deposition parameters can control coating stoichiometry, morphology, crystallinity, topography, roughness and morphology [116-119]. A study by Wang et al. (2019) investigated the growth of GaN thin-films using PLD and achieved a high-quality film with a smooth surface and low threading dislocation density [120]. Research by Yamada et al. (2014) GaN thin-film growth using PLD was explored, and it was shown that the characteristics of the film could be changed by varying the laser intensity and deposition pressure [121]. Research by Chen et al. (2017) explored The application of high-performance photodetectors made from thin-films of GaN produced on a PLD. The researchers found that the PLD-grown GaN thin-films exhibited excellent optical and electrical properties, making them suitable for use in photo detector devices [122].

2. APPLICATIONS GAN

Given the importance of large scale and its wide applications, gallium nitride is used in many applications, optical, medical, photon, and various gas sensors, as shown in Figure 2.

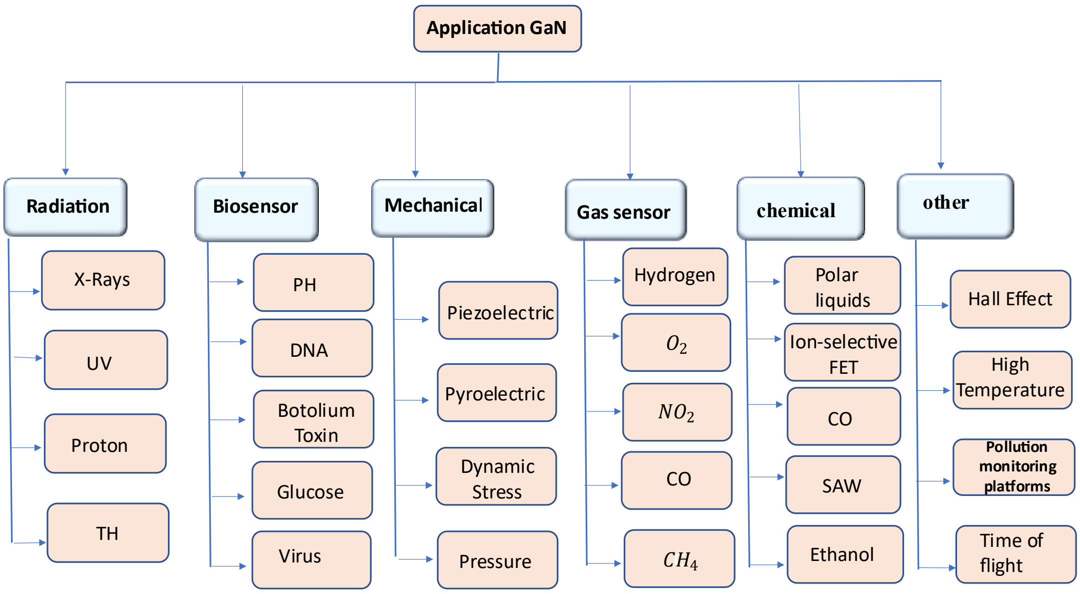

Figure 2. Application of GaN Sensors.

2.1. Biosensor

An analytical device called a biosensor, incorporates biological components like an enzyme or an antibody, interacts with the analysis, and generates electrical signals. Types of biosensors are enzyme-based biosensors, DNA biosensors (Deoxyribonucleic Acid), thermal and piezoelectric biosensors, magnetic biosensors, and optical biosensors.

The design of biological sensors has been used to research broad applications, example disease diagnosis, health care, interest, and use in food and water monitoring.

The biosensor is available in a variety of sizes and forms and has the ability to measure pH levels as well as tiny amounts of harmful substances that can lead to sickness. The biosensor consists of the analyses, bio receptor, transducer, electronics, and display screen (Fig 3) [123-125].

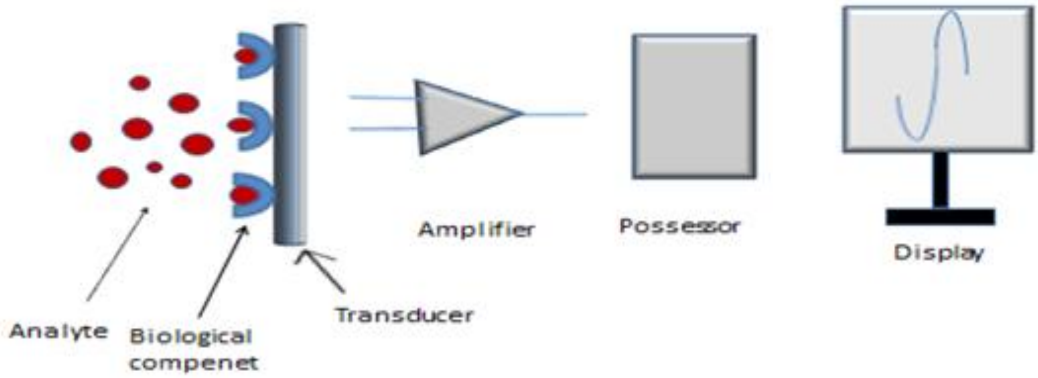

Figure 3. Aschematic design of a typical biosensor, which includes a bio receptor, a transducer, an electrical system (an amplifier and a processor), a display (a PC or printer), and many kinds of bio receptors and transducers that may be used in biosensors.

Analysis: It is an important substance that can be detected, such as (glucose, ammonia, alcohol, lactose, etc.). Bio receptors, the biological component, is what can distinguish between any form of the analyzer, including enzymes, antibodies, cells, DNA, and run types. the process of creating a signal as a result of biological receptors interacting with analysis tools using biological identification. Transducer: an apparatus that transforms energy from one type of cell to another; it is regarded as the primary electrical component of the biosensor since it translates biometric identification into an electrical signal. The optical signals that the transducers generate are proportionate to the ensuing interactions. Biological receptors are categorized as electrochemical, optical, electronic, and thermal transformers depending on how they operate.

Electronics: After processing, the transformed signal is output for display. The electrical signal is amplified and translated into digital form throughout this process, and we then use the display unit to measure the processed signal.

Display: incorporates an interpretation system, such as a printer or computer, that creates the output such that it is simple for the user to read and comprehend the answer. Tables, diagrams, or numerical figures can all be included in the outputs [126-128].

2.2. Characteristics of Biosensors

There are various static and dynamic requirements that must be followed in order to develop a biosensor system that is both effective and efficient. These requirements enable the performance of the biosensor to be improved and adapted for different commercial applications.

a) Selectivity: is a crucial factor to take into account when selecting a bioreceptor for a biosensor. In a sample that comprises undesired contaminants and other substances, the bioreceptor should be able to identify a particular target analyte molecule.
b) Sensitivity: is the capacity to detect and accurately identify the smallest quantity of analyte present in a sample, even at low concentrations (ng/mL or fg/mL), and to do so with the fewest possible steps.
c) linearity: For biosensor readings to be accurate, linearity is a key component. The concentration of the substrate can be detected more accurately with a higher linearity (straight line).
d) Response time: is the period of time needed to collect 95% of the data from a biosensor measurement.
e) reproducibility A biosensor's reproducibility refers to its capacity to produce consistent results whenever the same sample is analyzed more than once. It is distinguished by precision and accuracy, which assess the reliability and adequacy of the mean value produced by the sensor.
f) stability: Applications for biosensors that require continuous monitoring depend heavily on stability. It describes the degree to which environmental disturbances both within and outside the device have an impact on a biosensor. The affinity of the bioreceptor for the analyte and the bioreceptor's deterioration with time are two factors that can affect stability.

2.3. Classification of Biosensors

The classification of biosensors is a diverse and multidisciplinary field that involves various criteria. Figure 3 outlines the classification scheme, which includes different categories. Bioreceptors are the primary component of biosensor construction, and biosensors are classified based on the type of bioreceptor used. This includes enzymatic biosensors, immunosensors, aptamer or nucleic acid-based biosensors, and microbial or whole-cell biosensors [129, 130].

The second classification is based on the type of transducer used, and biosensors are categorized as electrochemical, electronic, thermal, optical, and mass-based or gravimetric sensors. Additionally, biosensors can be classified based on the bioreceptor-analyte combinations. Other classifications are made depending on the detection system (optical, electrical, electronic, thermal, mechanical, and magnetic) and the technology used (nano, surface plasmon resonance (SPR), biosensors-on-chip (lab-on-chip), electrometers, and deployable).

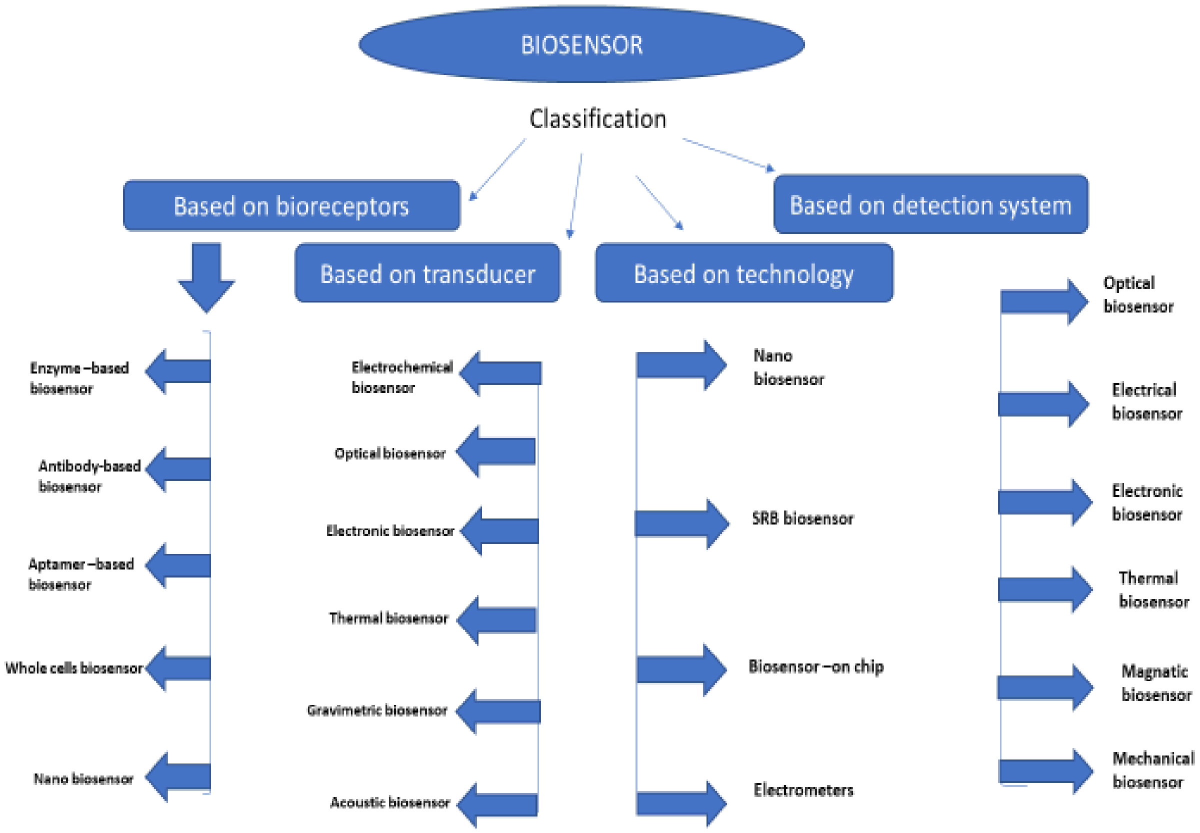

Figure 4. Biosensor classification based on the usage of diverse bioreceptors and transducers.

3. CONCLUSIONS

Commercial and nearly-commercial Gallium Nitride (GaN) power devices were examined, with an emphasis on their design and use rather than device manufacture. This evaluation examines a variety of products now on the market, in contrast to earlier studies that concentrated on products from certain manufacturers. The evaluation gives a general overview of the usual designs of both horizontal and vertical devices, their economic viability and ratings, as well as their distinctive characteristics. The paper also outlines the design issues that come up when dealing with GaN power devices, such as the specifications for board layout and gate driver. The overall state of GaN power devices and their prospective design applications are useful insights from this application-focused assessment.

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