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Recent developments in gallium nitride technology for sensor applications

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Abstract

The human race of industrialisation without being oblivious to environmental contaminants has attracted the attention of researchers for the development of chemical sensors to detect, measure and mitigate drastically detrimental effects of anthropogenic pollutants. A vast congregation of chemical sensors is available in the market. Still, a few factors such as cost, accuracy, time of response, sensitivity, operating environment (temperature and pressure range) and power consumption urges to improve and optimise sensors. For this purpose, various varieties of material, covering polymers and semiconductors to nanoparticles, have been utilised to manufacture chemical sensors. Recently, a tremendous paradigm shift has been observed due to the introduction of gallium nitride (GaN) in chemical sensing applications. This paper aims to review recent unprecedented sensing utilisations of GaN in terms of chemical sensing and power applications.

***Keywords*:** Gallium nitride; Sensor; Chemical sensor; Hydrogen sensor; pH Sensor

1. Introduction

In 1975, for the very first time, Silicon-based hydrogen sensors were introduced (Bae et al., 2019). A Si-based metal oxide semiconductor transistor with a 10 nm palladium gate with a 10 nm SiO2 gate insulator was devised that measured 40 ppm hydrogen as a function of the threshold voltage. Unfortunately, due to the low bandgap of Si, it could not operate at high temperatures, even at 250oC. This drawback of Si sensors sifted attention towards high bandgap semiconductors like GaN (Dey, 2018; Mhlongo, Motaung, Cummings, Swart, & Ray, 2019). Since then, the development of GaN-based sensors has been promising. The increasing number of publications on GaN applications is evident to the researcher's interest in utilising its potential. Figure 1 provides an overview of recent publications using GaN as hydrogen sensors.

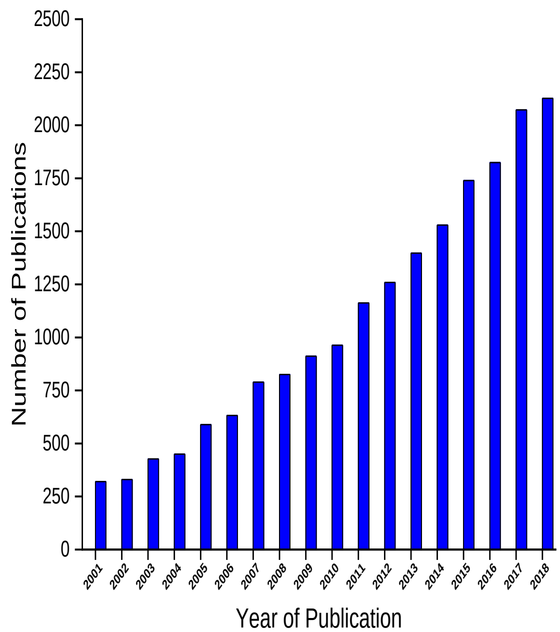


Figure 1: Increasing scope of hydrogen sensor development over last two decades (Source: Web of Science)

Biological molecules can interact chemically in a unique manner. This uniqueness of molecules such as proteins is used in biological sensors to transduction biological properties/ signals to readable and quantified electrical signals. According to GaN, silicon-based sensors have triumphed in the biosensor industry, but they were imposed to some strategic limitations. These limitations include, but are not limited to, degradation in a chemically corrosive environment and harsh environments such as high temperature and high pressure (Pearton, Ren, & Chu, 2013). These shortfalls led to the development of GaN-based biosensors. GaN sensors have been employed for various biological sensing applications by either biomimetic or bio-organic surface functionalisation techniques. The subsequent paragraphs shed light on recent developments in this arena (Yasmin Abdul Wahab, Soin, et al., 2020).

A device characterised by the detection of H+ concentration in a solution by producing a viable electrical signal is known as a pH sensor. GaN has a unique property; if the surface charges are altered, it demonstrates a change in drain current (ID). GaN is very sensitive to this change that owes its numerous applications as a sensor. In the case of the pH sensor, GaN with oxide layer attracts the hydroxyl group of fluid and changes surface charge density by its concentration. This change in charge ignites the alteration in two-dimensional electron gas (2DEG) that subsequently causes drain current to change. This is a fundamental principle of working pH sensors (Xue et al., 2020).

GaN finds its application as a three-phase inverter due to its high-performance efficiency, approaching 99.3% at 900 W. The explicated efficiency is relatively high as compared to silicon-based IGBTS. By comparing the three-phase inverter with insulated gates bipolar transistor in terms of efficiency, it turns out that the gallium nitride-based three-phase inverter's efficiency exceeds it. GaN also finds potential utilisation in power switching applications and is being preferred on silicon, GaN-on-silicon.

Due to the marvellous potential of GaN as a sensor, it has got much attention recently. This study is providing a review of the technological developments of GaN in recent years.

2. Applications

2.1 Chemical sensors

The odourless, tasteless, colourless and explosive nature of hydrogen, along with its unique characteristics of low ignition energy and enormously high combustion heat, makes its obscure presence, even a low fraction of concentration, quite dangerous and devastating. Therefore, the detection of hydrogen is incredibly crucial.

Hydrogen concentration measurement is not a new concept as it can be traced back to 100 years ago when it was first measured at filling stations for spaceships (Hübert, Boon-Brett, Black, & Banach, 2011; Yasmin Abdul Wahab, Soin, et al., 2020). The capability of forming potential explosives increase the significance of hydrogen detection sensors that can be forecasted from unforgotten past hydrogen explosion event of Mile Island and Fukushima incident.

Hydrogen detection has always been a vital concern for scientists. It can access from an increasing number of publications for the last two decades, as depicted in figure 1. A thorough review of various technologies adopted for the measurement of hydrogen is shown in figure 2.

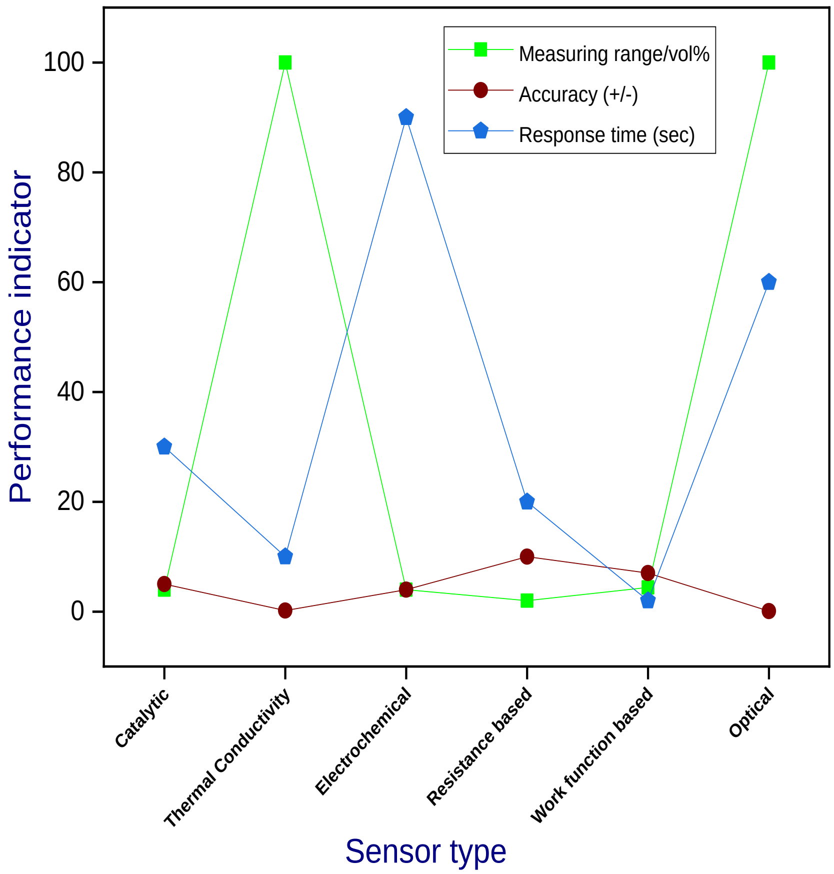


Figure 2: A precise performance review of various technologies adopted for hydrogen sensors (Hübert et al., 2011; Lundström, Shivaraman, Svensson, & Lundkvist, 1975)

A comparative analysis of hydrogen sensor development is depicted in table 1.

Table 1: Comparative study of hydrogen sensor development

Year	Synthesis	Performance	Ref
1975	10 nm Pd gate, 10 nm SiO_2 gate insulator, Si-based MOS transistor	40 ppm detection, operated up to 150°C	(Lundström et al., 1975)
1999	Pt Schottky diodes on n-type GaN	tested for 2.5 ppm, Operated up to 400°C	(Luther, Wolter, & Mohney, 1999)
2009	Pt gate, β-Ga_2O_3 oxide layer on GaN	10,000 ppm detection, at room temp.	(Yan & Lee, 2009)
2010	Nonporous Pt gate, GaN HEMT	ppb to 100ppm detection, at room temp.	(Eliza & Dutta, 2010)
2013	Pt nanonetwork gate, GaN HEMT	500 ppm, at room temp.	(Kim & Jang, 2013)
2014	Pt gate, planner GaN Schottky diode	2,000-10,000 ppm, at room temp.	(Zhong, Sasaki, & Hane, 2014)
2018	α- GaOOH nano rice precursor based GaN	150-750 ppm, at T >400 °C	(Hermawan, Asakura, Kobayashi, Kakihana, & Yin, 2018)
2018	Pd gate, HfO2/GaOx/GaN MOS diode	5-1,000ppm, up to 160 °C	(C.-H. Chang, Lin, Lu, Liu, & Liu, 2018)
2019	Pd gate, NiO/GaN-based HEMT	1000 ppm, up to 300 °C	(Liu, Chang, Huang, & Lin, 2019)

Based on operation, hydrogen sensors can be classified into two classes; metal/semiconductor (MS) and metal/insulator semiconductor (MIS). In the case of MS, gate metal-H2 contact dissociate molecules into monoatomic hydrogen. Diffusion causes these monoatomic hydrogens to form a dipole layer at the Schottkythe interface that ultimately drives a shift in threshold voltage, according to equation 1. Thus, the altering threshold voltage is a summon to the presence of hydrogen, as described in figure 3.

$\Delta V_{Threshold} = \frac{p\vartheta N}{\varepsilon}$ (1) (Eliza & Dutta, 2010)

Where

$p = dipole\ moment,\ \varepsilon = dipole\ layer\ permitivity\ ,\ N = \frac{availble\ interface\ sites}{unit\ area}$

$\vartheta = Hdrogen\ surface\ coverage = \frac{k.\sqrt{P}}{1+k.\sqrt{P}}$

$k = effective\ equilibrium\ constant,\ P = partial\ pressure\ of\ Hydrogen$

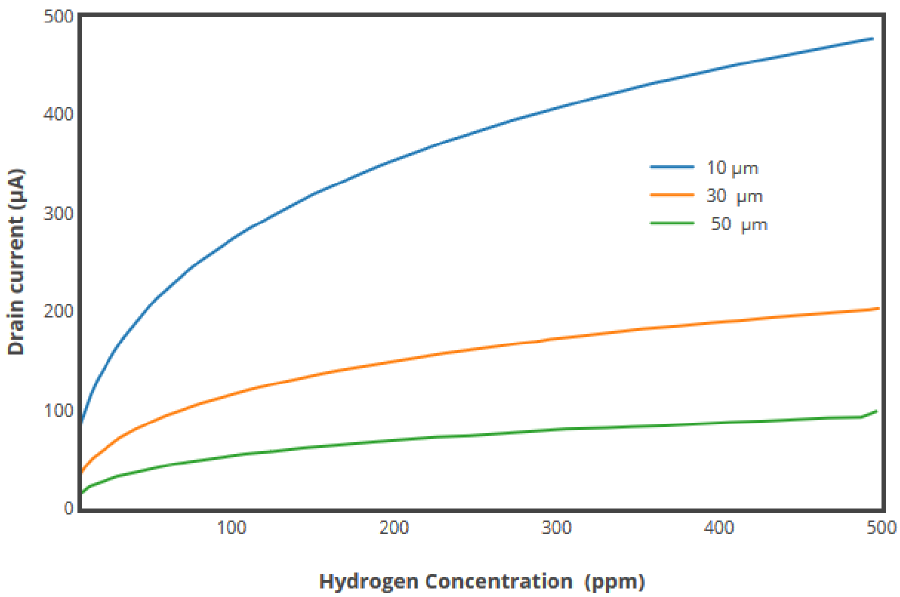


Figure 3: Variability of sensor drain current at various concentrations of hydrogen for MS (metal/semiconductor)

In MIS, an insulator layer is developed on the GaN layer, resulting in high sensitivity and low response time. A comparison of MS and MIS is performed in detail (Yan & Lee, 2009), and results, depicted in figure 4, prove MIS to be the best method for hydrogen sensing compared to that of MS. Additionally, various studies are provided in which metals from waste are extracted and used along with GaN applications (Siddiqi et al., 2020).

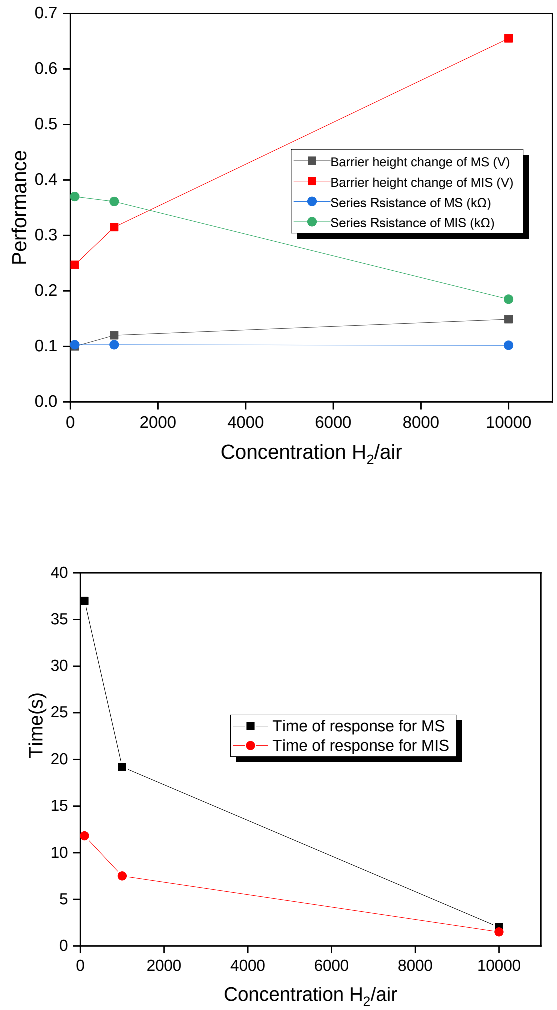


Figure 4: Performance of metal/semiconductor (Pt/GaN) and metal/insulator/semiconductor (Pt/β-Ga_2O_3/GaN) hydrogen sensors (Yan & Lee, 2009)

Other than hydrogen sensors, GaN has also acknowledged its significance in CO_2 sensing. CO_2, being 58% of total greenhouse emissions of the globe (Shahzad, Kumar, Zakaria, & Hurr, 2017), makes its quantification and detection a crucial factor for environmental safety. In recent years, nondispersive infrared sensors (NDIS) have been widely utilised to detect purposes, but these sensors demand a high-power consumption that convinced researchers to search for alternatives. GaN-based sensors can be an effective alternative to NDIS.

Chang (C. Chang et al., 2008) revealed that polyethylenimine (PEI) /starch functionalised gate of GaN HEMT could be used as a crucial sensor of CO_2. A schematic of Chang's proposed sensor is described in figure 5 (a). It was observed that PEI functionalised high electron mobility transistor to various concentrations of carbon dioxide within a range of 319-493 K makes HEMT to exabit a sublinear correlation with current change as depicted in figure 5 (b).

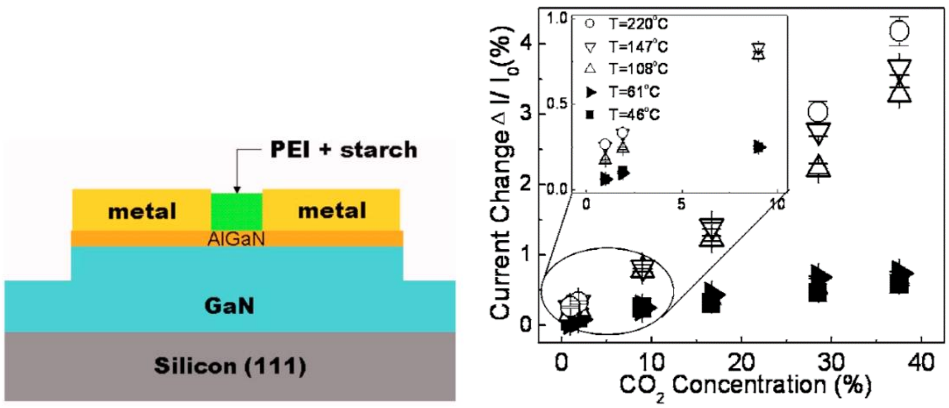


Figure 5: (a) Schematic of PEI/starch functionalised GaN HEMT CO_2 sensor (b) Sublinear correlation of CO_2 with change in current (C. Chang et al., 2008)

2.2 Biosensors

To sense the presence of biological chemicals/molecules, the gate of GaN HEMT is functionalised so that it may detect biological interactions. These interactions cause a change in the movement of charge carriers that finally contribute to quantification. Therefore, it is a matter of prime concern that GaN must be functionalised to operate in the presence of liquid and a suitable range of pH.

Streptavidin, a protein, was reported to be detected by GaN HEMT. The gate of HEMT was functionalised with isopropyl triethyoxysilane (NPTEO). In the first step, the gate was coated with NPTEO and left in the presence of oxygen. Oxygen forms a layer on the gate surface that acts as a detector. When coming in contact with a liquid medium, this oxidised gate detects the aforementioned protein (Kang et al., 2005). The presence of protein disturbs the carrier's distribution that generates electrical signals. Hence generated signals are detected and quantified. GaN has also played a vital role in detecting c-erbB2, a protein that is the main constituent of breast cancer. The GaN HEMT with Au gate was employed for the detection of c-erbB2. The Au gate was functionalised with thioglycolic acid. Au was first placed in Ozon/UV and then submerged in thioglycolic acid at room temperature. X-ray analyses proved the substantial binding of Au to dipped solution constituents. Hence prepared HEMT shows a change in drain current, with a delay time of 5 seconds, in the presence of c-erbB2 protein (K.-H. Chen et al., 2009).

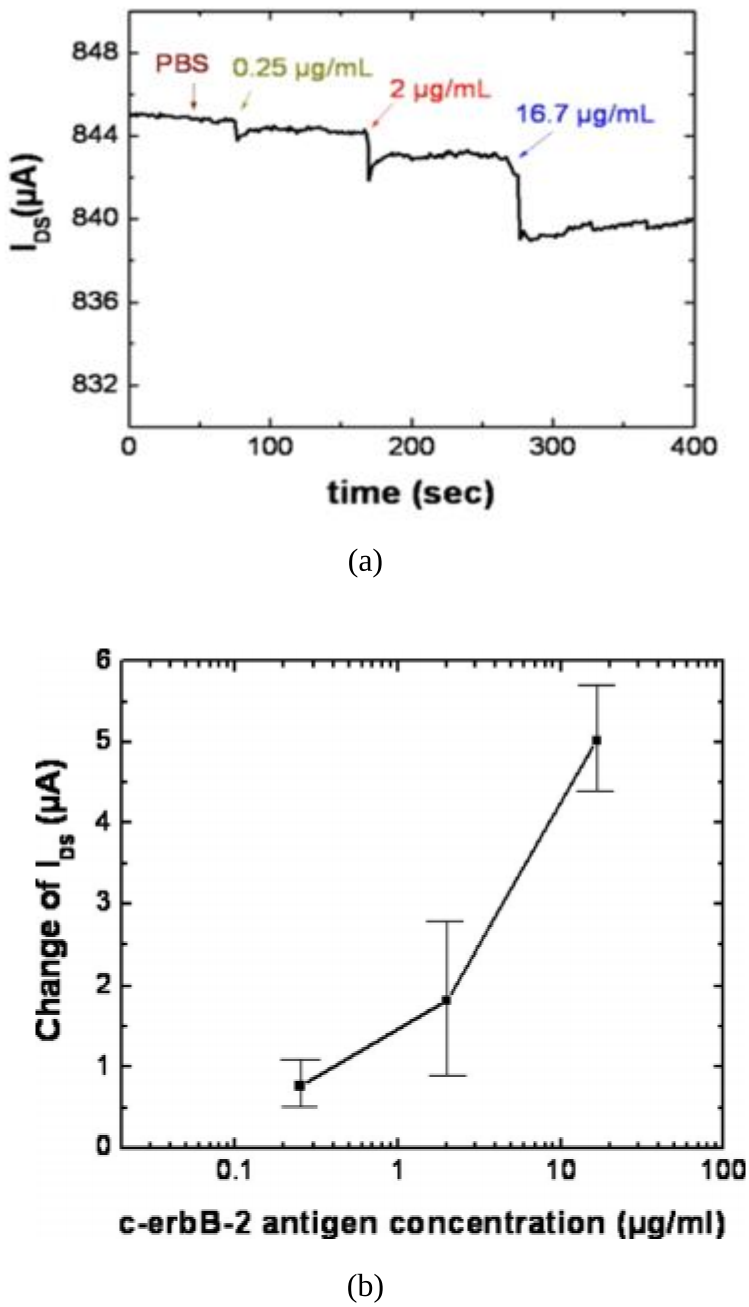
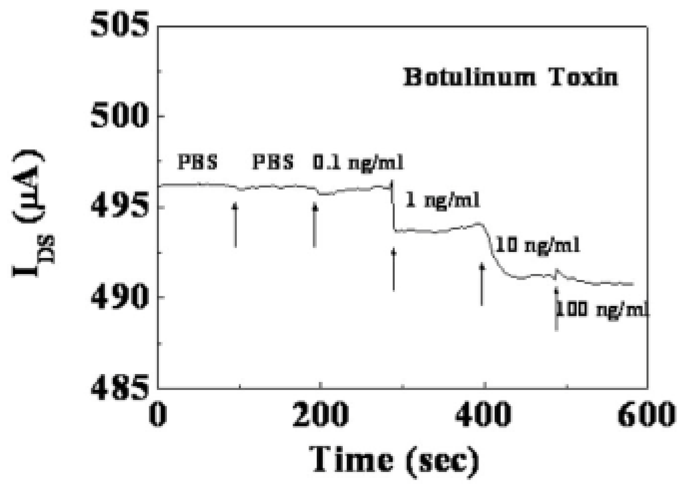
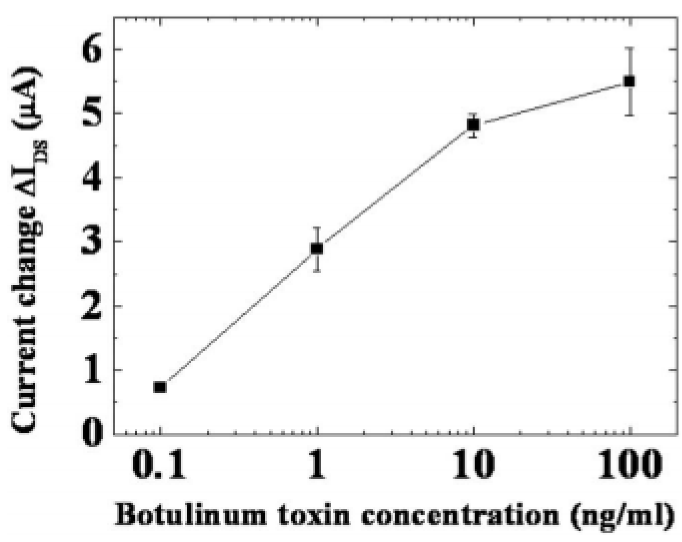


Figure 6: (a) Response time of GaN sensor at various concentrations of c-erbB2 (b) Variation of drain current with c-erbB2 concentration (K.-H. Chen et al., 2009)

Another charming application of GaN biosensor is found in the detection of Botulinum toxin. It is one of the most poisonous substances ever discovered, also credited as "miracle poison" (Nigam & Nigam, 2010). Au gated HEMT was developed with a 400 nm thick layer of Polymethyl methacrylate adsorbed on the source and drain. However, the Au gate was not encapsulated and allowed to be in direct contact with the solution. As a result, the presence of Botox concentration ranges 0.1-100 ng/ml was successfully detected as a mean of change in drain-source voltage, with a delay time of 5 seconds.



(a)



(b)

Figure 7: (a) Response time of GaN sensor at various concentrations of Botox (b) Variation of drain current with Botox concentration (Wang et al., 2008)

Cardiac troponin I protein can also be detected by a GaN-based biosensor. A traditional issue affiliated with GaN-based biosensors was charge screening, sample preparation and cost-inefficient equipment/sensor washings. The double-layered Al-based GaN biosensor promises a revolution by getting rid of charge screening and sample pre-treatments. This cost-effective and highly sensitive biosensor used an electrical double-layered Al gate to sense the presence of Cardiac troponin I protein, as depicted in figure 8.

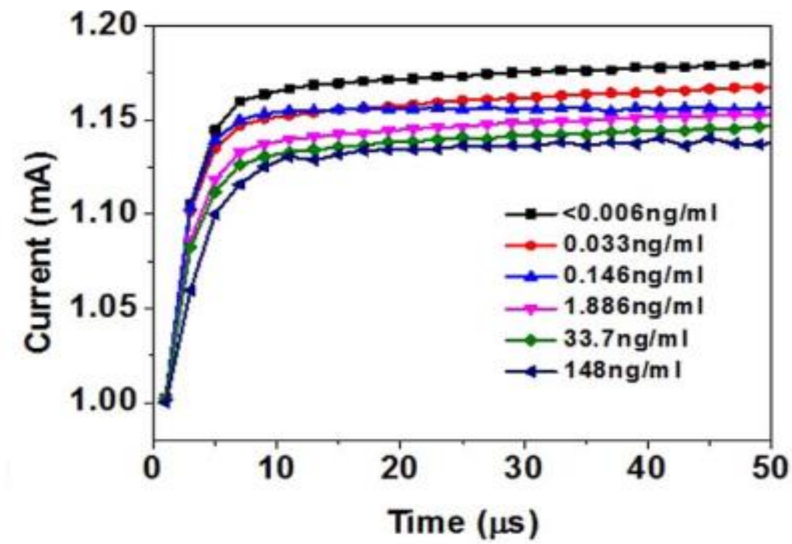


Figure 8: GaN biosensor response time for various concentrations of Cardiac troponin I (Sarangadharan et al., 2018)

Other than this, GaN-based biosensors are used for the detection of DNA (C.-P. Chen et al., 2011; Sahoo et al., 2013; Zhan et al., 2017), pathogens (Y. Chen et al., 2020), tumour markers (CA 19-9) (Wang et al., 2008), PDGF BB in serum (Qian et al., 2019), and lung cancer (Yang et al., 2019) etc. In a nutshell, GaN has revolutionised medical sensing technology due to its high sensitivity, low response time, and cost-efficiency.

2.3 pH Sensors

Due to high sensitivity and operational capability in extreme environments, GaN pH sensors focus on the dire revolution. To improve its sensitivity, various models have been proposed, such as gateless (Guo, Wang, Hao, & Luo, 2012), reference electrode free (Xue et al., 2020), multistage sensing (Dong et al., 2018) and cap layer sensing (Parish et al., 2019) etc. Before pH sensors, glass-based electrode type pH sensors have been widely used. But the application of these sensors is limited by low sensitivity, high response time and unsustainability in harsh environments (Parish et al., 2019). After this era of zirconia electrode-based pH sensors (Light & Fletcher, 1985) started that also not last for too long due to similar issues of non-availability in extreme conditions. After these failures, GaN pH sensors took place in the market with astonishing characteristics.

In GaN pH sensors, two options are available, either use an electrode-based sensor or use electrode free. In the electrode-based sensor, the sensor's response is not linear with a change in pH level. But the electrode free sensor gets preference due to its linear response, as depicted in figure 9. Furthermore, these sensors can be direct measuring (directly measure pH level) or indirect measuring (associated with anion level) sensors.

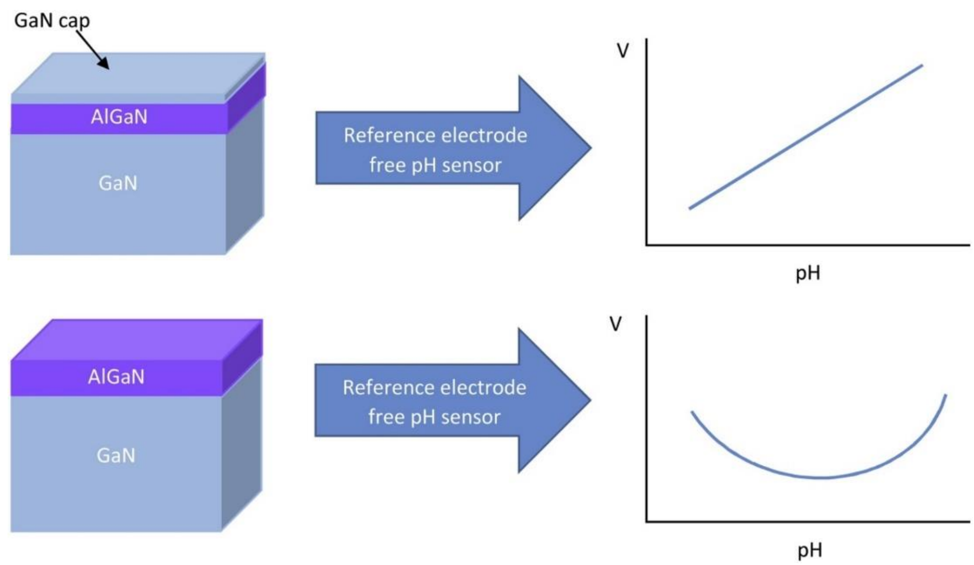


Figure 9: Response curve of GaN pH sensor (Parish et al., 2019)

2.4 GaN in the Power Industry

GaN promises flywheel free diodes; such diodes in conventional inverter systems were connected in parallel with IGBTs; in addition, they use the bidirectional operation of the GITs with a synchronous gate driving. Furthermore, the author (Morita et al., 2011) pointed to the use of bidirectional operations of lateral and compact GITs with low on-state resistance for synchronous gate driving. The demonstration of a three-phase inverter is significant to energy saving in the future and critical power switching systems (Morita et al., 2011).

For low voltage converters, the author (Morita et al., 2012) presented a novel transistor based on the integrated Scotty barrier diode(SBD). In this study, the silicon substrate was used for

Aluminium Gallium Nitride AlGaN/GaN hetero-structure; this silicon substrate was connected to the normally-off transistor GaN GIT (Gate Injection Transistor) through holes. The attractive feature of this design is lower operating loss which is being enabled by the reverse current of the diode during conversion operation accompanied by lower forward current compared to that of lateral GaN transistor. To achieve a highly efficient DC-DC converter for the purpose, GaN-based GIT (Gate injection transistor) and silicon Scotty barrier diode were connected in parallel. A novel integrated gallium nitride device was presented. The high efficiency of 89% was reported by DC-DC converters from 12V-1.3V at 2 MHz frequency, representing auspicious paternal gallium nitride devices for future applications.

Moreover, comparing the switching losses of both the diode operation of gate injection transistor and silicon-based SBD, it was turned out that forward voltage switching greatly helps in reducing switching losses in the case of Silicon SBD. Further, the measured peak high efficiency at 2Mhz is 89% for 12V down to 1.3V DC_DC converter using GaN devices, this peak high efficiency of 89% at 2<Hz cannot be achieved by using Si-based devices; therefore, GaN-based devices are very curial for the future DC-DC converters (Morita et al., 2012).

Applications of GaN are also reported in Quasi-Resonant (QR) flyback converters (Mauromicale et al., 2019) with the improved conversion of the efficiency and reduced volume. Furthermore, the author (Mauromicale et al., 2019) empirically proved an increment in efficiency by 0.8%, owes to reduced switching losses, compared to the super junction Si MOSFET. This efficiency was reported without optimisation of the GaN power switch (Mauromicale et al., 2019).

GaN electronic devices and nanopowders (Yasmin Abdul Wahab, Fatmadiana, et al., 2020) are reported as high sustainable devices in harsh environments such as deep well drilling and high-frequency power conversion application. Along with this, efficient power conversion, high efficiency, high frequency, and doubled switch capacitor voltage have also been reported. Hence, GaN can find applications in capacitors and supercapacitors (Abdul Wahab, Naseer, Abbasi, et al., 2020; Abdul Wahab, Naseer, Zaidi, et al., 2020). The results show that GaN devices lead to an output of 480W at 893 kHz switching frequency (Scott et al., 2013).

The use of silicon-based devices in integrated circuits can be replaced by GaN-based devices, referring to improved physical properties. It has been noted that high power electronics devices made from Group III-nitride semiconductors demonstrate auspicious characteristics (Zadeh, Tanabe, Watanabe, & Matsuzaki, 2016). Moreover, the efficiency of inverters which are commonly used in home appliances can only be significantly enhanced by replacing Si-based devices with GaN-based devices. Nitride semiconductors are a sort of compound semiconductor that is made out of a gathering III component and nitrogen, for instance, gallium nitride (GaN), aluminum nitride (AlN), indium nitride (InN), or a mix of these materials. These semiconductors have a band hole relating to short-wavelength light. This invigorates them with high potential materials for electronics, even in high-temperature situations (Y Abdul Wahab, Soin, & Hatta, 2014). GaN has generally been utilised in light-producing diodes (LEDs) as lighting gadgets instead of radiant lights or fluorescent lights. In a nutshell, an energy-saving society can be achieved by expiating GaN-on-silicon technology (Zadeh et al., 2016).

In the automotive sector, GaN power devices and power switches at high temperature, high frequency and low on-resistance are essential and crucial to the future advancement of electric and hybrid vehicles systems. Significant characteristics can be achieved using GaN-based power devices (Kachi, Kanechika, & Uesugi, 2011). GaN promises low-cost, high-performance devices (Yasmin Abdul Wahab et al., 2019). Epitaxial growth of GaN on silicon substrate helps reduce the chip's cost and ultimately leads to lower fabrications, which is a demanding issue to be addressed. Other than lower cost, GaN-based devices have reported the world's highest breakdown voltage of 10400V in Al GaN/GaN HFETs (Naidu, Hatta, Soin, Rahman, & Wahab, 2018; Ueda, Uemoto, Tanaka, & Ueda, 2009) that makes GaN’s future development flourished.

3. Conclusion

Scientists have always been concerned about developing precise sensors for biological applications and chemical sensing. In this regard, various materials have been tested, and some particular applications are provided. But all these applications are encircled in many limitations, specifically operations in harsh conditions. Preceding in view, GaN has emerged as a marvellous application to cope with these issues of harsh environment applications. This study reveals that GaN is the best option for different chemical sensors, including hydrogen and biological compounds. Additionally, GaN sensors can be used in the power industry due to its high bandwidth and promise to revolutionise this field in the years to come.

Conflicts of Interest

The authors declare no conflict of interest.

Acknowledgements

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