Fabrication and Characterization of GaN-Based Two Terminal Devices for Liquid Sensing

2011 IOP Conf. Ser.: Mater. Sci. Eng. 17 012024

(http://iopscience.iop.org/1757-899X/17/1/012024)

Fabrication and Characterization of GaN-Based Two Terminal Devices for Liquid Sensing

Wang Soo Jeat[1], Mastura Shafinaz Zainal Abidin[1], Abdul Manaf Hashim[1]*, Shaharin Fadzli Abd Rahman[1], Maneea Eizadi Sharifabad[1], Farahiyah Mustafa[1], Abdul Rahim Abdul Rahman[1], Rabia Qindeel[2] and Nurul Afzan Omar[3]

[1]Material Innovations and Nanoelectronics Research Group, Faculty of Electrical Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia.

[2]Department of Physics, Faculty of Science, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia.

[3]Telekom Research & Development, TM Innovation Centre, 63000 Cyberjaya, Malaysia.

Email: manaf@fke.utm.my

Abstract Gallium Nitride (GaN) based materials are highly suitable for liquid-phase sensor applications due to their chemical stability and high internal piezoelectric polarization. The sensitivity of GaN surfaces in aqueous solutions and polar liquids has been investigated. For this purpose, two terminal devices fabricated on bulk Si doped-GaN structures and undoped-AlGaN/GaN heterostructures with unpassivated open area are used to measure the responses to the changes of the H^+ concentration in aqueous solutions and the dipole moment in polar liquids. The I-V characteristics show that the devices are able to distinguish the variations of pH. It is observed that the drain current decreases linearly with pH for both device structures. Evaluating the sensitivity in aqueous solutions at V_{DS} = 2V, a quite large current change is obtained for both structures. For the response to polar liquids, it is also found that the drain current decreases with the dipole moments. The results indicate that both devices are capable of distinguishing molecules with different dipole moments.

1. Introduction

Many semiconductor materials have been tested for their suitability as ion sensors; especially there is an emerging interest in the use of wide band gap semiconductors as sensitive chemical sensors [1-3]. Group III-nitrides with wurtzite crystal structure are chemically stable semiconductors with high internal spontaneous and piezoelectric polarization, which make them highly suitable materials to create very sensitive but robust sensors for the detection of ions, gases and polar liquids [4, 5]. Solids with a large band gap such as diamond or gallium nitride (GaN) are among the prime candidates for a variety of sensor applications, particularly at high temperatures and in harsh environments.

AlGaN/GaN heterostructures have been extremely useful for gas and liquid sensor due to primarily three reasons: 1) a high electron sheet carrier concentration channel induced by piezoelectric polarization of the strained AlGaN layer, 2) the carrier concentration which is strongly depends on the ambient [6, 7] 3) an opportunity of on-chip co-integration with signal processing and

communication circuit. In addition, sensors fabricated from these wide band-gap semiconductors could be readily integrated with solar blind UV detectors or high temperature, high power electronics with wireless communication circuits on the same chip to provide high speed transmission of the data.

For these reasons, GaN-based HEMT structures are versatile structures that may be used for a variety of sensing applications. Due to their low intrinsic carrier concentrations, wide band gap semiconductor sensors based on GaN can be operated at lower current levels than conventional Si-based devices and offer the capability of detection up to 600 ˚C [8-12]. The ability of electronic devices fabricated on these materials to operate in high temperature, high power and high flux/energy radiation conditions enable performance enhancements in a wide variety of spacecraft, satellite, homeland defense, mining, automobile, nuclear power, and radar applications.

In this work, the sensitivity of GaN surfaces in aqueous solutions and polar liquids has been investigated. For this purpose, two terminal devices fabricated on bulk Si doped-GaN structures and undoped-AlGaN/GaN heterostructures with unpassivated open area are used to measure the responses to the changes of the H^+ concentration in aqueous solutions and the dipole moment in polar liquids.

2. Design and fabrication process

2.1 Material structure

In this study, the GaN-based material structures used are bulk Si doped-GaN and undoped-AlGaN/GaN heterostructure, as shown in Figure 1.

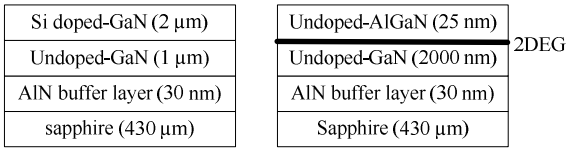


Figure 1. Cross sectional of material structure for (a) bulk Si doped-GaN (b) Undoped-AlGaN/GaN heterostructure.

Both structures are grown on 430 μm sapphire substrates. The heteroepitaxial growth of the group III-nitrides on sapphire substrate allows the application of simple planar device structures [7]. The following AlN buffer layer is necessary as it dramatically improves the surface morphology and crystalline quality of the following undoped-GaN layer [13]. Furthermore, the thermal expansion of the sapphire substrate is close to that of AlN and AlN is also often used as packaging materials for high temperature sensor [7]. For the bulk structure, Si doped-GaN channel is formed near to the surface of the top layer. For the heterostructure, undoped-GaN layer is formed on the buffer layer and is followed by the growth of undoped-AlGaN layer with 25% of Al composition. As a result, the two adjacent III-Nitride layers form a two-dimensional electron gas (2DEG) in between. From Hall measurement at room temperature, the carrier mobilities of bulk Si doped-GaN and undoped-AlGaN/GaN heterostructure are 222 cm^2/Vs and 1860 cm^2/Vs, respectively. The 2DEG sheet carrier density in the heterostructure is 6.61×10^{12} cm^{-2}.

2.2 Fabrication process

Figure 2 shows the top view and the cross sectional of GaN-based two terminal devices. The first fabrication process is mesa patterning. The mesa pattern of GaN-based wafer is obtained from photolithography, which is followed by the process of dry etching by reactive ion etching (RIE).

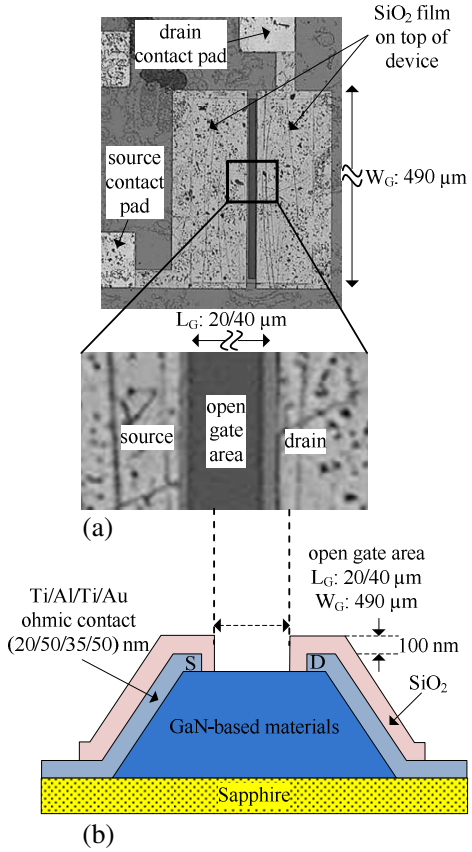


Figure 2. (a) Top view (b) Cross sectional of GaN-based two terminal devices.

In order to form source and drain ohmic contact, photolithography is done again before depositing metal layers of Ti/Al/Ti/Au (20/50/35/50nm). Methylethyl ketone (MEK) is then used for the lift off process. The alloyed Ti/Al/Ti/Au is obtained by the process of rapid thermal annealing (RTA) at 850°C in N_2 ambient for 30 seconds. Then, the ohmic contacts are coated with 100 nm of SiO_2 layer to insulate these contacts from being contacted to electrolyte. SiO_2 layer is deposited at 300°C by plasma-enhanced chemical vapor deposition (PECVD). Lastly, the SiO_2 layer at the opening area is etched out by wet etching using buffered hydrofluoric (BHF) solution.

The two-terminal devices chosen for measurement have the open area dimension of 490 × 20 µm for bulk Si doped-GaN structures and 490 × 40 µm for undoped-AlGaN/GaN heterostructures.

2.3 Measurement

Figure 3 shows the measurement circuit consisting of two working electrodes formed by copper lines on printed circuit board (PCB) and connected to source measure unit (SMU). The fabricated device is attached on the PCB and immersed in the electrolyte contained Teflon beaker.

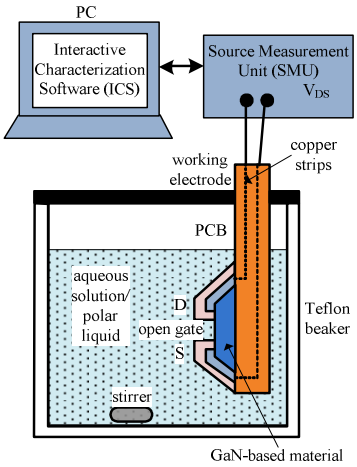


Figure 3. Schematic of measurement circuit

The drain-source of the fabricated devices are biased with drain-source voltage, V_{DS} by SMU and the drain current, I_D is measured by a computer installed with an interactive characterization software (ICS). Measurements are first done by immersing the working electrode in aqueous solutions with different H^+ concentration (*p*H) and then are followed by polar liquids with different dipole moment, at room temperature (25°C).

3. Experimental results

3.1 Current response to variation H^+ concentration

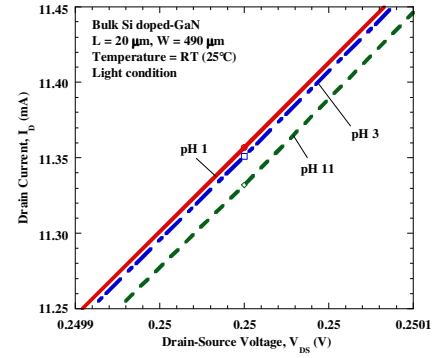
Variation of H^+ is represented by *p*H. Higher *p*H value shows the lower H^+ concentration present in the aqueous solution. Figure 4 shows the *I-V* characteristics of devices fabricated on bulk Si doped-GaN structure and undoped-AlGaN/GaN structure in aqueous solutions with different *p*H. Figure 4(a) does not start at V_{DS} = 0V because its scale has to be enlarged in order to observe clearly the micro-range current variations.

In order to analyze the current response of H^+ concentration, data of aqueous solutions with *p*H 1, *p*H 2 and *p*H 11 are used for bulk Si doped-GaN device, whereas data of aqueous solutions of *p*H 2, *p*H 4 and *p*H 6 are used for undoped-AlGaN/GaN device. From the *I-V* characteristics, higher *p*H which contains less H^+ concentration is observed to have lower current. This phenomenon can be explained by using site-binding model [14]. It was reported that amphoteric hydroxyl groups (*M*OH: *M* may represents Ga) are formed at the oxide surface in contact with aqueous solutions. The amphoteric hydroxyl groups may be neutral, protonized or deprotonized, depending on the H^+ concentration. The equilibrium constants for the relevant reactions are:

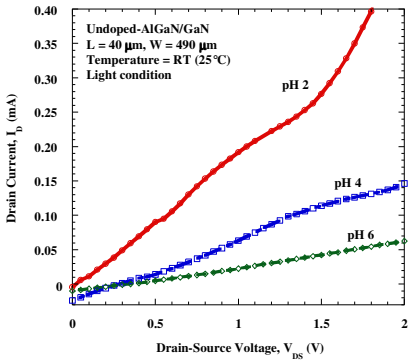
$$MOH \leftrightarrows MO^- + H^+ \qquad (1)$$

$$MOH + H^+ \leftrightarrows MOH_2^+ \qquad (2)$$

When H^+ concentration decreases in aqueous solution, charges on the oxide surface become negative due to deprotonized hydroxyls (MO^-), as represented by Eq. (1). On the other hand, the increase of H^+ concentration in aqueous solution induces positive charges on oxide surface due to protonized hydroxyls (MOH_2^+), as represented by Eq. (2). These result in a potential change at GaN surface and change the current of the devices.



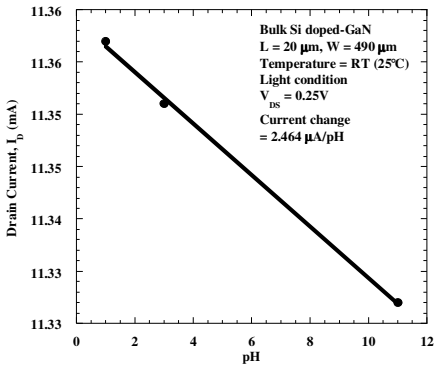
(a)



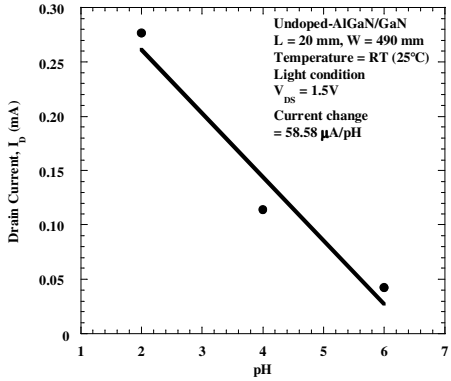
(b)

Figure 4. *I-V* characteristics of (a) bulk Si doped-GaN device (b) undoped-AlGaN/GaN device in aqueous solutions with different *p*H.

The linearity of current as a function of *p*H, which indicates systematic potential change at GaN surface of both devices, is shown at V_{DS} = 0.25V with currrent change (□*I*) = 2.464 □A/*p*H for bulk Si doped-GaN device and V_{DS} = 1.5V with □*I* = 58.58 □A/*p*H for undoped-AlGaN/GaN device, as shown in Figure 5.



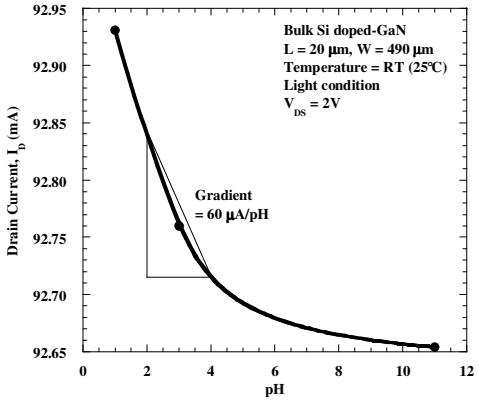
(a)



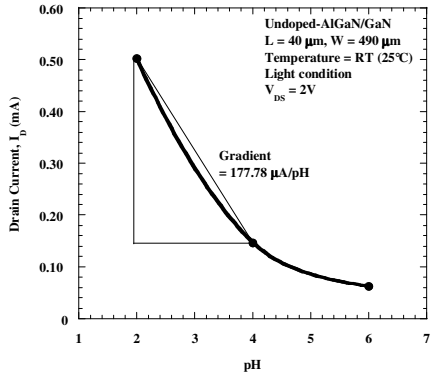
(b)

Figure 5. Drain current as a function of *p*H measured at (a) V_{DS} = 1.5V for Si doped-GaN device (b) V_{DS} = 1.5V for undoped-AlGaN/GaN device.

For device performance comparison, Figure 6 presents the drain current measured at V_{DS} = 2V for both devices.



(a)



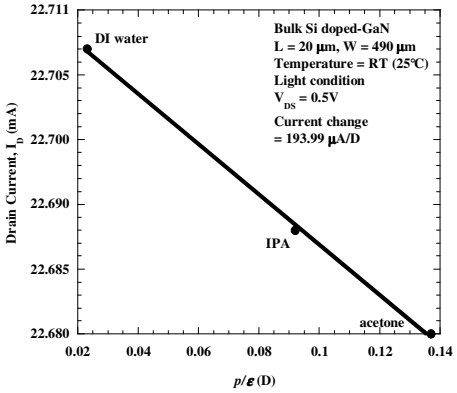
(b)

Figure 6. Drain current as a function of *p*H measured at V_{DS} = 2V for (a) Si doped-GaN device (b) undoped-AlGaN/GaN device.

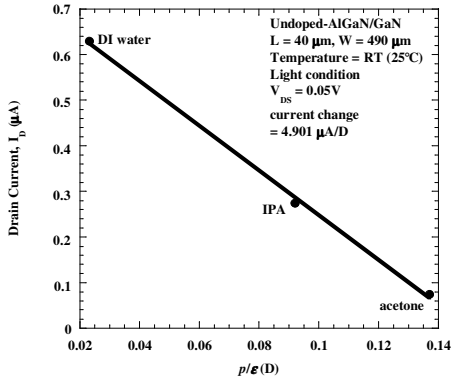
Since the graphs obtained are non-linear, the curve gradient from *p*H 2 to *p*H 4 is calculated, so that current change can be compared. It can be seen that the undoped-AlGaN/GaN device has a larger current change of 177.78 □A/pH, as compared to bulk Si doped-GaN device with a smaller current change of 60 □A/*p*H.

3.2 Current response to polar liquids

The liquids used to investigate the current response of dipole moments are DI water, IPA and acetone. Figure 7 shows the drain current as a function of p/ε values for both devices (p is the dipole moment and ε is the dielectric constant of the liquid).



(a)



(b)

Figure 7. Drain current as a function of p□□□value measured at (a) V_{DS} = 0.5V for Si doped-GaN device (b) V_{DS} = 0.05V for undoped-AlGaN/GaN device.

Systematic potential change (□V) at GaN surface of both devices is observed where current decreases linearly with the increase of p□□□value. Current changes, □I of 193.77 □A/D at V_{DS} = 0.5V for bulk Si doped-GaN device and □I of 4.901 □A/D at V_{DS} = 0.05V for undoped-AlGaN/GaN device are obtained.

The potential drop (ΔV) at the polar liquid/GaN interface can be described by the Helmholtz model [15, 16]:

$$\Delta V = \frac{N_s p(\cos\theta)}{\varepsilon\varepsilon_0} \qquad (3)$$

Where p is the dipole moment, N_s is the dipole density per unit area, θ□is the angle between the dipole and the surface name, ε is the dielectric constant of the polar liquid, and ε_0 is the permittivity of free space. Hemholtz model describes that p□□□value causes voltage drop at GaN surface and thus the relationship between current and dipole moment can be observed. Polar liquid with high p□□ value gives more voltage drop, which decreases the current.

4. Conclusion

In aqueous solutions with H^+ concentration (*p*H), higher *p*H give lower current. This relationship is explained by using the site-binding model. In polar liquids with dipole moments (*p*), higher *p*/□□value also give lower current. This phenomenon is described by using the Hemholtz model. In short, this work has successfully proven the ability of GaN-based two terminal devices to distinguish aqueous solutions with different *p*H and polar liquids with different dipole moments. For liquid sensor applications, systematic potential change in GaN-based two terminal devices is very important to ensure stable operation. Linearity of current change is observed indicating systematic potential change in both structures.

Acknowledgements

The authors wish to extend their thanks for the support provided by the Ibnu Sina Institute, Universiti Teknologi Malaysia, Malaysia and Nano-Optoelectronics Laboratory, Universiti Sains Malaysia, Malaysia. This work is supported by the Ministry of Science, Technology and Innovation, Malaysia government under science-fund grant 03-01-06-SF0394, Ministry of Higher Education, Malaysia government under FRGS grant 78348 and Universiti Teknologi Malaysia under Foreign contract staff grant 77540. We also wish to thank our colleagues for useful discussions, particularly, Assoc. Prof. Dr Azlan Abdul Aziz, Assoc. Prof. Dr Roslan Mat Hashim at Universiti Sains Malaysia, Malaysia and Assoc. Prof. Dr Zulkafli Othaman at Universiti Teknologi Malaysia, Malaysia.

References

[1] O. Ambacher, *Growth and applications of Group III-nitrides*, J. Phys. D: Appl. Phys, 1998. 31: p. 2653–2710.

[2] S. J. Pearton, J. C. Zolper, R. .J. Shul and F. Ren, *GaN: processing, defects, and devices*, J. Appl. Phys, 1999 . 86:p. 1–78.

[3] S. C. Jain, M. Willander, J. Narayan and R. V. Overstraeten, *III-nitrides: growth, characterization, and properties*, J. Appl. Phys., 2000. 87: p. 965–1006.

[4] M. Stutzmann, G. Steinhoff, M. Eickhoff, O. Ambacher, C. E. Nebel, J. Schalwig, R. Neuberger and G. M¨uller, *GaN-based heterostructures for sensor applications,* Diamond Related Materials, 2002.11: p. 886–891.

[5] M. Eickhoff, J. Schalwig, G. Steinhoff, O. Weidemann, L. G¨orgens, R. Neuberger,M. Hermann, B. Baur, G. M¨uller, O. Ambacher and M. Stutzmann, *Electronics and sensors based on pyroelectric AlGaN/GaN heterostructures. Part B: sensor applications,* Phys. Stat. Sol., 2003: p. 1908–1918.

[6] Y. Alifragis, A. Volosirakis, N. A. Chaniotakis, G. Konstantinidis, E. Iliopoulos and A. Georgakilas, *AlGaN/GaN high electron mobility transistor sensor sensitive to ammonium ions*, Phy. Stat. Sol., 2007.204: p. 2059.

[7] M. Eickhoff, J. Schalwig, G. Steinhoff, O. Weidemann, L. Görgens, R. Neuberger, M. Hermann, B. Baur, G. Müller, O. Ambacher and M. Stutzmann, *Electronics and sensors based on pyroelectric AlGaN/GaN heterostructures,* Phys. Stat. Sol. (c), 2003.0: p. 1908.
A. Baranzahi, A. Lloyd Spetz, and I. Lundström, *Reversible hydrogen annealing of metal-oxide-silicon carbide devices at high temperatures* , Appl. Phys. Lett., 1995. 67: p. 3203.

[8] A. Lloyd Spetz, L. Unéus, H. Svenningstorp, P. Tobias, L. G. Ekedahl, O. Larsson, A. Göras, S. Savage, C. Harris, P. Mårtensson, R. Wigren, P. Salomonsson, B. Häggendahl, P. Ljung, M. Mattsson and I. Lundström*, SiC based field effect gas sensors for industrial applications*, Physica Status Solidi A, 2001. 185: p. 15.

[9] B. P. Luther, S. D. Wolter and S. E. Mohney, *High temperature Pt Schottky diode gas sensors on n-type GaN*, Sensors Actuators B, 1999 .56: p. 164 .

[10] J. Schalwig, G. Müller, O. Ambacher, and M. Stutzmann, *Group-III-nitride based gas sensing devices*, Phys Status Solidi A, 2001.185: p. 39 .

[11] J. Schalwig, G. Müller, M. Eickhoff, O. Ambacher and M. Stutzmann, *Gas sensitive GaN/AlGaN-heterostructures,* Sens. Actuat B, 2002.87: p. 425.

[12] L. Liu and J. H. Edgar, *Substrates for gallium nitride epitaxy*, *Material Science and Engineering*, 2002.R(37): p. 61-127.
[13] D. E. Yates, S. Levine and T. W. Healy, *Site-binding model of the electrical double layer at the oxide/ water interface,* J. Chem. Soc. Farady Trans. I, 1974.70: p. 1807.

[14] S. Bastide, R. Butruille, D. Cahen, A. Dutta, J. Libman, A. Shanzer, L. Sun, and A. Vilan, *Controlling the work function of GaAs by chemisorption of benzoic acid derivatives*, J. Phys. Chem. B, 1997.101: p. 2678-2684.
[15] T. Kokawa, T. Sato, H. Hasegawa and T. Hashizume, Liquid phase sensor using open-gate AlGaN/GaN high electron mobility transistor structure, J. Vac. Sci. Technol. B., 2006.24(4): p. 1972-1976.