Design and development of Gallium Nitride HEMTs based liquid sensor

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***Abstract*—This paper reports on the design and fabrication of Gallium Nitride HEMTs based liquid sensor. Sensor is packaged using thick film Alumina based packaging. A drain current of 6.17 mA is measured on packaged HEMTs at 1.0 V. The packaged HEMT sensor is used for the sensing of different polar liquids namely Acetone, Water, and Methanol. It shows reduction in the drain current as the dipole moment of the liquid increases. Lowest drain current is recorded when the package is dipped into Acetone as compared to Water and Methanol.**

Four different designs (50_G, 50_ID, 25_G and 25_ID) of sensors are used to detect heavy metal ion Hg^{+2}. The detection limit of design 25_G, 50_G and 50_ID is found to be in mM range. Best results are obtained on design 25_ID which shows a 4.8 % change in the drain current with respect to dry response for nM concentration. Not to mention, design "25_ID" is novel and has never used before for the HEMT sensing. Design is unique in the sense of having multiple gates arranged in the electrode fashion.

***Keywords*—HEMTs; Polar liquid sensor; Heavy metals ions; Mercury Chloride**

I. Introduction

GaN HEMTs combine the properties of GaN material and heterostructure. GaN materials are highly chemically stable and inert. GaN HEMTs enjoy high mobility, high transconductance and sheet carrier density due to high spontaneous and piezoelectric polarization. The 2DEG properties of GaN HEMTs are closely related to surface states. As the surface states charging-properties change due to polar liquids, ions, pH or dielectric films for surface passivation, the concentration of 2DEG changes. Therefore, GaN lateral transistors based sensors are quite sensitive to polar liquids and could provide much better liquid sensors as compared to their Si counterparts in terms of sensitivity, short response time, robustness, radiation tolerance, and capability to operate at elevated temperatures above 400°C. The combination of all these properties at the same time is very beneficial for space and societal applications. Additionally, these sensors can be monolithically integrated with a corresponding GaN based read-out electronics.

This paper reports on the design and development of AlGaN/GaN HEMTs based liquid sensor for analyzing and detecting polar liquids such as Water, Acetone and Methanol and heavy metal ion Mercury using Mercury chloride. We investigate a wide range of Hg^{2+} ion concentration from 1mM to 1 nM [1].

II. Experimental

The HEMT epitaxial structure is grown on Sapphire using MOCVD. It consists of a 2.0 µm thick Fe-doped GaN buffer layer and a 22.0 nm AlGaN layer. The top AlGaN layer is capped by a 5.0 nm thick GaN. Sensor fabrication starts with the e-beam deposited Ohmic contacts and then followed by rapid thermal annealing. TLM contact pads separated by 2.0 µm, 4.0 µm, 8.0 µm, 16.0 µm are used to measure the contact resistance. We passivate the devices thereafter using Silicon Nitride and Ion implant through Nitride for isolation. Gate module consists of a Gate trench defined in nitride layer using ICP-RIE followed by Ir sputtering. Over the top of it, gate head of 3.0 µm is structured using lift off. Nitride is etched away from remaining area. Contacts are interconnected using connecting Ti/Au metal layer. Device are then passivated with the Second SiN_x and structured to open only the gate sensing area and bias pads. HEMT in use has a unit gate width of 100 µm. Four different designs (1; 25_G, 2; 25_ID, 3; 50_G and 4; 50_ID) based upon the variations in source gate distance and gate structures are used for sensing. Design 'G' and 'ID' have single standard gate geometry and multiple gates arranged in electrodes fashion respectively for better sensing. Not to mention, design "ID" is novel and has never used before for the HEMT sensing.

We characterize (d.c) the devices after fabrication and dice in 11x11 mm^2 chips for packaging. Thick-film alumina based packaging is used to package AlGaN/ GaN HEMT device. Overall device dimension is 2118 µm x 550 µm with two wire bonding pads of dimension 300 µm x 260 µm. In order to test the packaged device by dipping inside a fluid, individual package in the form of vertical strip is designed with an overall dimension of 50.8 mm x 10 mm using HYDE CAD software. There are two pads for outer connections from the device while the third designed pad is not connected (NC) and is used to provide mechanical strength to the package.

Standard alumina substrate of dimensions 2" x 2" is chosen for fabrication of package base. Screens are prepared as per the design layout for further processing of alumina substrate. DuPont palladium-silver conductor paste is used to screen print the die bonding pads, conductor tracks and lead attachment pads. Wire bonding pads are provided using thick-film gold conductor paste. Each printing process is followed by drying and firing of the substrate with appropriate time-temperature profile. Dicing of individual package base is done to singulate the fabricated package. Leads are attached to each package using reflow-soldering technique. Die bonding and wire bonding of the device is followed by capping of conductor tracks with alumina substrate of appropriate dimensions. Wire bonds are protected using nonconductive potting compound. We characterize these packages and use for liquid sensing.

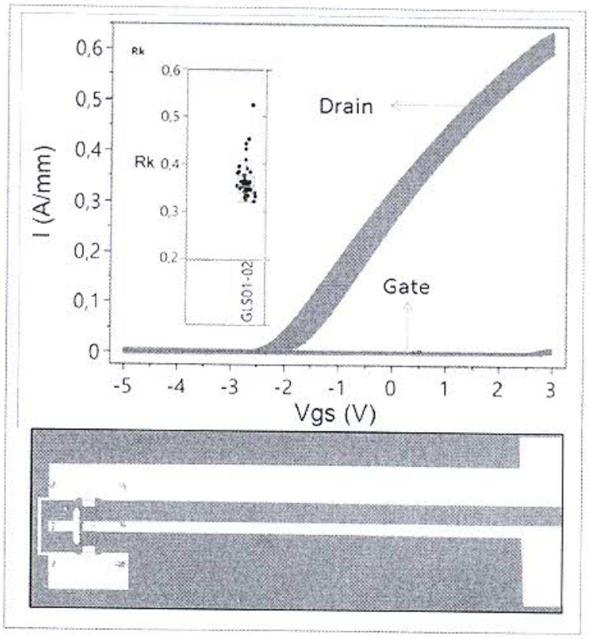


Fig. 1. D.C characteristics of fabricated HEMT device.

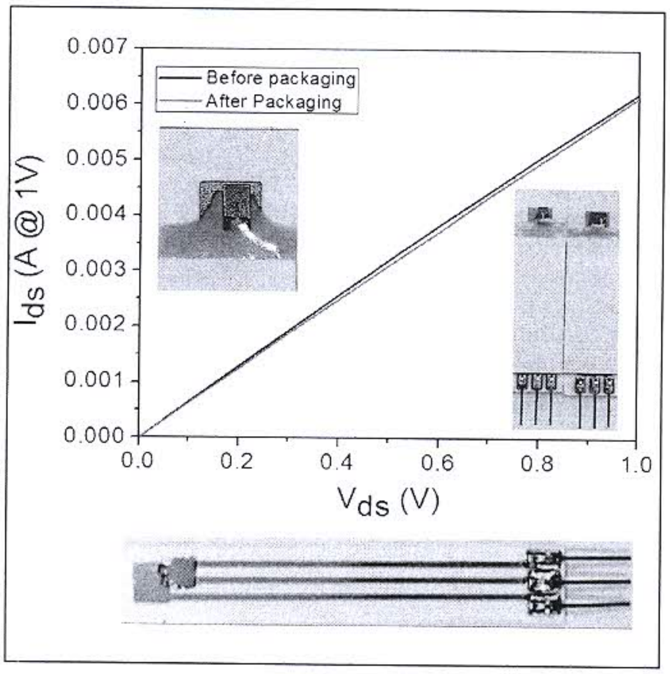


Fig. 2. D.C characteristics of Packaged HEMT.

III. RESULTS AND DISCUSSIONS

Fig.1 shows the HEMT chip along with the d.c characterization. Contact resistance and Sheet resistance values measured on TLM structures range from 0.35 to 0.45 Ω-mm and 480 to 510 Ω/sq. respectively.

The maximum drain current measured at a gate voltage of +2.0 V range from 0.47 A/mm to 0.52 A/mm depending upon the device design variations along with wafer. In addition, the pinch off value range from -1.8 V to -2.3 V related to the current values based upon the device design.

Fig.2 shows the characteristics of a packaged HEMT before and after packaging at 1.0 V for sensing applications. The measured drain current after packaging is 6.17 mA @ 1.0 V for a 100 μm device. A minor change in the drain current before and after packaging ensures the good quality packaging.

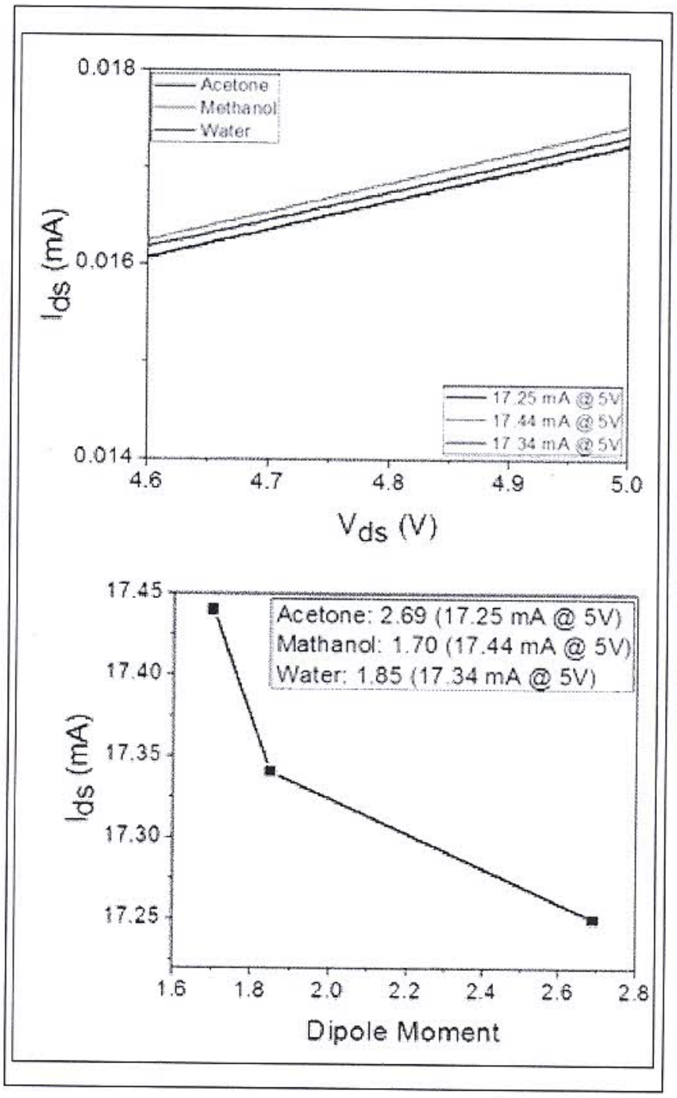


Fig. 3. Polar liquids sensing (Acetone, Water, Methanol).

ne packaged HEMT is used for liquid sensing based upon the dipole moments of different liquids namely Acetone, Water, and Methanol as shown in Fig. 3. Dipole moment of Acetone, Water and Methanol are 2.69, 1.85 and 1.70 respectively.

Following the cleaning and rinsing sequence, Package is dipped into Acetone, and then transferred into Methanol solution. At the end, it is immersed into water. Drain current is measured in all these three solutions at 5.0 V. Change in the drain current while changing the solution from Acetone to Methanol and Methanol to Water is 0.19 mA and 0.10 mA respectively. Lowest current is recorded in the Acetone and highest is recorded in Methanol. These graphs correlate the dipole moment with drain current. Since the dipole moment of the Acetone is highest among other two, the drain current is lowest [2]

The larger the dipole moment is, the larger will be the difference in electronegativity of bonded atoms. In other words, the electrons will spend more time around atom that has larger electronegativity [3]. This will result in reduced 2deg and hence the reduced current. Hence, by looking at the drain current graphs of the unknown liquids, one could differentiate between the liquids of high dipole moments from the liquids of low dipole moments.

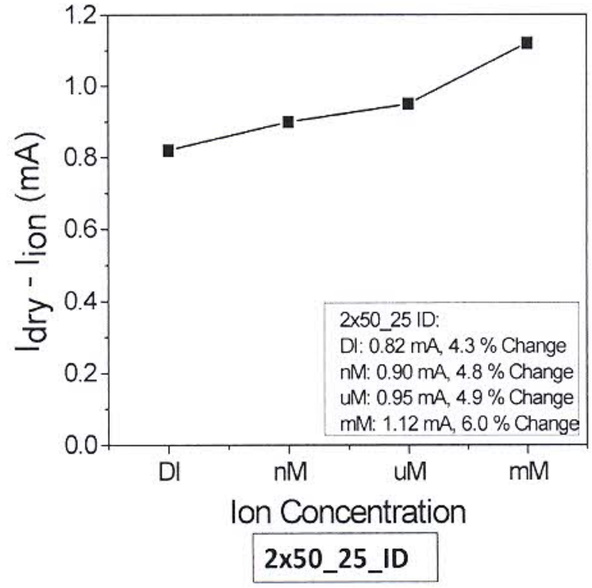
Presence of Heavy metal ions in environment, particularly the Mercury ions (Hg^{+2}) has a catastrophic impact on the ecosystem. Therefore, quantitative detection of this ion is highly desirable. The acceptable detection limit of a Hg^{+2} ion is below 10^{-8} M as per the Government regulation [4].

In the next series of experiments, we prepare different molar concentration of $HgCl_2$ to detect Hg^{+2}. For making 10^{-2} M solution, 0.028 gm. $HgCl_2$ is added into 10 ml of water. Three main concentrations of interest (nM, µM and mM) are made using 10^{-2} M solution. Four packaged HEMT of different designs (50_G, 50_ID, 25_G and 25_ID) are immersed first into DI water and then sequentially to nM, µM and mM solutions of $HgCl_2$. After each dip, packages are dried using N_2 and then measured before the next solution test. Fig. 4 show the effect of molar concentrations on the drain current difference in $HgCl_2$ solution with respect to dry condition (air).

Best results are obtained on Design 25_ID. Fig 4 a shows an increase in the drain current with molar concentration. For nM concentration, 4.8 % change is recorded in the drain current with respect to dry response. Also for other concentrations (µM and mM), the percentage changes in the drain current values are greater than 4%. These values are indicating a very good design for circuit implementation.

Drain current response of the designs 50_G and 50_ID are compared. Both of these designs could not detect nM concentration. They show an increased change in mM solution with respect to DI. Hence, these designs could detect mM concentration of Hg^{2+} and best suitable for this range.

Design 25_G show different response for nM and µM concentration. However, the trend of current response is not correct. It should increase with an increase in the concentration.



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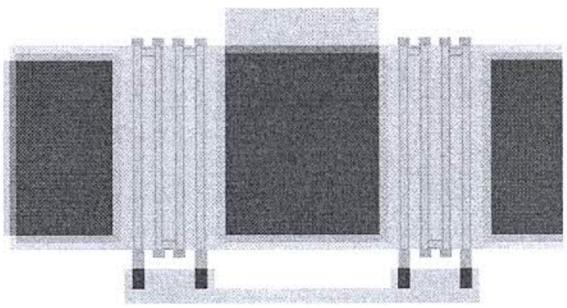

4b

Fig. 4. Detection of heavy metal ion (Hg^{+2}) at different concentration for 25_ID designs.

Again, the design is capable to detect mM concentration. In summary, the detection limit of design 25_G, 50_G and 50_ID is in mM range. Device 25_ID is capable to detect Hg^{+2} ion in nM range.

Design in discussion (Fig. 4b) is unique in the sense of having multiple gates arranged in the electrode fashion. For a source drain distance of 25 µm, four turn of three µm are densely packed to increase the control over channel. Hence, the device sensitivity increases to sense nM concentration.

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