AlGaN/GaN HEMT for highly sensitive detection of Biomolecules using transconductance method

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Abstract: For the first time, AlGaN/GaN HEMT is demonstrated for bio-sensing application using transconductance analysis. A lot of HEMT based biosensors were developed experimentally but very few reported on sensing applications. These devices are ideal for sensing or tracking biomolecule because of the spontaneous and piezoelectric polarization properties. AlGaN/GaN HEMT with nanogap cavity is used to detect different biomolecule like streptavidin, protein and uricase. The sensitivity of AlGaN/GaN HEMT is investigated through drain current ($I_D$) and transconductance ($g_m$) and is analyzed using Technology Computer Aided Design (TCAD) tool. The result shows a noticeable change in drain current on introducing different biomolecules below the gate cavity region. Higher sensitivity was obtained for with Transconductance analysis than with drain current analysis.

Keywords: AlGaN/GaN HEMT, Bio-sensor, Sensitivity, Transconductance.

1. INTRODUCTION

Gallium Nitride (GaN) high Electron Mobility Transistor (HEMT) is an excellent choice for Radio frequency, space applications, power applications and optoelectronics [2-5,15-17]. Owing to its excellent electrical property like wide band-gap, higher thermal conductivity and higher electron mobility [18]. HEMT devices based on AlGaN / GaN heterostructure have special electronic properties, such as piezoelectric and spontaneous polarization, leading to increased electron density of the two-dimensional electron gas (2DEG). FET based sensors like diamond-FET, FET based charge sensor, underlap-embedded silicon nanowire FET, underlap FET and Nanogap FET have been used for sensing neurotoxins, ammonia ions and urea, HIV-1 Tat protein, detection of DNA sequence, avian influenza and HIV reported in [6-14]. It is reported in[19] that MOSFET-embedded cantilever biosensor has been used for detection of anthrax stimulant. MOSFET with ZnO Nanowires extended gate has been reported in [20] for detection of glucose. MOSFET-BJT hybrid mode of lateral bipolar junction transistor is used for detection of C-reactive Protein [21]. In recent decades AlGaN/GaN HEMT attracted a lot of attention for sensing application. GaN is more sensitive to stress as the conducting channel is very close to the surface to increase sensitivity. GaN based biosensor HEMT has exceptional good biological compatibility, stable material property and high sensitivity to surface charge change as the channel is close to the surface [13]. Biomolecule, gas, polar liquids and other chemical substances [7-9] has great effect over the surface potential. The change in the surface charge results in change in 2DEG, thereby higher sensitivity is obtained. In addition, the sensitivity of GaN based Biosensor is not affected by ambient temperature and harsh environmental condition because of its excellent chemical stability and thermal conductivity [23]. Several structure and methodologies are proposed and experimental verified to enhance the device performance. However, these methodology and techniques are not verified for sensing application. This provides a great research area in GaN.
HEMT for sensing application. Work on single channel AlGaN/GaN HEMT for bio-sensor on Drain current analysis has been proposed early in [1,24-25] and further extension to transconductance analysis has been carried out in this paper. AlGaN-GaN layer structure with lower AlGaN barrier layer with limited layer thickness and low Al composition proves to be a successful solution for HEMT implementation [18]. A very few AlGaN/GaN HEMT has been reported for sensing application. Structural and Physical Optimization [22] has been carried out on HEMT to enhance breakdown voltage, and to reduce current collapse, self-heating effect and trapping effect. Hence, there is space for structural optimization to enhance the sensitivity. Thus, in this paper, HEMT with transconductance analysis is proposed to enhance sensitivity. Biomolecule with different permittivity value is used for sensing and the simulation is carried out. As GaN HEMT is chemically stable and form ionic bond, thus biomolecule can easily attach to the surface. This hereby largely modulates 2DEG. In this work, AlGaN/GaN HEMT using transconductance peak has been proposed for detection of biomolecule. Drain current is sensitive parameter to observe change in surface potential, 2DEG and gate voltage. The sensitivity of HEMT is investigated through drain current and analyzed using ATLAS TCAD software with polarization model, Shockley-read-hall (SRH) model, field dependent drift velocity (FLDMOB) and calc. strain to calculate the strain produced.

2. DEVICE STRUCTURE

Figure 1 shows architecture of designed AlGaN/GaN HEMT constitutes 3–nm GaN cap, 18-nm AlGaN layer, 18 nm GaN layer, 5-µm GaN buffer layer and 486-µm Si substrate. The source to gate distance (L_{SD}), gate length (L_{G}) and gate to drain distance (L_{GD}) are 2.5µm, 1µmand4.5µmrespectively. A 100 nm SiN passivation layer is used to reduce current collapse and microwave power degradation. In device structure GaN cap layer is considered to scale down the surface traps effect. The gate is considered close to the source electrode to boost the device's efficiency and thus improve the device's drain current. Considering the economic importance and widespread use, Si is used as substrate.

Firstly, the cavity between the GaN cap layer and the gate is filled with SiO₂ and later 0.5µm long (L_{cavity}) and 3nm wide (W_{cavity}) nanogap cavity is considered to induce and detect biomolecule.

![Figure 1. Schematic cross-section of the developed AlGaN/GaN HEMT.](image-url)
Table 1. Materials modeling parameters used

| Atlas parameters | GaN  | AlGaN |
|------------------|------|-------|
| Electron Affinity (eV) | 4.2  | 3.62 |
| $V_{sat}(10^7 \text{ cm/s})$ | 2.68 | 1.05 |
| $E_g(300\text{eV})$ | 3.7  | 5.2  |
| $N_{300}(10^{19}/\text{cm}^3)$ | 2.28 | 2.78 |
| $N_{300}(10^{19}/\text{cm}^3)$ | 2.57 | 2.12 |
| Permittivity $\varepsilon$ | 8.8  | 8.7  |
| $\mu_n(\text{cm}^2/\text{v} \cdot \text{s})$ | 1500 | 500  |

Table 2. Physical Properties used in the Simulation

| Layers           | Thickness | Layers            | Thickness |
|------------------|-----------|-------------------|-----------|
| Si Substrate     | 486 $\mu$m | AlGaN            | 18 nm     |
| GaN Buffer       | 5 $\mu$m  | GaN cap           | 3 nm      |
| GaN              | 18 nm     | SiN passivation   | 100 nm    |

3. RESULTS & DISCUSSION

Electrical parameters have been analyzed for the designed bio-sensor. It is observed that sensitivity is more for transconductance technique when compared to drain current analysis.

3.1. $I_d-V_g$ Characteristics

The DC transfer characteristics ($I_d-V_g$) under gate to source bias voltage swept is analyzed. The characteristics are obtained for single channel by introducing different biomolecule in the Region of nanogap cavity. The figures 2a, figure 2b, figure 2c shows the change in output current with and without biomolecules for various biomolecules. It is evident from the figure that the drain current obtained with bio-molecule is higher. The drain current is selected as output metric used in this paper to calculate device sensitivity and compared the result with transconductance peak. Sensitivity with Drain Current is calculated using [1].

$$S = \frac{I(\text{With Biomolecule}) - I(\text{Without Biomolecule})}{I(\text{Without Biomolecule})}$$

![Figure 2. $I_d-V_g$ characteristics with and without bio-molecule. (a) Uricase. (b) Streptavidin. (c) Protein.](image)

Table 3. Sensitivity values from base paper formula

| Bio-molecule | Permittivity [1] | Sensitivity |
|--------------|------------------|-------------|
| Uricase      | 1.54             | 0.01753     |
3.2. Transconductance ($G_m$)

One of the distinct features of HEMT is peak is more with bio-molecule than without bio-molecule in the transconductance and gate voltage curve derived from $I_d$-$V_g$ measurement. Transconductance is the first-order drain current derivative with respect to constant drain voltage at the gate. Transconductance is chosen as performance metric used in this paper to measure the sensitivity of the device. The $G_m$- $V_g$ is extracted and depicted in the figure 3a, figure 3b, figure 3c, peak in $G_m$ are observed at gate voltage -3V. The curve shows a linear increase in as the values of dielectric constant increases. Sensitivity calculated from peak value of $G_m$ as calculated from drain current in [1], the sensitivity is written as

$$S = \frac{P(\text{With Biomolecule}) - P(\text{Without Biomolecule})}{P(\text{Without Biomolecule})}$$

![Figure 3. Transconductance with and without bio-molecule. (a) Uricase. (b) Streptavidin. (c) Protein.](image)

| Bio-molecule | Permittivity [1] | Sensitivity |
|--------------|-----------------|-------------|
| Uricase      | 1.54            | 0.2269      |
| Streptavidin | 2.1             | 0.2019      |
| Protein      | 2.5             | 0.1421      |

4. CONCLUSION

In this paper, detection of biomolecule using single channel AlGaN/GaN HEMT has been investigated by designing a simulation model. It is observed that higher sensitivity with transconductance analysis than with drain current for single channel HEMT based bio-sensor. Transconductance analysis has been done in this paper as a performance metric to measure sensitivity. Higher sensitivity values are obtained for biomolecule with lesser permittivity value. The results show better sensitivity which can be used in the future to perform combustion gas sensors, strain sensor and also chemical detectors.

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