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Development of GaN MOS-HEMTs transistors based biosensors for the detection of a novel SARS-Cov-19 Virus

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ABSTRACT

In this paper, the electrical biosensing device is modeled and analyzed for AlGaN/GaN metal-oxide-semiconductor high electron mobility transistors (MOS-HEMTs) based biosensors with different cavity heights. In this work, AlGaN/GaN metal-oxide-semiconductor high electron mobility transistors (MOS-HEMTs), with the cavity under the gate electrode is studied for its sensitivity analysis and viability as a biosensor. The analytical model has been developed to enhance the sensitivity of the electrical biosensing device, by using dielectric modulation approach with different cavity height (h_{cavity}). The analytical model results are in good agreement with Atlas-TCAD for output characteristics for the proposed cavity height h_{cavity}= (5, 7, 9, 11 and 13) nm. The maximum drain current on sensitivity which has been achieved in this work with h_{cavity}= 13 nm, while that better sensitivity with $h_{cavity=}$ 5 nm shift up to 81.67%. The MOS-HEMTs transistors based biosensor structures proposed are simulated and analyzed by using commercially available Atlas-TCAD and compared with developed analytical model.

KEY WORDS

Biosensors; AlGaN/GaN; MOS-HEMTs; Corona virus; SARS-CoV-2; Dielectric constant, sensitivity.

I. INTRODUCTION

The coronavirus disease 2019 (COVID-19) pandemic is considered a public health emergency of international concern [1]. Label-free detection of these virus using biosensors based metal-oxide-semiconductor high electron mobility transistors (MOS-HEMTs), due to its potential for low cost, smaller sizes, less fabrication complexity, and high sensitivities. Recently, gallium nitride (GaN) is emerging as one of the most promising semiconductor due to their wide band gap of 3.4 eV, large electron saturation velocity, high breakdown field (∼3 MV/cm), and can operate at high temperature (>300 K) [2, 3]. GaN based MOS-HEMTs has become more suitable for high power and high frequency applications, due to low capacitance and low gate leakage current [4].

Among them, the better studied structure is the AlGaN/GaN heterostructure with a two-dimensional electron gas (2DEG) formed at the heterointerface, which is induced by piezoelectric and spontaneous polarizations [5]. Besides, there are many novel insulators being used above the AlGaN barrier but two of the more popular insulators are HfO_2 [6] and Al_2O_3 [7], HfO_2 provides high dielectric constant but poor band offset to GaN. On the other hand, Al_2O_3 provides a large band offset to GaN but has a lower dielectric constant. A high dielectric constant is preferred to preserve maximum channel control but a large conduction band offset is favorable to reduce gate leakage current.

In this paper, the effect of the cavity height on electrical performance of AlGaN/GaN MOS-HEMTs based biosensors for the detection of a neutral biomolecules, especially viruses in the cavity region has been studied. We have simulated the electrical characteristics such as I_{ds}–V_{ds} and sensitivity parameters of AlGaN/GaN MOS-HEMTs for detection of a novel coronavirus. The rest of the paper is organized as follows. Section 2 presents the biosensor structure and analytical model used for simulation. In section 3 derives the expressions of the analytical model for the electrical properties. Results including output characteristics and sensitivity are discussed in section 4. Finally, the paper is included in conclusion section.

II. MOS-HEMTS BASED BIOSENSORS STRUCTURE AND ENERGY BAND DIAGRAM

Fig. 1 explines the process flow to use AlGaN/GaN MOS-HEMTs transistors based SARS-CoV-2 Virus biosensors [8]. The 2D schematic of vertical MOS-HEMTs transistors based biosensors designed for sensing SARS-CoV-2 is included in Fig. 1. Its consists from top to bottom, metal/SiO_2/Al_2O_3/AlGaN/undoped-AlN/undoped-GaN with a 2-DEG formed at the AlGaN/GaN heterointerface. GaN buffer layer is employed on Al_2O_3 substrate. The two oxide is inserted for reduce gate leackage current. A cavity has been created in the oxide which is used to detect the virus and hence change in the device electrical characteristics. The information obtained from the sample corresponds to either the concentration/activity of the presence of a coronavirus, which is transduced to an electrical signal via the field effect. The sensing process is occur in a dry environement.

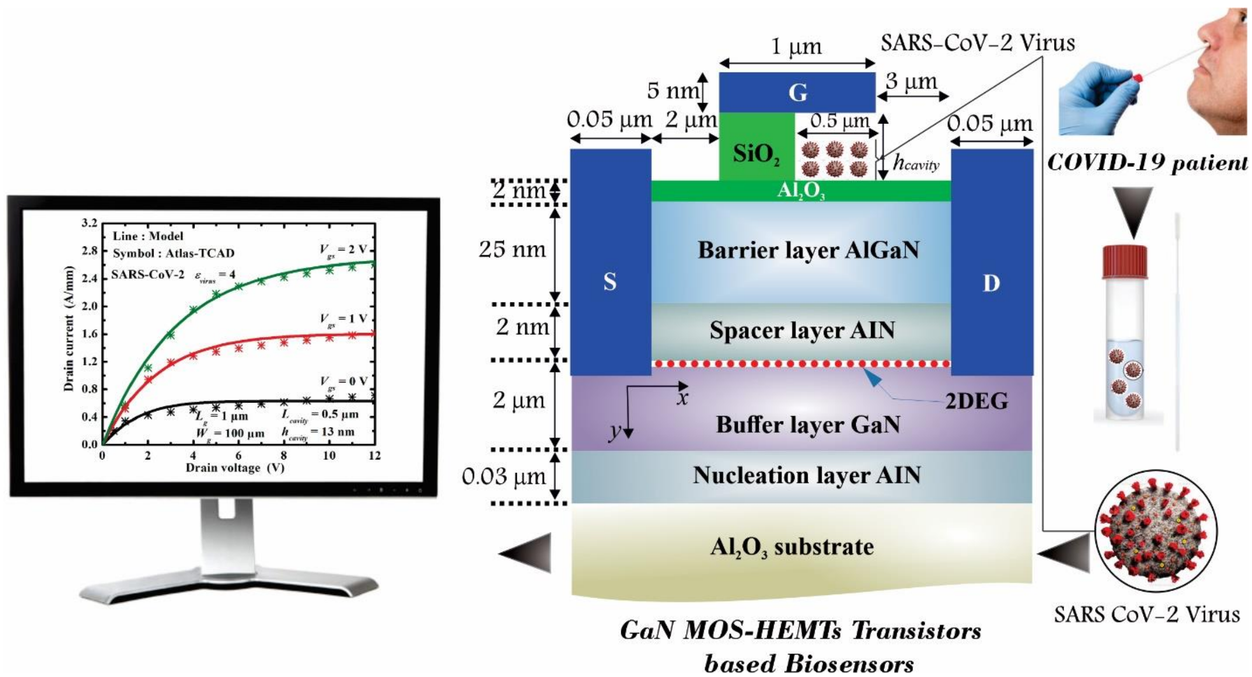

Fig. 1. Process flow to use AlGaN/GaN MOS-HEMTs transistors based SARS-CoV-2 Virus biosensors [8].

III. ANALYTICAL MODEL OF GAN MOS-HEMTS BASED BIOSENSORS

The basic operating principle of AlGaN/AlN/GaN MOS-HEMTs based biosensors is the modulation of charge density n_s at the heterointerface AlN/GaN, which is given by Eq. (1).

$$n_s = \frac{\sigma_{pol}}{q} - \frac{C_{eff}}{q^2}\left(q\phi_b + E_F - \Delta E_C\right) \tag{1}$$

Where σ_{pol} is the induced charge concentration due to spontaneous polarization, q is the elementary charge.

The total capacitance of GaN MOS-HEMTs based biosensors is expressed as

$$\frac{1}{C_{eff}} = \frac{1}{C_{region}} + \frac{1}{C_{MOS-HEMTs}} \tag{2}$$

Where $C_{region} = C_{cavity} + C_{SiO_2}$ (2a)

And the gate capacitance of the MOS-HEMTs transistors can be calculated as

$$\frac{1}{C_{MOS-HEMTs}} = \frac{1}{C_{AlGaN}} + \frac{1}{C_{AlN}} + \frac{1}{C_{Al_2O_3}} \tag{2b}$$

Where $C_{AlGaN} = \varepsilon_{AlGaN} / d_{AlGaN}$ is the capacitance of AlGaN barrier layer, $C_{AlN} = \varepsilon_{AlN} / d_{AlN}$ is the capacitance of AlN spacer layer, $C_{SiO_2} = \varepsilon_{SiO_2} / d_{SiO_2}$ is the capacitance of SiO_2 oxide layer, $C_{Al_2O_3} = \varepsilon_{Al_2O_3} / d_{Al_2O_3}$ is the capacitance of Al_2O_3 insulator layer and $C_{cavity} = \varepsilon_{virus} / h_{cavity}$ is the capacitance of cavity region [8].

Where d_{AlGaN}, d_{AlN}, d_{SiO_2} and $d_{Al_2O_3}$ are the thicknesses of the doped AlGaN layer, AlN spacer layer, SiO_2 and Al_2O_3 oxide layers, respectively. h_{cavity} is the cavity height and ε_{virus} is the dielectric constant of the virus.

And $q\phi_b$ represents the gate barrier height, E_F is the Fermi level position and ΔE_C is the conduction band offset. ε_{AlGaN} represents the dielectric constant of AlGaN barrier layer, it can be expressed as follows [9]

$$\varepsilon_{AlGaN} = 9.5 - 0.5x \ . \tag{3}$$

The threshold voltage of AlGaN/AlN/GaN MOS-HEMTs based biosensors without and with virus in the cavity region is strongly dependent on polarisation charge density, can be given by [10]

$$V_{th} = \gamma_{virus}\left[\phi_M - \chi_{AlGaN} + (1-\gamma_{virus})\phi_0 - \gamma_{virus}\frac{qN_D d_{AlGaN}}{C_{eff}} - \Delta E_C - \frac{q\sigma_{pol} d_{AlGaN}}{\varepsilon_{AlGaN}}\right] \tag{4}$$

Where $\gamma_{virus} = \dfrac{1}{1 + D_{it} q^2 / C_{eff}}$.

III.1 Drain current model

The model of the drain current can be formulated as [11]

$$I_{ds} = \frac{W_g \mu_0 C_{eff}}{L_g \rho}\left\{\sum_{i=1}^{6} k_i\left(\psi_{gd}^{i} - \psi_{gs}^{i}\right) + k_0 \ln\frac{\psi_{gd}}{\psi_{gs}}\right\} \tag{5}$$

Where $\psi_{gs} = (V_{gs} - V_{th} - V_s)^{1/3} + 2\theta$ and $\psi_{gd} = (V_{gs} - V_{th} - V_{ds})^{1/3} + 2\theta$ represents the channel potential for 2DEG, with a limit $V(x=0) = V_s = 0V$ and $V(x = L_g) = V_d = V_{ds} \cdot \rho = V_d - V_s / E_T L_g$ and $\theta = \lambda/3\left(C_{eff}/q\right)^{2/3}$..

Table I gives the physical constants terms obtained during the integration of the sheet charge density as defined by [11].

Tab 1. Constants terms. [11]

Constants	Expressions
k_0	$-288\theta^6$
k_1	$270\theta^5$
k_2	$-960\theta^4$
k_3	$200\theta^3$
k_3	$-700\theta^2$
k_4	39θ
k_5	-3

III.2 SENSITIVITY

The sensitivity parameter $S_{I_{ds}}$ of the biosensor can be defined in terms of drain current, ε_{air} = 1 is considered as a reference dielectric and the formula used for the drain current sensitivity is defined as follows [13]

$$S_{I_{ds}}(\%) = \frac{I_{ds(air)} - I_{ds(virus)}}{I_{ds(air)}} \times 100 \tag{11}$$

IV. RESULTS AND DISCUSSION

In this section, the simulation results of the analytical model in terms of the drain current and the sensitivity have been discussed and affirmed with those extracted by Atlas-TCAD. The AlGaN/AlN/GaN MOS-HEMTs based biosensors parameters with the corresponding values used for calculations are resume in Table 2.

Tab 2. List of physical model parameters used for simulations.

Parameters	Description	Values	Units	Refs.
E_T	Critical electric field	178×10^5	*V/m*	[14]
N_D	Doping concentration	1.5×10^{16}	m^{-3}	[14]
ϕ_M	Metal work function	5.1	*eV*	[14]
ϕ_0	Natural level potential	1.2		[14]
μ_0	Low field mobility	0.06	m^2/Vs	[14]
x	Al mole fraction	30%	/	[15]
σ_{pol}	Spontaneous polarization charge	3.38×10^{17}	m^{-2}	[16]
χ_{AlGaN}	AlGaN electron affinity	3.21	*eV*	[16]
L_g	Gate lenght	1	*µm*	[15]
W_g	Gate width	100	*µm*	[15]

Fig. 2 plots the output characteristics for AlGaN/GaN MOS-HEMTs based biosesnors for various cavity height h_{cavity}= (5, 7, 9, 11 and 13) nm at zero gate voltage with filled cavity (in air). As shows in Fig. 2, with the increase of cavity height, the drain current I_{ds} increases, this is due to the area of the virus is available to interact with underneath AlGaN barrier layer. A two dimensional (2D) calibrated simulation results of the analytical model are affirmed with those the extracted by Atlas-TCAD simulator.

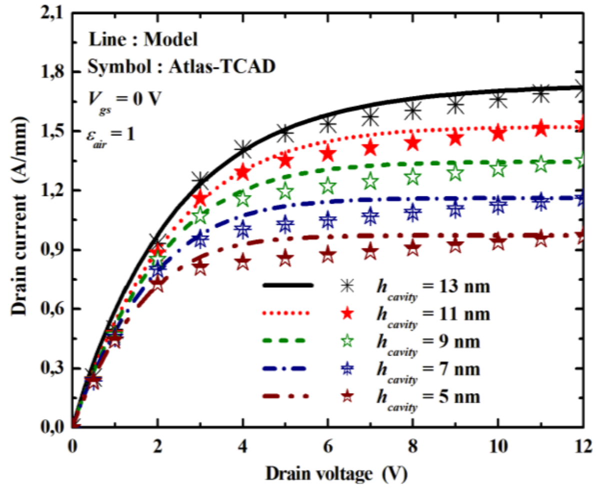

Fig. 2. Comparison of the output characteristics of GaN MOS-HEMTs biosensors with different cavity heights in the air (without virus).

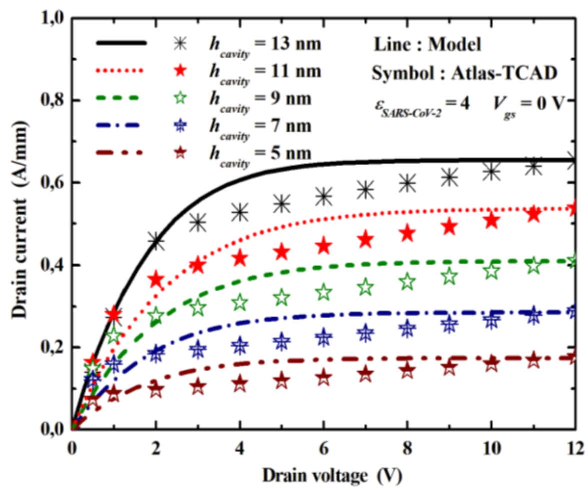

Fig. 3. Output characteristics of GaN MOS-HEMTs based biosensors with different cavity heights for $\varepsilon_{SARS\text{-}CoV\text{-}2} = 4$ of coronavirus 2 (SARS-CoV-2) dielectric constant.

A comparison of the output characteristics of the proposed AlGaN/AlN/GaN MOS-HEMTs transistors based biosensors calibrated simulation model and extracted by Atlas-TCAD with different cavity heights for $\varepsilon_{SARS\text{-}CoV\text{-}2} = 4$ is shown in Fig. 3. When the coronavirus is filled in the cavity region, there is improvement in the carrier concentration in the channel region which causes change in the drain current, that presents the GaN MOS-HEMTs transistors based biosensors are in good performance for biosensing applications. The maximum drain saturation current density of 0.65 A/mm is obtained at h_{cavity} = 13 nm to detect the presence of SARS-CoV-2. Further more, the sensitivity of GaN MOS-HEMTs transistors based biosensors with distinct cavity gap height are too calculated (Fig. 4), exposing that for high sensitivity applications, the cavity height should be lower. Thus, the nanogap inserted under the gate electrode indicated to improve sensitivity of 81.67% for SARS-CoV-2 virus with h_{cavity}= 5 nm.

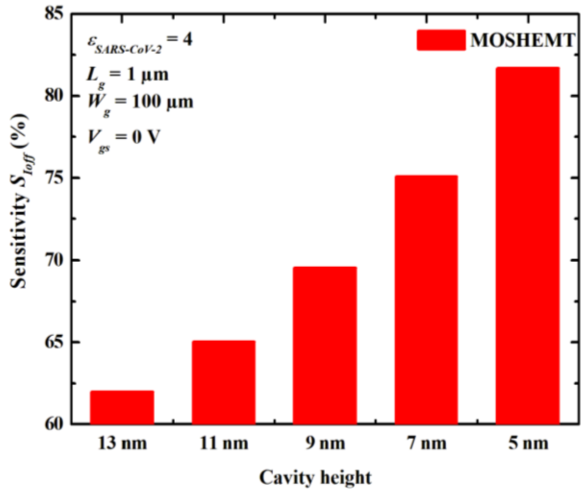

Fig. 4. Sensitivity parameter as a function of cavity height.

V. CONCLUSION

The sensitivity of the GaN MOS-HEMTs transistors based biosensors are relatively high, which has been obtained, which is very suitable for application in the field of ultra-sensitive. A maximum variation of the drain current density are observed when the virus introduced in the cavity region and also the variation in geometrical of the device reveal a properly chosen cavity height. Good agreement is observed between developed analytical model results and Atlas-TCAD simulation results for different gate lengths.Therefore, it is observed that the GaN MOS-HEMTs based biosensors show superior electrical performance the good sensitivity improve sensitivity of 81.67% for SARS-CoV-2 with h_{cavity}= 5 nm. Finally, it is concluded that with cavity height of 5 nm of the GaN MOS-HEMTs biosensors shows better electrical performance and high sensitivity intelligent biomedical applications.

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