# Study of Heterojunction Dual Gate Vertical TFET Applications in Gas Sensing

Karthik Nasani
*Department of ECE,National Institute of Technology,*
Silchar, Assam, India
*karthik21_rs@ece.nits.ac.in

Brinda Bhowmick
*Department of ECE, National Institute of Technology,*
Silchar, Assam, India
bbhowmick@ece.nits.ac.in

Puspa Devi Pukhrambam
*Department of ECE,National Institute of Technology,*
Silchar, Assam, India
puspa.devi@ece.nits.ac.in

***Abstract*— MOSFET based gas sensors have appeared as preferred choices for environmental safety across various sectors due to their durability, low cost, and rapid sensing capability. This work proposes the use of catalytic metals as gate contacts in Heterojunction Dual Gate Vertical TFET (HJ-DGVTFET) for gas sensing applications. For band-to-band tunnelling (BTBT), the vertical double-sided gate design offers superior gate controllability compared to traditional TFETs. The HJ-DGVTFET architecture is examined for hydrogen sensing using palladium (Pd) as the gate metal, ammonia sensing using cobalt (Co), oxygen sensing using silver (Ag) and carbon monoxide using platinum (Pt) metals as the gate contacts. Using the Sentaurus TCAD simulator, the characteristics of the suggested structure are examined regarding the surface potential, electric field, and energy bandgap graphs pertaining to the adsorption of gas molecules. For Ag, Co, Pd, and Pt as gate metals, simulation results of HJ-DGVTFET provide strong sensitivity calibrations ($S_{Idoff}$ ~ 7, 3.37, 2.75 and 2.18) and high $I_{don}/I_{doff}$ ratios (~ $9.14\times10^4$, $1.58\times10^4$, $7.11\times10^4$, and $3.65\times10^3$).**

***Keywords— HJ-DGVTFET, Gas sensor, Sensitivity***

## I. INTRODUCTION

Environmental, medical, and defence sectors are always in need of gas sensors to reduce the number of accidents and losses brought on by toxic gas leaks. Gases that are hazardous or even fatal when present in high amounts include carbon monoxide (CO), ammonia ($NH_3$), and various volatile organic compounds[1]. When these gases are detected in high concentrations, an immediate emergency evacuation is necessary. Generally speaking, gas sensors are required to guarantee safety, health, environmental quality, and operational efficacy. Semiconductor sensors can detect a extensive range of gases, including flammable, toxic, and other kinds.

The band-to-band (BTBT) tunnelling process, which regulates carrier transport to identify harmful gaseous compounds in the atmosphere, is the fundamental theory underlying TFET-based sensors. Because of its label-free detection, ability to scale to tiny devices, and quick responsiveness to changes in the chip's integration with mass manufacturing, TFET-based devices are becoming increasingly common in various gas sensing applications[2]. In this article, a double gate vertical TFET (HJ-DGVTFET) with an Inp-InGaAs layer at the source channel interface is constructed. Regarding gate controllability, the double-sided gate vertical architecture outperforms conventional TFETs for BTBT tunnelling [3,4].

The goal of this study is to create a gas sensor that can detect ammonia, oxygen, carbon monoxide, and hydrogen gases using a catalytic metal gate. The suggested sensor's sensing method is derived from the catalytic metal gate's work function modulation. This is because gas molecules deposit or absorb on the metal surface, changing its chemical composition and, consequently, the transistor's electrical parameters.

## II. DEVICE SPECIFICATIONS AND GEOMETRY

The two-dimensional schematic of the suggested InP/InGaAs heterojunction dual gate vertical TFET (HJ-DGVTFET) based gas sensor device is exposed in Fig.1[5]. The dimensions of the gadget are the same as those mentioned in the reference[5].The suggested gas sensor's detecting element, the gate electrode, is made of a highly reactive catalytic metal. For oxygen, ammonia, carbon monoxide, and hydrogen gas sensors, highly reactive catalytic metals such as silver (Ag), cobalt (Co), platinum (Pt), and palladium (Pd) have been employed. The catalytic gate metal changes its work function due to the reactivity of gas molecules on its perimeter. A high k dielectric substance provides insulation between the source and channel material to the gate electrode. An increase in work function causes a shift in the energy band diagrams, as seen in Fig.1. Because of the increased work function at the gate metal electrodes, the tunnelling barrier is highest in the case of platinum. The increased work function, which stimulates a higher concentration of p-type carriers, is the leading cause of energy band changes.

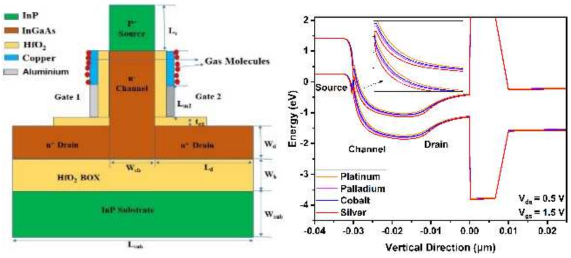

Fig.1. Structure and band diagram of HJ-DGVTFET based gas sensor

## III. RESULTS AND DISCUSSION

We have inspected the electric field, surface potential, and energy band characteristic curves to investigate the conduction operations of the suggested HJ-DGVTFET. Fig.2 illustrates that an increase in work function results in a more considerable electric field value being reached because of the channel's reduced charge flow mobility[6]. The Fermi–Dirac distribution function and the electron density of states are the gradient products that define the electric field. Because of the reduced mobility of charge flow in the channel region, Fig.2 illustrates how the electric field is progressively raised via the channel. The higher the work function, the stronger the resulting electric field. Consequently, we observe that silver, which has a far lower work function, exhibits a low electric field, while platinum, which has a more significant work function, shows a higher electric field.

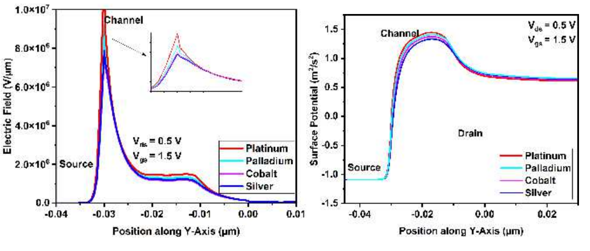

Fig.2. Electric field and channel potential graphs of the HJ-DGVTFET device

The electric field and associated potential fluctuation about the different gate metal contacts are shown in Table.1. The electric field value increases steadily in the drain zone, which is reflected in the potential curve as a constant, gradually dropping slope. The electric field in the channel reaches its most significant magnitude as we travel the length of the device. The electric field in the channel region decreases sharply before sloping practically continuously from there.

In the source zone along the channel, there is a modest rise near the tunnelling area, followed by a steady slope. In the drain and channel areas of the graph, there is a reversal when the potential is measured as the negative integral of an electric field.

Gas molecules react chemically at the metal gate surface, altering the catalytic gate's work function and producing considerable band bending and flat band voltage fluctuation. This modulation affects electrical outputs, including surface potential, drain current, etc. An rise in the tunnelling barrier causes the surface potential to drop, and this variation in the metal gate's work function is connected with it. With gate metals composed of Pt, Pd, Co, and Ag, respectively, The impact of the work function changes on a HJ-DGVTFET's surface potential is seen in Fig. 2..

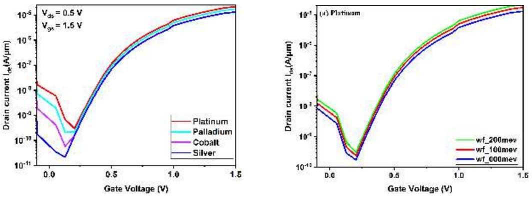

Fig.3. $I_{ds}$-$V_{gs}$ curves of the HJ-DGVTFET Gas Sensor

It has been determined that the $I_{ds}$-$V_{gs}$ curve is a crucial component for identifying the targeted gas molecules. Fig.3 illustrate the $I_{ds}$-$V_{gs}$ curve and the effects of altering the work function to 100 meV and 200 meV on the drain current characteristics for platinum as metal gate. The graphs suggest that off-current varies far more than on-current does. Compared to on-current, the variability of off-current is substantially greater. When the work function of the order of meV shifts, off current, is more affected than on current, which significantly increases sensitivity in the subthreshold zone. As a result, this device uses very little power, making it an inexpensive gas sensor. The only area where the BTBT tunnelling process occurs is in the source and slanted channel. Moreover, $V_{th}$ varies due to TFETs' decreased resistance to variations in the gate electrodes' work function. This causes a fantastic change in the $I_{doff}$ aspect.

The sensitivity equation for the suggested device is shown in equation (1).

$$S_{idoff} = \frac{S_{idoff(after\ gas\ adsorption)}}{S_{idoff(before\ gas\ adsorption)}} \qquad (1)$$

Table.1 list the sensitivity factors for the HJ-DGVTFET based sensor that uses silver, cobalt, palladium and platinum as the gate metal electrodes, respectively.

| Gate Electrode | Δwf | $I_{doff}$ (A/μm) | $I_{don}$ (A/μm) | $I_{don}/I_{doff}$ | $S_{Idoff}$ |
|---|---|---|---|---|---|
| Platinum (Pt) | Without gas | 3.47E-11 | 1.34E-05 | 3.86E+05 | 1.00 |
| | 100mev | 9.63E-11 | 1.78E-05 | 1.85E+05 | 2.78 |
| | 200mev | 2.43E-10 | 2.22E-05 | 9.14E+04 | 7.00 |
| Palladium (Pd) | Without gas | 4.12E-10 | 1.33E-05 | 3.23E+04 | 1.00 |
| | 100mev | 7.96E-10 | 1.77E-05 | 2.22E+04 | 1.93 |
| | 200mev | 1.39E-09 | 2.20E-05 | 1.58E+04 | 3.37 |
| Cobalt (Co) | Without gas | 1.12E-09 | 1.32E-05 | 1.18E+04 | 1.00 |
| | 100mev | 1.95E-09 | 1.76E-05 | 9.03E+03 | 1.74 |
| | 200mev | 3.08E-09 | 2.19E-05 | 7.11E+03 | 2.75 |
| Silver (Ag) | Without gas | 2.72E-09 | 1.31E-05 | 4.82E+03 | 1.00 |
| | 100mev | 4.21E-09 | 1.74E-05 | 4.13E+03 | 1.55 |
| | 200mev | 5.94E-09 | 2.17E-05 | 3.65E+03 | 2.18 |

Table.1. Sensitivity calculations of HJ-DGVTFET based gas sensor

The band diagram of the source-channel interface becomes less steep as the work function increases, which lowers the likelihood of tunnelling to the conduction band. A high enough potential barrier can either prohibit tunnelled electrons from passing through it or enable only electrons with sufficient energy to flow straight from the channel towards the drain. As a result, only electrons with enough energy are included in the BTBT process. Due to this, $I_{doff}$ decreases exponentially as WFV increases. Work function changes have little effect on the ON state current ($I_{don}$).According to Table.1, Platinum has a notably more considerable ON/OFF ratio value ($I_{don}/I_{doff}$) than others due to the relative values of their work functions.

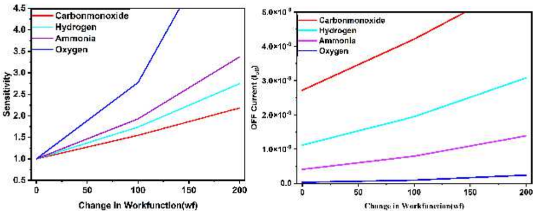

Fig.4. Sensitivity and Off current graphs of the HJ-DGVTFET device

The $I_{doff}$ sensitivity curvatures for several metals employed as gate electrodes are displayed in Fig.4. The computation of $S_{Idoff}$ is done using Equation (1). Because lower work function metals like silver and cobalt, have less of an influence from higher work function changes and, thus, less possible barrier effects, their OFF current sensitivity is significantly higher than that of Platinum. The graph shows that the sensitivity value grows as the OFF current diminishes.

## IV. CONCLUSION

The idea of a heterojunction dual gate vertical TFET as an extremely sensitive gas detector has been realized in this literature. Platinum, and Palladium, a highly reactive catalytic metals, can detect Carbonmonoxide, and ammonia with a high sensitivity of 7, and 3.37. In contrast, gate metals such as silver and cobalt produce sensitivity values between 2.18 and 2.75 for a minimal change in work function of 200 meV. These results demonstrate the efficacy of the suggested structure. The obtained $I_{don}/I_{doff}$ ratios illustrate the effectiveness of the proposed structure. It is possible to optimize further regarding channel-related factors and gate engineering. Studying the device behaviour in the subthreshold regime offers opportunities for greater sensitivity and can help develop a low-cost, low-power gas sensor with less on-chip space. Because of its vertical design, sharp doping gradient-free surface, and enhanced gate controllability, HJ-DGVTFET is a good option for further study on gas sensing devices.

## REFERENCES

1. R.N. Goswami, S. Poorvasha, B. Lakshmi, Tunable work function in Junctionless Tunnel FETs for performance enhancement. Aust. J. Electr. Electron. Eng. 15(3), 80–85 (2018). https ://doi.org/10.1080/14488 37X.2018.1525173
2. K.M. Choi, W.Y. Choi, Work-function variation effects of tunneling field-effect transistors (TFETs). IEEE Electron Device Lett. 34(8), 942–944 (2013). https ://doi.org/10.1109/LED.2013.2264824
3. D. López-Torres et al., Sensitivity optimization of a microstructured optical fiber ammonia gas sensor by means of tuning the thickness of a metal oxide nano-coating. IEEE Sens. J. 19(13), 4982–4991 (2019). https ://doi.org/10.1109/JSEN.2019.29013 61
4. A. Kumar, "Palladium-based trench gate mosfet for highly sensitive hydrogen gas sensor." Materials Science in Semiconductor Processing, 120, 105274 (2020).
5. K. Nasani, B. Bhowmick and P. D. Pukhrambam, "Study of parametric variations on Heterojunction Dual Gate Vertical TFET for performance Enhancement," 2023 IEEE Silchar Subsection Conference (SILCON), Silchar, India, 2023, pp.1-6, https://doi.org/10.1109/SILCON59133.2023.10405010
6. W.V. Devi, B. Bhowmick, P.D. Pukhrambam, "N+ pocket-doped vertical TFET for enhanced sensitivity in biosensing applications: modeling and simulation," IEEE Trans. Electron Devices, vol. 67, no. 5, pp. 2133– 2139, 2020.