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Research Article

Keywords: Dual Gate Thin Film Transistor, TIPS-Pentacene, HfO2 Dielectric, Glucose Oxidase, Threshold Voltage, Glucose Sensing

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Design and Simulation of a Glucose Oxidase-Functionalized Dual-Gate HfO_2/TIPS-Pentacene Organic Transistor for Glucose Sensing Application

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Abstract- In this work, a dual-gate organic thin-film transistor (DG-OTFT) architecture for potential glucose-sensing applications is simulated and investigated. The proposed device has a Ge/HfO_2 upper-gate stack, a poly-Si/SiO_2 lower-gate stack, Au source/drain contacts and a TIPS-pentacene active layer functionalised with glucose oxidase (GOx). The high-k HfO_2 dielectric is used to increase the gate-capacitance density, increase the electrostatic control and maintain practical dielectric thickness. In the simulation framework, glucose oxidation is modeled as a surface-potential or interfacial-charge perturbation which is proportional to the concentration of glucose, which acts as an additional modulation of the drain current and the apparent threshold voltage. Compact-model-based simulations are used to analyze transfer characteristics, output characteristics, electric-field distribution, channel-charge density, and electrical response due to glucose, using compact capacitance and threshold-voltage relations. The reported characteristics are examples of simulations and are not experimental measurements. The framework is physically consistent and lays the groundwork for future experimental fabrication, calibration, and biological validation of glucose sensors in the transistor.

Index Terms- Dual Gate Thin Film Transistor**,** TIPS-Pentacene, HfO_2 Dielectric, Glucose Oxidase, Threshold Voltage, Glucose Sensing

I. INTRODUCTION

In general, transistor-based biosensors measure biochemical events by converting changes at the sensing interface into measurable electrical response, which can be change in drain current, change in threshold voltage or transconductance. The fabrication of the organic thin-film transistors (OTFTs) can be achieved at low-temperature, and they can easily be incorporated to the flexible, lightweight, and disposable sensing platforms [1, 2], which make them particularly promising for such applications. For this reason, pentacene and TIPS-pentacene have been given great consideration in view of their relatively good hole-transport characteristics, and their dependence on gate bias, contact engineering, molecular packing, and semiconductor–dielectric interface [3]–[5].

The original dual-gate device combines a Ge/HfO_2 gate and a poly-Si/SiO_2 gate around a TIPS-pentacene active layer. The high-permittivity HfO_2 gate dielectric increases capacitance without aggressive oxide thinning, whereas the second gate provides independent control of the channel operating point. In the present work, this architecture is extended toward glucose sensing by placing a GOx-functionalized layer over the exposed source–drain channel. GOx provides selective enzymatic recognition, while the transistor provides electrical amplification of the resulting interfacial perturbation [6]–[10].

The scope is restricted to device design and simulation. No measured glucose sensitivity, detection limit, response time, or clinical performance is claimed. The contribution is the integrated physical framing of glucose oxidation, interfacial charge formation, and drain-current modulation in an HfO_2-based dual-gate organic transistor.

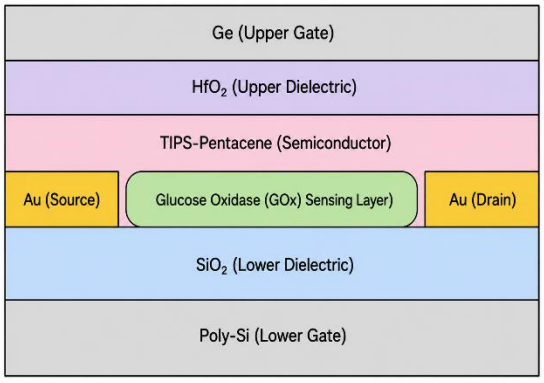


Figure. 1. Cross-sectional structure of the proposed Ge/HfO_2/TIPS-pentacene/SiO_2/poly-Si dual-gate transistor with Au contacts and a GOx-functionalized source–drain channel.

II. DEVICE STRUCTURE AND MATERIAL RATIONALE

A. Dual-Gate Architecture

The upper gate consists of Ge and HfO_2, while the lower gate consists of poly-Si and SiO_2. Au source and drain electrodes contact the TIPS-pentacene layer. The GOx film is positioned above the electrically active channel rather than inside the gate dielectric, allowing the biochemical reaction to influence the local channel potential while preserving the dual-gate electrostatic configuration.

B. High-k HfO_2 Gate Dielectric

The gate-capacitance density is

$$Cox = \kappa\, \varepsilon 0/tox \qquad (1)$$

where κ is the relative dielectric constant and tox is the actual thickness of the oxide film. For HfO_2/SiO_2 ratio at equal thickness, the ratio of κ's is approximately 20/3.9 = 5.13. The capacitance densities at these 50 nm are about 3.54×10^{-7} F/cm² and 6.91×10^{-8} F/cm², respectively. The increased HfO_2 capacitance enhances the control of the gate over the channel and enables the operation of the device at lower voltages [11]–[13].

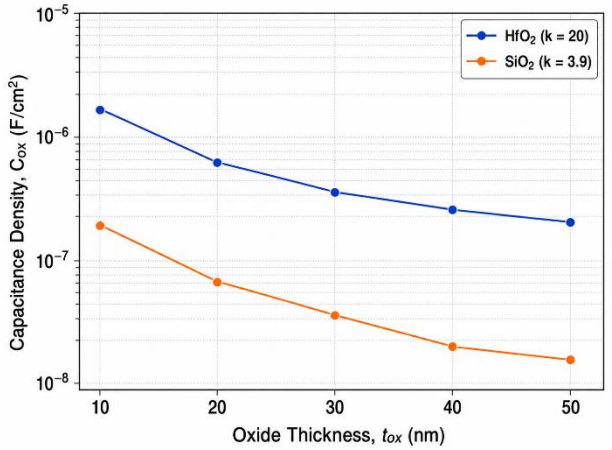


Figure. 2. Calculated oxide-capacitance density versus physical thickness for HfO_2 and SiO_2 using (1).

III. GOx-CHANNEL SENSING MECHANISM

A. Enzymatic Reaction

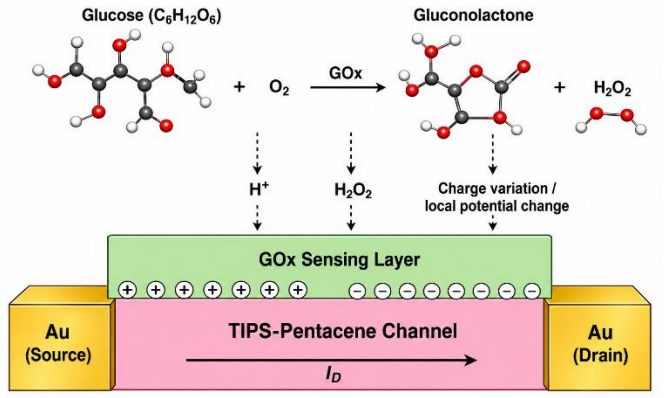


Figure. 3. Proposed coupling of GOx-mediated glucose oxidation to interfacial charge and drain-current modulation in the TIPS-pentacene channel.

GO_x catalyzes glucose oxidation in the presence of oxygen:

$$Glucose + O_2 \rightarrow (GOx)\ gluconolactone + H_2O_2 \qquad (2)$$

Gluconolactone subsequently hydrolyzes to gluconic acid. The reaction can modify proton concentration, ionic distribution, peroxide concentration, and the electrochemical potential near the organic semiconductor [6], [8], [14].

B. Equivalent Electrical Representation

A standard semiconductor simulator does not explicitly solve enzymatic kinetics, the GOx reaction is represented through an equivalent concentration-dependent surface charge or sensing potential:

$$Q_{surf}(CG) = Q0 + \Delta QGOx(CG) \qquad (3)$$

$$V_{sense}(CG) = V0 + \Delta VGOx(CG) \qquad (4)$$

Here CG denotes glucose concentration. The device response can be written using an effective gate voltage,

$$VGS,_{eff} = VGS + \eta \Delta V_{sense},$$

where η is the biochemical-to-channel coupling factor. For a p-channel transistor in saturation, the sign and magnitude of the current shift depend on the polarity of the generated interfacial charge, the dual-gate biases, trap occupancy, ionic screening, and the stability of TIPS-pentacene in the sensing environment.

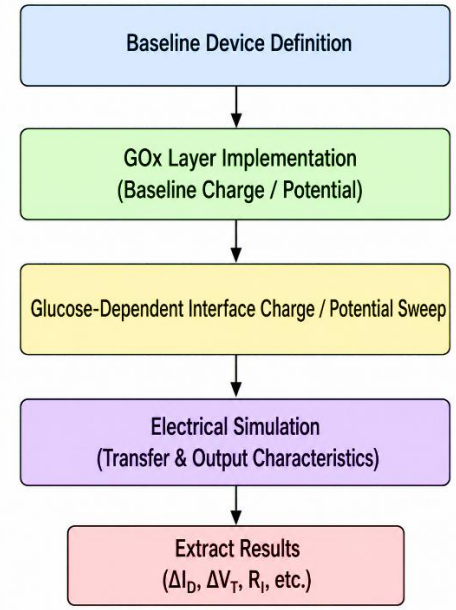


Figure. 4. Simulation sequence used to introduce the baseline device, GOx interfacial state, glucose-dependent perturbation, and electrical-response extraction.

IV. DEVICE-SIMULATION FRAMEWORK

A two-dimensional simulation domain contains Ge, HfO_2, TIPS-pentacene, Au contacts, SiO_2, poly-Si, and an equivalent GOx interface. The baseline transistor is solved first. A fixed enzyme-layer charge is then introduced, followed by a sweep of glucose-equivalent surface charge or potential. At each condition, transfer and output curves, threshold voltage,

channel-hole density, electric field, and gate leakage are extracted.

The analytical threshold relation is represented as

$$VT = \varphi GC - 2\varphi F - QB/Cox - Qox/Cox \qquad (6)$$

Using the original work function values from this study, the analytically calculated baseline threshold voltage values are close to −1.644 V for the Ge/HfO_2 gate stack and close to −0.791 V for the poly-Si/SiO_2 gate stack. These values are theoretical reference values based on the analytical model. However, for real fabricated devices there are a number of other factors, such as semiconductor morphology, source/drain contact properties, interface trap states, environmental humidity, and the properties of glucose oxidase (GOx) immobilization that can affect the effective threshold voltage.

V. SIMULATION RESULTS AND DISCUSSION

A. Transfer Characteristics

The illustrative transfer characteristics given in Fig. 5 show a progressive shift of the transfer characteristics as a result of the increase in the equivalent interfacial charge created by the addition of GOx. The results shown are physics-based simulation to show the electrical response from biochemical interaction at the sensing interface and not a calibrated glucose measurement. A change in the threshold voltage region and the corresponding shift in apparent turn-on voltage are observed demonstrating the feasibility of threshold-voltage sensing and the underlying mechanism by which changes in the charge at the interface affect the transistor operation.

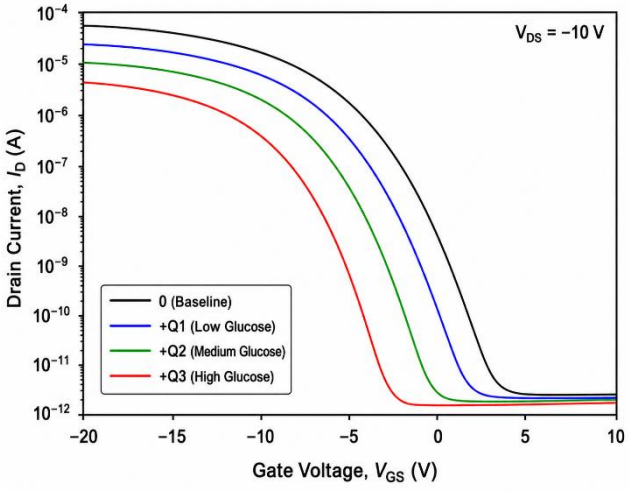


Figure. 5. The transfer characteristics for a baseline case and various interfacial charge conditions for glucose are illustrated by simulation results at VDS = −10 V.

B. Output Characteristics

The simulated drain current shows a progressive increase in magnitude for the assumed biochemical perturbation in the adopted modeling framework under a fixed negative gate bias. The output characteristics remains clearly saturated, indicating that the sensing response observed is mainly due to modulation of the channel charge and electrostatic conditions, rather than to a purely ohmic conduction process.

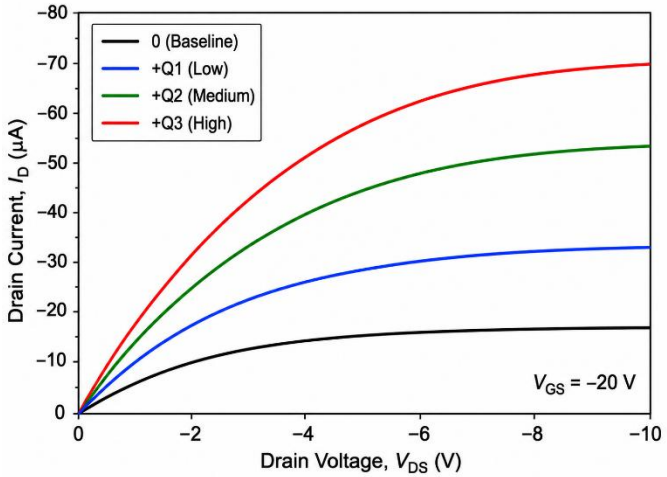


Figure. 6 Simulated output characteristics at VGS=−20 V, under baseline and increasingly increased glucose-equivalent interfacial charge conditions.

C. Extracted Sensing Metrics

The threshold-voltage shift and relative-current response are defined as

$$\Delta VT = VT(CG) - VT(0) \qquad (7)$$

$$RI = [ID(CG) - ID(0)] / ID(0) \times 100\% \qquad (8)$$

Figures 7 and 8 show the normalized simulation trends generated with an equivalent input concentration to test the device response. The concentration scale is used only to simulate, and is not a calibration based on experimental data of the blood-glucose concentration. To establish a glucose calibration, a quantitative measurement would need to be performed using buffer standards with well-defined concentrations, blank-noise characterization, multiple device replicates, and validation against an established reference glucose measurement technique.

D. Electric-Field and Channel-Charge Distribution

Figure 9 compares the simulated baseline and high-perturbation conditions across the vertical device structure. The introduced interfacial perturbation modifies the electric-field distribution within the HfO_2/TIPS-pentacene region and results in an increased simulated hole concentration in the vicinity of the active channel.

These observations are consistent with the proposed sensing mechanism, in which the glucose oxidase (GOx)-induced interfacial potential variation influences channel charge accumulation and subsequently produces a measurable change in the drain current.

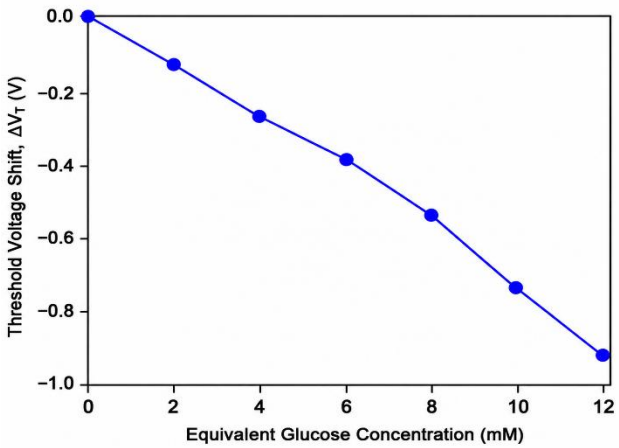


Figure. 7. Simulated threshold-voltage shift versus equivalent glucose concentration used in the simulation sweep.

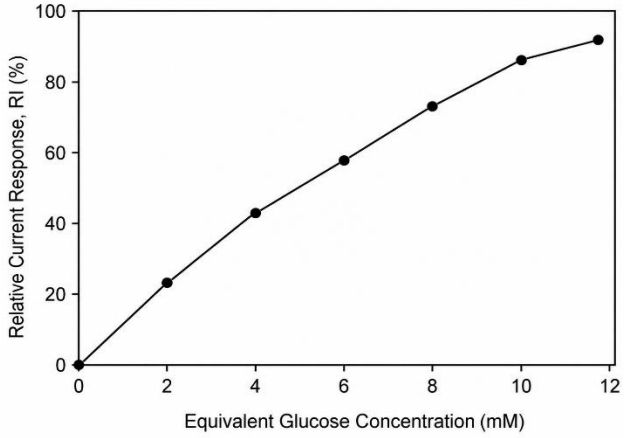


Figure. 8. Simulated relative drain-current response versus equivalent glucose concentration.

The results are intended to illustrate the underlying device physics within the simulation framework and should not be interpreted as direct experimental evidence.

VI. POTENTIAL GLUCOSE-SENSING PROTOCOL

The baseline ID at fixed drain and dual-gate biases in blank buffer would be initially recorded in a practical measurement. Next, a sample containing glucose would come into contact with the immobilised GOx layer. An experimentally obtained calibration curve would be used to translate the resulting ΔID or ΔVT to concentration following reaction and stabilisation. The lower gate may set the operating point, while the HfO_2 gate may provide stronger electrostatic control and compensate device drift.

Direct exposure of an unprotected TIPS-pentacene layer to blood is not assumed. A realistic implementation may require a hydrogel or cross-linked GOx matrix, ion-permeable protective membrane, microfluidic chamber, passivated source/drain contacts, and possibly an extended-gate configuration. Selectivity must be assessed against uric acid,

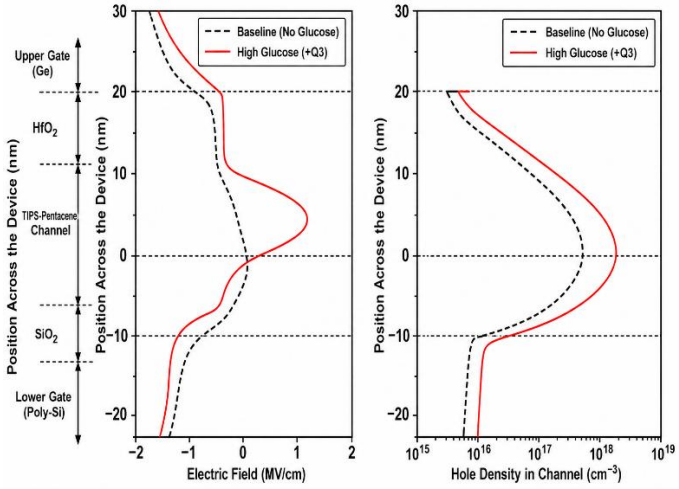


Figure. 9. Simulated electric-field distribution and channel-hole-density profiles for baseline and high glucose-equivalent interfacial perturbation.

ascorbic acid, lactate, urea, pH, temperature, oxygen concentration, and ionic-strength changes.

VII. LIMITATIONS

The present results are simulation-based. The enzyme-to-channel coupling coefficient, immobilization-induced mobility change, aqueous stability, response polarity, dynamic response, sensitivity, detection limit, repeatability, and shelf stability are unknown. Experimental fabrication and calibration are therefore essential before claiming glucose-sensor performance. The plotted values should be treated as device-design targets and trend demonstrations only.

VIII. CONCLUSION

An HfO_2-based dual-gate TIPS-pentacene transistor with a GOx-functionalized source–drain channel has been formulated as a potential glucose sensor. HfO_2 provides substantially higher capacitance than SiO_2 at equal thickness, while the second gate enables operating-point control. GOx-mediated oxidation is coupled to the transistor through an equivalent interfacial charge or surface potential, producing simulated changes in transfer curves, output current, threshold voltage, electric field, and channel-hole density. The study provides a clear mapping of the device to the application without making any experimental claims of glucose detection. Next step involves fabrication, immobilization of GOx, electrical calibration, interference testing and validation with standard glucose samples.

IX. DECLARATIONS

Funding: No funding was received for this work.

Ethics Declaration: Ethics declaration: Not applicable.

Ethics, Consent to Participate, and Consent to Publish:
Ethics, Consent to Participate, and Consent to Publish declarations: Not applicable.

Competing Interests:
The authors declare that they have no competing interests.

REFERENCES

[1] X. Ma, H. Chen, P. Zhang, et al., "OFET and OECT, two types of organic thin-film transistor used in glucose and DNA biosensors: A review," IEEE Sensors Journal, vol. 22, no. 12, pp. 11405–11414, 2022, doi: 10.1109/JSEN.2022.3170405.

[2] C. Y. Wei, F. Adriyanto, Y. J. Lin, et al., "Pentacene-based thin-film transistors with a solution-process hafnium oxide insulator," IEEE Electron Device Letters, vol. 30, no. 10, pp. 1039–1041, 2009, doi: 10.1109/LED.2009.2027067.

[3] D. Gupta, N. Jeon, and S. Yoo, "Modeling the electrical characteristics of TIPS-pentacene thin-film transistors: Effect of contact barrier, field-dependent mobility, and traps," Organic Electronics, vol. 9, pp. 1026–1031, 2008, doi: 10.1016/j.orgel.2008.08.005.

[4] P. G. Schroeder, C. B. France, J. B. Park, and B. A. Parkinson, "Energy level alignment and two-dimensional structure of pentacene on Au(111) surfaces," Journal of Applied Physics, vol. 91, no. 5, pp. 3010–3014, 2002, doi: 10.1063/1.1448399.

[5] C. Baldacchini, C. Mariani, and M. G. Betti, "Molecular gap and energy-level diagram for pentacene adsorbed on filled d-band metal surfaces," Applied Physics Letters, vol. 89, Art. no. 152119, 2006, doi: 10.1063/1.2360892.

[6] C. Ravariu, A. Arora, F. Babarada, et al., "Optimized technologies for cointegration of MOS transistors and glucose oxidase enzymatic biosensors," Biosensors, vol. 11, no. 12, Art. no. 497, 2021, doi: 10.3390/bios11120497.

[7] A. K. Mishra, S. K. Jha, S. K. Gupta, and R. Chandra, "CuO nanoparticles decorated ZnO nanorods based extended-gate field-effect transistor for enzyme-free glucose sensing," IEEE Transactions on NanoBioscience, vol. 21, no. 1, pp. 3–9, 2022, doi: 10.1109/TNB.2021.3112539.

[8] M. Farahmandpour, M. A. Y. Behnam, and M. H. R. Ghoreishi, "Blood glucose sensing by back-gated transistor strips sensitized with CuO hollow spheres decorated with reduced graphene oxide," Scientific Reports, vol. 12, Art. no. 21688, 2022, doi: 10.1038/s41598-022-26124-4.

[9] W. Wang, X. Ma, H. Chen, et al., "High-performance field-effect-transistor glucose biosensors based on bimetallic Ni/Cu metal-organic frameworks," Biosensors and Bioelectronics, vol. 171, Art. no. 112736, 2021, doi: 10.1016/j.bios.2020.112736.

[10] A. Song, M. J. Kim, D.-J. Yi, et al., "Control of sensitivity in metal oxide electrolyte-gated field-effect transistor-based glucose sensor by electronegativity modulation," Scientific Reports, vol. 14, Art. no. 27251, 2024, doi: 10.1038/s41598-024-76885-x.

[11] S. H. Lo, D. A. Buchanan, Y. Taur, and W. Wang, "Quantum-mechanical modeling of electron tunneling current from the inversion layer of ultra-thin-oxide nMOSFETs," IEEE Electron Device Letters, vol. 18, no. 5, pp. 209–211, 1997, doi: 10.1109/55.568766.

[12] G. Ribes, J. Mitard, M. Denais, et al., "Review on high-k dielectrics reliability issues," IEEE Transactions on Device and Materials Reliability, vol. 5, no. 1, pp. 5–19, 2005, doi: 10.1109/TDMR.2005.845236.

[13] W. T. Wondmagegn, N. T. Satyala, I. Mejia-Silva, et al., "Experimental and modeling study of the capacitance-voltage characteristics of a pentacene/parylene MIS capacitor," Thin Solid Films, vol. 519, pp. 4313–4318, 2011, doi: 10.1016/j.tsf.2011.02.014.

[14] P. Zhang, S. Zhao, H. Wang, et al., "Relation between interfacial band bending and electronic properties in organic semiconductor pentacene," Advanced Electronic Materials, vol. 3, Art. no. 1700136, 2017, doi: 10.1002/aelm.201700136.