JOURNAL OF NANO- AND ELECTRONIC PHYSICS
Vol. **13** No 2, 02029(5pp) (2021)
ЖУРНАЛ НАНО- ТА ЕЛЕКТРОННОЇ ФІЗИКИ
Том **13** № 2, 02029(5cc) (2021)

Performance Assessment of a New Gaussian-doped Junctionless ISFET: A Numerical Study

Khadidja Dibi[1,2,*], Zohir Dibi[1], Ahmed Bouridane[2]

[1] *Laboratory of Advanced Automatic and Analysis Systems (LAAAS), Department of Electronics, University of Batna2, 05000 Batna, Algeria*
[2] *Department of Computer and Information Sciences, Northumbria University, Newcastle, UK*

(Received 14 November 2020; revised manuscript received 15 April 2021; published online 20 April 2021)

Recently, a major research focus has been devoted to the development of ISFET sensors for future biomedical, environmental and food-processing sensing applications using special taste sensors based on Ion Sensitive Field-Effect Transistor (ISFET) technology. This has resulted in various sensor designs attracting increased interest by the research community as demonstrated by a number of proposed designs. In this work, we propose to relax the ISFET concept by dropping the junction of the ISFET design, hence proposing a new JL ISFET (junctionless ISFET) sensor structure based on a Gaussian doping (GD) profile strategy. The electrical parameters and performances of the proposed *pH* sensor are numerically analyzed, where the sensitivity properties are reported. In this context, we address the influence of a modified channel doping profile with a Gaussian shape on the variation of the sensor Figures of Merit (FoM) parameters, such as power consumption, thermal stability, leakage current and sensitivity. The proposed design also exhibits an enhanced threshold voltage shift with a varying *pH* of the solution resulting in improved electrical and sensitivity behavior characteristics. The results have demonstrated that the proposed design provides promising pathways for enhancing the ISFET performances as compared to the conventional FET-based sensor counterparts where the recorded sensitivity reaches 66.3 mV/*pH*. Furthermore, the results obtained clearly show the excellent *pH* modulation of the channel conductivity performance. Therefore, the proposed structure demonstrates the effectiveness of the adoption of a Gaussian-doped JL ISFET design as a potential candidate for high-performance and ultra-low power FET-based sensing applications as demonstrated from the proportional improvement in both the device electrical performance and the sensor sensitivity.

Keywords: Junctionless ISFET, *pH*, Taste sensor, Gaussian-doping profile, Sensitivity.

DOI: 10.21272/jnep.13(2).02029 PACS numbers: 87.85.Fk, 07.07.Df

1. INTRODUCTION

Nowadays, monolithic co-fabrication of biomaterials and microelectronic devices has drawn a surge of research focus to develop efficient devices for biomedical applications [1-3]. The emerging field of chemical and biomedical sensors, a technology that uses microelectronic devices for elaborating effective chemical or biomedical information transfer, is promising for a novel application paradigm in chip-level diagnostic [1-4]. The rapid progress in the design of microelectronic devices is forecasted to markedly expand the possibilities of using CMOS-based technology for low power consumption and high-performance biomedical sensing applications [2]. Accordingly, considerable efforts have been devoted to the development of high-performance sensors, and consequently, researchers have turned their focus on exploring alternative strategies that can provide not only highly integrated sensors based on silicon-on-insulator (SOI) platform, but also new pathways for reducing the power dissipation. A variety of architectures have been proposed to design efficient biomedical sensors offering improved sensitivity [5, 6]. Despite the maturity of these sensors, there are still some major roadblocks such as CMOS incompatibility, low sensitivity and high-power consumption that can consequently influence the performance of the biomedical diagnostic.

ISFET sensor, which is described by a monolithically integrated version of the Ion Sensitive membrane and FET transistor, demonstrates several benefits such as label-free detection, fast response, and compatibility with CMOS fabrication technologies [7]. These advantages make these devices an outstanding building block for efficient biomedical or chemical sensing systems. However, the sensitivity of the conventional ISFET sensors is limited by the Nernst response of 59 mV/*pH*, which is considered the most common challenge leading to induce signal-to-noise problems, merged with several undesired effects, including thermal reliability and large leakage current. For this purpose, a major research focus has been devoted to the development of ISFET sensors, aiming to beat the Nernst limit, while maintaining reduced power consumption [5, 6]. Accordingly, various strategies based on multigate configuration, thin-film transistors, alternative sensitive membranes and design optimization have been proposed to enhance the device performance [5-8]. Although these aspects have opened up exciting opportunities for reaching promising sensitivity values, it is still costly and sophisticated to boost the sensitivity/fabrication cost ratio of ISFETs by synthesizing new membrane layers using new nanotechnology-based approaches. Moreover, as the CMOS technology moves toward submicron technologies, the realization of abrupt junctions at the source and drain sides becomes extremely complicated; otherwise, the fabrication cost will be increased because of the requirement of high-cost thermal treatments [9-11]. Besides, the low dimension silicon-based *pH* sensors cannot be ready to follow the actual downscaling capabilities since it has not yet proven a noticeable benefit over the conventional coun-

* k.dibi@univ-batna2.dz

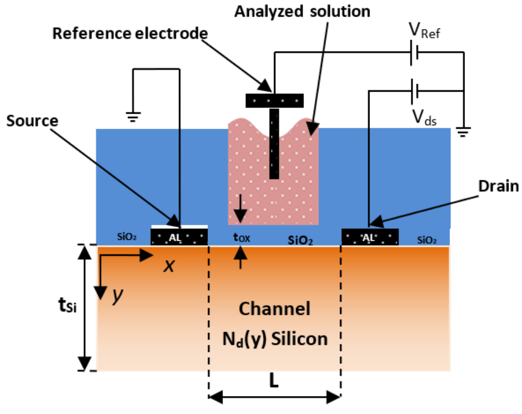
terparts concerning the device reliability and power consumption aspects [10]. Therefore, in light of the fact that ion-selective FET-based sensors can be used as a versatile diagnostic tool for biomedical applications, breaking the sensor Nernst response, while avoiding the abovementioned undesired effects is strongly required. In this perspective, in the present work, a new design approach based on combining doping profile engineering aspect and JL FET structure is proposed to improve the sensor performances and reduce the fabrication cost by removing the abrupt junctions in the device. The obtained results show that the optimized Gaussian doped JL ISFET design could open up a new route for the development of *pH* sensors suitable for future biomedical, environmental and food-processing sensing applications using especially taste sensors.

2. DESIGN OF THE GAUSSIAN DOPED JL ISFET

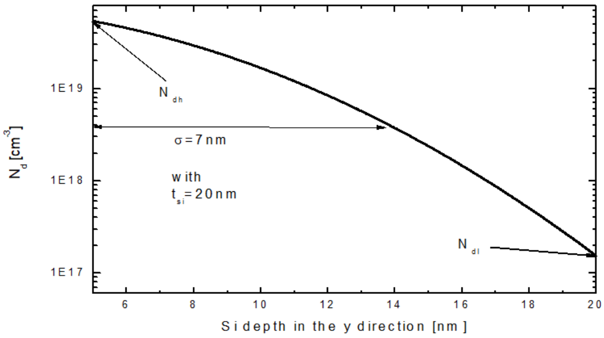
In the conventional JL FET design, the channel is doped using a uniform doping profile with high concentration values, but without source/channel and drain/channel metallurgical junctions. In our proposed JL ISFET sensor design, we consider a modification of the channel doping profile using a Gaussian shape in the vertical direction, where the maximum doping N_{dh} was suggested at the top interface between the oxide layer (SiO_2) and the silicon channel and then gradually decreased to attain its lower value N_{dl} in the depth of the silicon substrate.

The electrolyte potential is considered with KCl buffered Ag/AgCl reference electrode. From a design point of view, the modified channel doping profile is considered technically feasible and only necessitates appropriate control of both the energy for ion-implantation and the phosphor concatenation during the fabrication process. In our study, the cross-sectional view of the proposed JL ISFET sensor with engineered Gaussian doping (GD) profile is shown in Fig. 1a, where L is the channel length of the sensor and $N_d(y)$ represents the channel doping concentration in the vertical direction. The ISFET membrane is suggested with SiO_2 for which t_{ox} denotes its thickness. In this work, the channel doping concentration is given by a Gaussian distribution as shown in Fig. 1b. The standard deviation (σ) associated with the suggested GD profile can be varied to achieve better sensing characteristics of the ISFET-based *pH* sensor, while the channel length L is fixed at 200 nm. In addition, an ultrathin channel (t_{si} = 20 nm) is considered to ensure efficient control of the channel conductivity behavior when the electrolyte *pH* is varied. The idea behind this modified and proposed doping profile is to modulate the electric field and potential distributions in the sensor channel in order to improve the device performances in terms of electrical behavior and the *pH* sensitivity properties.

In our simulation study, ATLAS 2D device simulator has been chosen and exploited for the numerical simulations, where the well-known drift-diffusion transport model is used to model the carrier transport across the transistor channel including the GD profile.



a



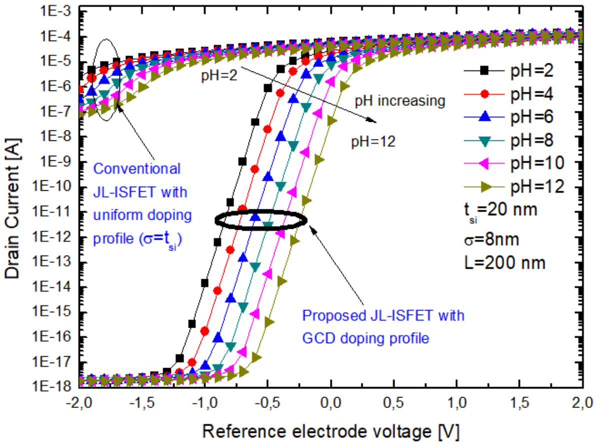
b

Fig. 1 – (a) Cross-sectional view of the proposed JL ISFET with GD profile, (b) Gaussian channel doping profile

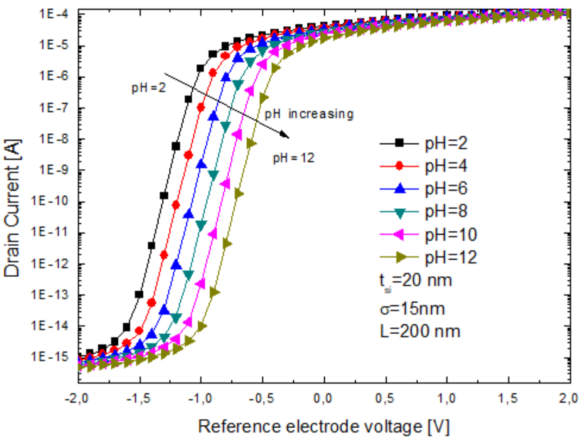
Moreover, recombination models (Shockley-Read-Hall (SRH), Auger and surface recombination) are also adopted. The parallel electric field dependence is used to include the velocity saturation effect in our numerical model. Further, the carrier mobility degradation as a function of the channel doping level is also considered due to the high concentration used in the JL design. It is worth mentioning that the channel doping associated with the investigated *pH* sensors is taken more than 10^{18} cm^{-3} in order to avoid the Schottky barrier effect at the substrate/back contact interface.

3. RESULTS AND DISCUSSION

The assessment of the electrical modulation performance associated with the proposed *pH*-ISFET design based on a GD profile allows exploring its strength as compared to the conventional counterparts. In this context, Fig. 2a compares the *pH* dependence of the drain current provided by the proposed design and the conventional JL ISFET sensor with L = 200 nm, t_{si} = 20 nm and $N_d = 10^{18}$ cm^{-3}. It can be observed from this figure that the proposed design based on the GD profile shows an excellent *pH* modulation of the channel conductivity as compared to the conventional structure, where it exhibits an enhanced threshold voltage shift with varying the *pH* of the solution, emphasizing its improved electrical and sensitivity behavior. These benefits are mainly attributed to the role of the channel doping engineering paradigm in modulating the transistor electrostatic behavior, thus promoting enhanced sensitivity of the FET-based sensor.



a



b

Fig. 2 – I_{ds}-V_{gs} characteristics for different *pH* values of (a) the con-ventional and the proposed JL ISFETs with the amended doping profile with $N_{dh} = 5 \times 10^{18}$ cm^{-3}, $N_{dl} = 10^{17}$ cm^{-3} and applied drain voltage $V_{ds} = 0.1$ V; (b) the proposed design with $N_{dh} = 5 \times 10^{18}$ cm^{-3}, $N_{dl} = 5 \times 10^{17}$ cm^{-3} and the standard deviation value of 15 nm

On the other hand, the investigated JL TFET sensor with GD aspect opens up the route for reaching a very low OFF-state current ($I_{OFF} = 3.24 \times 10^{-9}$ A) as compared to the conventional JL design, which offers exciting opportunities to avoid using filters to suppress noise effects for the read-out circuits. In fact, the JL design operates on the basis of volume conduction, surface accumulation, and depletion operation mechanisms. In the OFF-state, the sensor works in the volume conduction mode owing to the high doping level of the sensor channel, which induces a high diffusion current as it is shown in Fig. 2 ($I_{OFF} = 1.62 \times 10^{-5}$ A). This phenomenon can greatly affect the ISFET electrical performances, causing high power dissipation. Interestingly, the use of the GD profile can allow improved control of the channel conductivity in the OFF-state, where the relatively low doping level in the channel depth can induce partial depletion. This effect can contribute enormously to reducing the diffusion current, thus reducing power consumption of the sensor. Fig. 2b depicts the transfer characteristics of the ISFET device for different *pH* values and with higher standard deviation of 15 nm. It can be seen from this figure that by increasing the standard deviation of the GD profile, the *I-V* characteristics are shifted to negative voltages, thus indicating the role of the suggested channel doping engineering aspect in modulating the potential distribution over the sensor channel. This leads to modulation of the device subthreshold behavior and induces significant changes concerning the JL ISFET threshold voltage, thus confirming the fact that the standard deviation should be optimized to reach better sensitivity values. In addition, by increasing the standard deviation to 15 nm, a higher OFF-state current is recorded as compared to that of the device with $\sigma = 8$ nm. This phenomenon can be explained by the increased doping level in the channel depth, promoting an enhanced diffusion mechanism.

Now we get more insights concerning the effect of the standard deviation on the electrical behavior of the studied *pH* sensor. Fig. 3 illustrates the variation of the threshold voltage as a function of the *pH* of the analyzed electrolyte for the conventional JL ISFET, inversion mode (IM) ISFET, and the proposed design with dissimilar standard deviation ranging from 5 to 15 nm. It can be noticed from this figure that the investigated designs exhibit a linear response with the *pH* variation. Moreover, the JL ISFET designs demonstrate lower threshold voltage values as compared to the conventional IM ISFET, which is mainly due to the discrepancies of the transport mechanisms associated with both IM and JL structures. Besides, the proposed design with the GD profile shows higher threshold voltage values when compared to the conventional JL ISFET device. This is mainly due to the effect of the engineered doping profile resulting in significant changes in the electric field distribution over the channel. Therefore, the obtained results in terms of the device electrical behavior demonstrate that the proposed GD profile can also influence the *pH*-ISFET sensitivity performances. Aiming at analyzing the influence of the GD profile on the sensing properties of the investigated JL ISFET sensor, the effect of standard deviation of the Gaussian shape on the device sensing characteristics has been carried out. In this framework, the ISFET sensitivity (in mV/*pH*) is typically considered as the most important figure of merit (FoM) used to assess the sensor response to the *pH* of the analyzed elect. This performance metric is useful because it not only provides a global insight regarding the device sensing capabilities, but also enables comparing dissimilar *pH* sensor designs, where ISFETs are required to possess high sensitivity.

Accordingly, Fig. 4 depicts the sensitivity of the investigated JL ISFET design based on the channel doping engineering aspect against the standard deviation of the proposed GD profile. This figure outlines the ability of the proposed design with a GD shape to enhance the device sensing characteristics, where, by taking the standard deviation of 8 nm, a high sensitivity exceeding 66 mV/*pH* is achieved. This sensitivity value is higher than that of the conventional JL ISFET sensor, yielding a relative improvement of 16 %. This enhancement can be attributed to the effect of the GD on the channel potential distribution as discussed above. Thus, the efficient gate control offered by the use of a GD profile plays a central role in improving the carrier transport efficiency, which enables boosting the *pH*-sensor electrical and sensing performances. Moreover, it can be seen from this figure that a further increase in the standard deviation to the critical value of 8 nm leads to degradations of the device sensitivity, underlining the complex electrical behavior of the sensor when a GD profile is adopted. In other words, selecting the appropriate standard deviation that could ensure better threshold voltage shift with the *pH* variation is extremely complex.

For the completeness of this work, overall performance comparison between the proposed Gaussian-doped JL ISFET design and the conventional *pH* sensor based on JL and IM structures is required to assess the capability of the adopted strategy to meet the demands of the next-generation biomedical sensing devices.

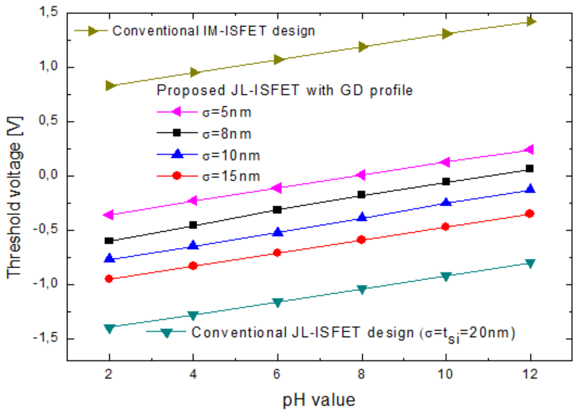


Fig. 3 – Variation of the threshold voltage shift as a function of *pH* values for both the conventional IM ISFET and the proposed design with the GD profile with different standard deviation values

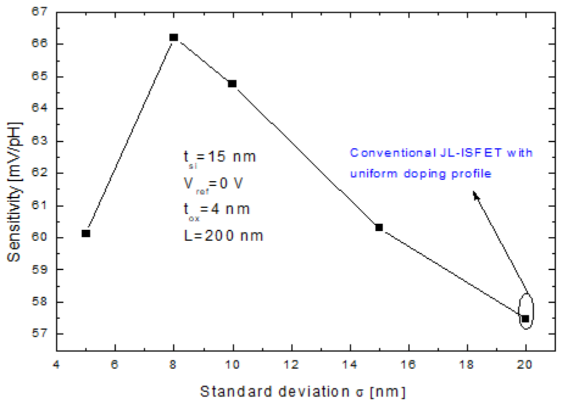


Fig. 4 – Variation of the device *pH* sensitivity as a function of the standard deviation (σ) with t_{Si} = 20 nm and L = 200 nm

Table 1 recapitulates the *pH* sensor FoMs exhibited by the conventional JL and IM ISFET-based devices compared to that of the proposed Gaussian-doped JL ISFET design. It was found that the proposed design with optimized GD profile outperforms greatly the conventional JL and IM-based *pH* sensors in terms of the leakage and sensitivity performances. Accordingly, the optimized JL ISFET design with engineered channel doping profile exhibits a high sensitivity, breaking the Nernst limit of the standard ISFET device. This outstanding result can be explained by the role of the GD shape in promoting a strong vertical electric field, which leads to a uniformly enhanced threshold voltage shift with improved leakage performances. As a result, the *pH* sensor sensitivity and power consumption are greatly enhanced, where the proposed design demonstrates a high sensitivity of 66.3 mV/*pH*, while maintaining a very low energy dissipation of 3.2×10^{-9} mW. This underlines the ability of the proposed structure based on the channel doping engineering aspect to offer exciting opportunities to reduce the complexity of the readout circuit associated with the analyzed ISFET sensor due to its high signal-to-noise ratio. On the other hand, the proposed design with an amended doping profile is considered highly stable against thermal effects in comparison with the conventional IM and JL designs as it is proved in our previously published work [12]. This correlates with the electric field modulation near the drain side induced by the introduced GD profile, greatly improving the carrier velocity, thus providing an increased thermal reliability. From the elaboration cost viewpoint, the proposed design can be fabricated using a simple controlled ion implementation process and without the need of realizing costly abrupt *p-n* junctions at the source and drain sides, confirming its very low elaboration cost as compared to the conventional *pH* sensor based on IM operating mechanism.

Therefore, the use of a Gaussian channel doping profile allows achieving better control over of the channel electrostatic behavior, which enables bridging the gap between high sensitivity of ISFET designs and ultralow power consumption aspects, resulting in promising pathways to design high-performance, thermally stable and low-cost *pH* sensors firmly appropriate for the next-generation biomedical applications.

4. CONCLUSIONS

In this paper, a new ISFET sensor based on a JL design is proposed and numerically studied. A systematic performance investigation of the proposed *pH* sensor is carried out, where the impact of a new Gaussian channel doping profile on the device sensitivity and electrical behavior is thoroughly analyzed. In this context, it has been found that the use of a GD doping profile plays an important role in improving both the device electrical performance and the sensor sensitivity. Interestingly, the proposed channel doping engineering paradigm offers the opportunity to modulate the potential and electric field distributions over the channel, promoting exciting opportunities for achieving reliable *pH* sensors with superior electrical performances. The obtained results demonstrate that the proposed device based on GD aspect could provide a novel strategy to design high-performance, low-cost and ultralow power consumption CMOS-compatible ISFET-based sensing systems highly suitable for biomedical applications, especially when using taste sensors.

Table 1 – Overall performance comparative study between the conventional IM and JL designs against the proposed JL ISFET sensor approach

Parameters	Conventional IM ISFET	Conventional JL ISFET with uniform doping profile	Proposed JL ISFET with GD profile
Output conductance [A/V]	4.68×10^{-6}	1.98×10^{-8}	8.23×10^{-10}
Off-current [A]	7.14×10^{-5}	1.62×10^{-5}	3.24×10^{-9}
Power consumption [mW]	0.19×10^{-6}	1.7×10^{-7} (low)	3.2×10^{-9} (very low)
Sensitivity [mV/*pH*]	57.5	60.02	66.3
Thermal stability	stable in a wide temperature range	stable in a wide temperature range	highly stable in a wide temperature range
Cost	average	very low	very low
Readout circuit complexity	high	high	low
Derived current and threshold voltage controllability	low	high	very high

REFERENCES

1. P. Bergveld, *IEEE Trans. Biomed. Eng.* **17**, 70 (1970).
2. N. Moser, C. Panteli, K. Fobelets, P. Georgiou, *Sensor. Actuat.: B. Chem.* **292**, 297 (2019).
3. J-W. Kang, W-J. Cho, *Solid State Electron.* **152**, 29 (2019).
4. X. Huang, H. Yu, X. Liu, Y. Jiang, M. Yan, D. Wu, *IEEE Trans. Biomed. Eng.* **62**, 2224 (2015).
5. Y. Jiang, X. Liu, T.C. Dang, X. Huang, H. Feng, Q. Zhang, H. Yu, *IEEE Trans. Biomed. Circuit. Syst.* **12**, 402 (2018).
6. T.N. Lee, H.J.H. Chen, K.C. Hsieh, *IEEE Electron Dev. Lett.* **37** No 12, 1642 (2016).
7. S. Sinkha, R. Bhardwaj, N. Sahu, H. Ahuja, R. Sharma, R. Mukhiya, *Microel. J.* **97**, 104710 (2020).
8. W. Chaisrirattanakua, W. Bunjongpru, A. Pankiew, A. Srisuwan, W. Jeamsaksiri, E. Chaowicharat, N. Thornyanadacha, P. Pengpad, M. Horprathum, D. Phromyothin, *Appl. Surf. Sci.* **512**, 145664 (2020).
9. Y. Pratap, M. Kumar, S. Kabra, S. Haldar, R.S. Gupta, M. Gupta, *J. Comput. Electron.* **17**, 288 (2018).
10. E. Chebaki, F. Djeffal, H. Ferhati, T. Bentrcia, *Superlattice. Microstr.* **92**, 80 (2016).
11. H. Ferhati, F. Djeffal, *J. Comput. Electron.* **15**, 550 (2016).
12. H. Ferhati, F. Doua, Djeffal, *Superlattice. Microstr.* **109**, 869 (2017).

Оцінка ефективності нового безперехідного ISFET з профілем легуванням за кривою Гауса: чисельне дослідження

Khadidja Dibi[1,2], Zohir Dibi[1], Ahmed Bouridane[2]

[1] *Laboratory of Advanced Automatic and Analysis Systems (LAAAS), Department of Electronics, University of Batna2, 05000 Batna, Algeria*

[2] *Department of Computer and Information Sciences, Northumbria University, Newcastle, UK*

Останнім часом увага в дослідженнях приділяється розробці датчиків на основі ISFET для майбутніх біомедичних, екологічних та харчових додатків з використанням особливих сенсорів смаку на основі іонно-чутливого польового транзистора (технологія ISFET). Це призвело до появи різних конструкцій датчиків, які викликають підвищений інтерес з боку дослідницького співтовариства. У роботі ми пропонуємо послабити концепцію ISFET, відкинувши перехід в конструкції, пропонуючи таким чином нову безперехідну структуру датчика на основі JL ISFET, засновану на стратегії профілю легування за кривою Гауса. Чисельно аналізуються електричні параметри та характеристики запропонованого *pH* датчика і повідомляється про властивості його чутливості. У цьому контексті ми розглядаємо вплив модифікованого профілю легування каналу за кривою Гауса на варіацію таких параметрів, як енергоспоживання, термічна стабільність, струм витоку та чутливість. Запропонована конструкція також демонструє посилений зсув порогової напруги із зміною *pH* розчину, що призводить до поліпшення електричних параметрів та характеристик чутливості. Результати продемонстрували, що запропонована конструкція забезпечує перспективні шляхи для підвищення характеристик датчиків на основі ISFET у порівнянні зі звичайними аналогами датчиків на основі FET, де зареєстрована чутливість досягає 66,3 мВ/*pH*. Крім того, отримані результати чітко показують відмінну модуляцію *pH* провідності каналу. Отже, запропонована структура демонструє ефективність використання легування за кривою Гауса в конструкції JL ISFET як потенційного кандидата для високоефективних додатків та додатків з наднизькими потужностями на основі польових транзисторів, що продемонстровано пропорційним вдосконаленням як електричних характеристик пристрою, так і чутливості датчика.

Ключові слова: Безперехідний ISFET, *pH*, Сенсор смаку, Профіль легування за кривою Гауса, Чутливість.