Modelling and performance evaluation of Si-NW ISFETmicrosensor

N. Ayadi, B. Hajji, H. Madani, Ahmet Lale, Jérôme Launay, Pierre Temple-Boyer

▶ To cite this version:

N. Ayadi, B. Hajji, H. Madani, Ahmet Lale, Jérôme Launay, et al.. Modelling and performance evaluation of Si-NW ISFETmicrosensor. 2020 International Conference on Electrical and Information Technologies (ICEIT), Mar 2020, Rabat, Morocco. pp.1-5, 10.1109/ICEIT48248.2020.9113203 . hal-03004573

HAL Id: hal-03004573
https://laas.hal.science/hal-03004573

Submitted on 13 Nov 2020

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire **HAL**, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.

Modelling and performance evaluationof Si-NW ISFETmicrosensor

N. ayadi [1], B.Hajji [1], H. Madani [1], A. Lale [2], J. Launay [2], P.Temple-Boyer [2]
[1]*Renewable Energy, Embedded System and Data Processing Laboratory , National School of Applied Sciences, Mohamed First UniversityMohamed First University,* Oujda, Morocco
[2]*Laboratory* for Analysis and Architecture of Systems(LAAS-*CNRS), Université de Toulouse*, 31400 Tououse, France

Abstract–**Compared to the conventional ISFET device, the silicon nanowire ion-sensitive field-effect transistors sensors (Si-nw-ISFET) has attracted a lot of attention andis considered as one of the most promising candidates because of their biocompatibility, very high surface-to-volume ratiodue to the very small sizes of the nanowires, fast response, and good reliability of the signal. This paper deals with the modeling and performance evaluation of Si-nw-ISFET(Silicon-nanowire chemical fieldfield effect transistor) microsensor.**

The modeling approach used in this work takes into account the nanowire size effects to evaluate the response of Si-nw-ISSFET transistor and introduces two parameters: the total resistance of nanowire R_T and the rectangular capacity Cox of the gate insulator all-around the Si-nw. This model investigate the main influential parameters of nanowire on the sensor response as: (i) different wire lengths Lnw, (ii) channel gate lengths of Si-nw-ISFET (i.e. short and large gate length) and (iii) different numbers of parallel wires. The model developedis tested on large pH range, evidencinga good fit between simulation and experimental results.The model developed can predict the Si-nw-ISFET response behaviour and creates new opportunities for new innovative applications.

Keywords- Modeling, Si-nw-ChemFET; silicon nanowire; pH measurement; gate all-around

I. INTRODUCTION

Ion sensitive field effect transistors (ISFETs) were firstintroduced in 1970 by Bergveld as pH sensors and developed for many applicationsespecially in the areas of environmental monitoring devices, analytical chemistry as well as biomedical applications [1, 2].

CMOS manufacturing process compatibility, which leads to low-cost devices, mass production capability, and ability to integrate sensors and read-out circuits directly together makes ISFETs as a promising candidate for a complete biological lab-on-a-chip [3, 4].

Despite those advantages of ISFET, challenges still remain for the demand of the new innovative applications that are in particularly, the increase the sensitivity, decrease response times and detection limit of ISFET [5].

To overcame this obstacles, the transistor based on silicon nanowires with surrounding gate seems to be the ideal candidate because of the high surface-to-volume ratio due to the very small sizes of the nanowires. Furthermore, with new device Si-nw-ISFET, rapid and fully electronic measurements are feasible in real-time [6, 7].

This paper deals with the modeling and performance evaluation of Si-nw-ISFFET. This model is based on the MOSFET theory and site-binding model [8, 9]. to investigate the effects of nanowire size on the response of Si-nw-ISFET.

Finally, the model developed is tested on large pH range, evidencing a good fit between simulation and experimental measurements.

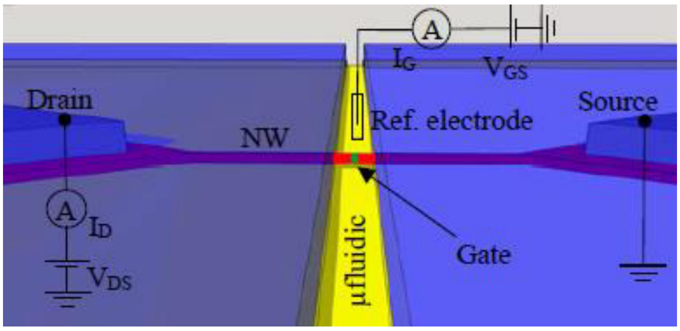

Fig1. Schematic view of Si-nw-ChemFET sensor

The rest of paper is organized as follow. Section II outlines the modeling of Si-nw-ISFFET microsenors that is divided in two parts: Si-nw-MOSFET part modeling and response of Sinw-ISFFET part modeling. Section III lists simulations results and discussion. The conclusion of present work is presented in section IV.

II. Modeling of Sinw-ISFET microsensors

Thedeveloped model used in this work to evaluate the performances of Sinw-ChemFET micro-sensor is composed of two components: (i) a MOSFET model representing the electrical properties oftransistors; (ii) a membrane model describing thebinding event of receptors immobilized on FET devices in the measuring solutions.

A. *Modeling the Si-nw-MOSFET*

<u>Case 1: Single nanowire:</u>

The working principle of the Sinw-ISFFET is based on the standard MOSFET structure as shown in Fig. 1. Therefore, a robust model, of the MOSFETpart, is suitable for performing robust and valid model ina large interval of pH.

The Level 3 model in SPICE is particularly suitable to simulate the Si-nw-MOSFET transistors as it provides accurate modeling with a small set of parameters.

The setof equations includes modeling of basic physical effects, geometricalaspect, substrate effect, modeling of mobility reductiondue to vertical field and modeling of thermal behavior.

The Level 3 model proposes the following expression of source-drain current (I_{DS}) valid for $V_{gs} > V_{T0}$:

$$I_{DS} = K_p(V_{gs} - V_{T0} - \frac{\alpha V_{ds}}{2})V_{ds} \qquad (1)$$

$$V_{TO} = V_{FB} + \emptyset_F + \gamma\sqrt{\emptyset_F} \qquad (2)$$

$$\alpha = 1 + fb \qquad (3)$$

$$K_p = \frac{W}{L}\mu_{eff}C_{OX} \qquad (4)$$

$$\mu_{eff} = \frac{\mu_0}{1+\theta(V_{gs}-V_{T0})} \qquad (5)$$

$$fb = fn + \frac{\gamma fs}{4\sqrt{\emptyset_F}} \qquad (6)$$

where V_{FB} is the flat-band voltage, ϕ_F is the bulk Fermi potential, $\gamma$is the body effect parameter, K_P is the transconductance parameter, W is the channel width, L is the channel length, μ_0 is the low-field mobility and θ is the first order mobility degradation factors due to the gate field (Vgs).

The modeling approach used in this work takes into account the nanowire size effects to evaluate the response of Si-nw-ISFET transistor and introduce two parameters: Total resistance of nanowire Rnw and the capacity C_{ox} of the gate insulator all-around the Si-nw:

$$C_{OX} = \left(\frac{0.5\varepsilon_{ox}\varepsilon_0}{Ln(1+\frac{5\,T_{OX}}{4W_{nw}})} + \frac{0.5\varepsilon_{ox}\varepsilon_0}{Ln(1+\frac{5\,T_{OX}}{4H_{nw}})}\right)\frac{1}{2(H_{nw}+W_{nw})} \qquad (7)$$

With
$$\begin{cases} \varepsilon_{ox} = \dfrac{T_{ox}}{\frac{T_{Al2O3}}{\varepsilon_{Al2O3}}+\frac{T_{SiO2}}{\varepsilon_{SiO2}}} \\ T_{ox} = T_{Al2O3} + T_{SiO2} \end{cases}$$

Where T_{ox} is the gate insulator thickness, H_{nw} is the height of devices, and W_{nw} is the width of devices.

The total resistance R_{nw} of nanowire consists of the channel resistance R_{ch} and residual parasitic resistance (R_{S1}+ R_{S2}), as shown in Fig. 2:

$$R_{nw} = R_{S1} + R_{S2} + R_{ch} \qquad (8)$$

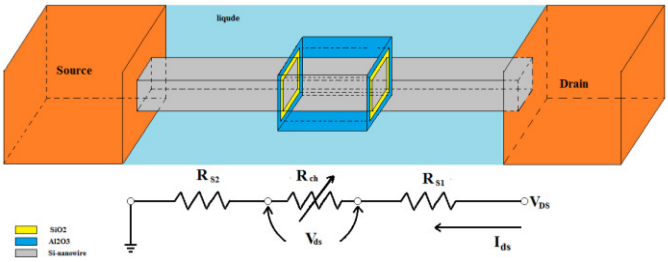

Fig2: parasitic series resistance of nanowire

$$R_{nw} = \frac{V_{DS}}{I_{DS}} = R_{S1} + R_{S2} + \frac{V_{ds}}{I_{DS}} \qquad (9)$$

V_{DS} is the externally applied drain voltage.

Therefore :

$$V_{ds} = V_{DS} - (R_{S1} + R_{S2})I_{DS} \qquad (10)$$

And $$R_{S1} + R_{S2} = \frac{\rho(L_{nw}-L)}{S_{nw}} \qquad (11)$$

Where :ρ: is the resistivity of the doped silicon, S_{nw}: is the surface of nanowire and L_{nw} is the length of nanowire.

Substitution of Eq. (8) and Eq. (9) into Eq. (1) yields:

$$I_{DS} = K_p(V_{gs} - V_{T0} - \frac{\alpha(V_{DS}-(R_{S1}+R_{S2})I_{DS})}{2})(V_{DS} - (R_{S1} + R_{S2})I_{DS}) \qquad (12)$$

$$\frac{\alpha}{2}(R_{S1} + R_{S2})^2K_pI_{DS}^2 + I_{DS}\left(K_p(R_{S1} + R_{S2})(V_{gs} - V_{T0} - \alpha V_{DS}) + 1\right) - K_p\left(V_{gs} - V_{T0} - \frac{\alpha}{2}V_{DS}\right)V_{DS} = 0 \qquad (13)$$

$$aI_{DS}^2 + bI_{DS} + c = 0 \qquad (14)$$

Equation (12) is a second degree equation, where the coefficients a, b and c are:

$$a = \frac{\alpha}{2}(R_{S1} + R_{S2})^2K_p \qquad (15)$$

$$b = \left(K_p(R_{S1} + R_{S2})(V_{gs} - V_{T0} - \alpha V_{DS}) + 1\right) \qquad (16)$$

$$c = -K_p\left(V_{gs} - V_{T0} - \frac{\alpha}{2}V_{DS}\right)V_{DS} \qquad (17)$$

The solution of Eq. 12 is described as follows:

$$I_{DS} = \frac{-b+\sqrt{b^2-4ac}}{2a} \qquad (18)$$

$$I_{DS} = \frac{b^2-(b^2-4ac)}{2a(-b-\sqrt{b^2-4ac})} \qquad (19)$$

$$I_{DS} = \frac{2c}{-b-\sqrt{b^2-4ac}} \qquad (20)$$

Finally:

$$I_{DS} = \frac{V_{DS}}{R_{ON}+\sqrt{R_{ON}^2+R_0^2}} \quad (21)$$

We pose:

$$R_{ON} = \frac{\left(K_p\left(\frac{\rho(L_{nw}-L)}{S_{nw}}\right)(V_{gs}-V_{T0}-\alpha V_{DS})+1\right)}{2K_p\left(V_{gs}-V_{T0}-\frac{\alpha}{2}V_{DS}\right)} \quad (22)$$

$$R_0^2 = \frac{\alpha\left(\frac{\rho(L_{nw}-L)}{S_{nw}}\right)^2 V_{DS}}{2\left(V_{gs}-V_{T0}-\frac{\alpha}{2}V_{DS}\right)} \quad (23)$$

For the particular case of $V_{DS} = 0$, the $R_0^2 = 0$ and Eq. (22) implies that R_{ON} represents half of the measured source-to-drain resistance Rnw.

Case 2 : multiples nanowaire in parallel :

For one nanowire, the total resistance R_T is equal:

$$R_T = R_{ON} + \sqrt{R_{ON}^2 + R_0^2} \quad (24)$$

For multiple nanowires in parallel, the total equivalent resistance R_{Teq} is equal:

$$\frac{1}{R_{Teq}} = \frac{1}{R_T} + \frac{1}{R_T} + \cdots + \frac{1}{R_T} = \frac{n}{R_T} \quad (25)$$

With n is number of nanowire

Therefore:

$$I_{DS} = \frac{nV_{de}}{R_{ON}+\sqrt{R_{ON}^2+R_0^2}} \quad (26)$$

B. *Modeling the response of Sinw-ISFFET*

The Si-nw-ISFET threshold voltage V_T is related to the pH at aluminaAl2O3 surface according to the simplified site-binding model [8,9]:

$$V_T = V_{T0} + V_{pH} \quad (27)$$

$$V_{pH} = E_{ref} - \psi_0 + x^{sol} - \frac{\phi_{Si}}{q} \quad (28)$$

$$\psi_0 = 2.303\frac{KT}{q}\frac{\beta_0}{\beta_0+1}(pH_{PZC} - pH) \quad (29)$$

whereT is the temperature of the system, K is the Boltzmann's constant, q the electron charge, pH_{pzc} is the non zero pH, and β_0 is a parameter which reflects the chemical sensitivity of the gate insulator and is dependent on the density of surface sites Ns and the double layer capacitance C_{DL}. The parameter β_0 is given by:

$$\beta_0 = \frac{2q^2 N_S\sqrt{\frac{K_b}{K_a}}}{KTC_{DL}} \quad (30)$$

Where K_a, K_b are dissociation constants for the chemical reactions at the insulator interface.

III. RESULTS AND DESCUTION

The Si-nw-MOSFET and Si-nw-ISFET were fabricated at the Laboratoire d'Analyseetd'Architecture des Systèmes (LAAS), in Toulouse, France. These devices consist in single and networked silicon nanowires field effect transistors. Different wire lengths, gate lengths and number of parallel wires were fabricated.The SiO_2/ALD-Al_2O_3double layer was used as a gate chemically sensitive layer as well as the microdevice passivation layer in liquid phase. The gate insulator alumina Al_2O_3 deposedby Atomic Layer deposition ALD. The advantage of this technique is to deposit extremely compliant films and whose thicknesses are controlled close to the molecular monolayer

A. *Simulation results*

The goal of this part is to investigate the influence of main parameters of nanowire on response of Si-nw-ISFET sensor as the length of nanowire, the number of nanowire and the gate length.

1) **Influence on the gate length L_G**

The influence of the gate length L_G (0.73µm "short" and 3.73µm "long") on the Si-nw-ISFETs characteristics has been studied in this work. The simulations results as depicted in Fig. 3 are obtained for one nanowire of 10 µm, Vds = 1V and fixed pH equal 4.

It should be noted that a saturation phenomenon of the Si-nw-ISFET sensor appears clearly when the gate length L_G increases from 0.73 to 3.73 µm. This phenomenon decreases the value of the current in the ON state of the transistor and it is related to the length of the wire.

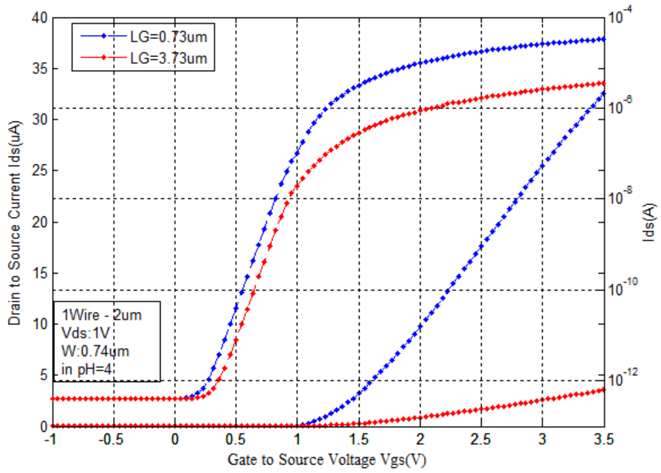

Fig3. In linear and semi-logarithmic scale the Si-nw-ISFFET Ids (Vgs) consist of a single nanowire, different gate lengths (0.73 µm and 3.73 µm) and the length of 2 µm nanowire. (VDS = 1 V)

2) **Influence ofnumber of nanowire**

The Fig. 4 (4(a) and 4(b)) show the characteristics Ids(Vgs) of Si-nw-ISFET sensor for different numbers of nanowires. Through this simulation,the clear modulation of the Ids with changing numbre of nanowire values is verified. This phenomenon can be related to the transconductance that is inversely proportional to the gate length.

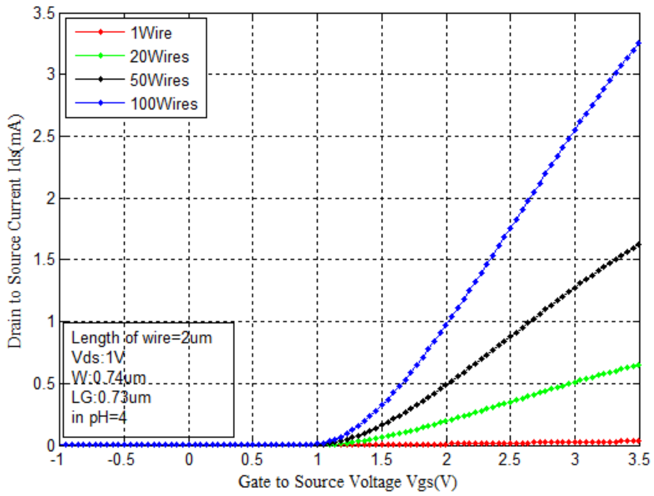

Fig4(a). Id(Vgs) characteristic of Si-nw-ISFETs, with a linear scale, different number wires and the length of 2 µm nanowire (Vds = 1 V).

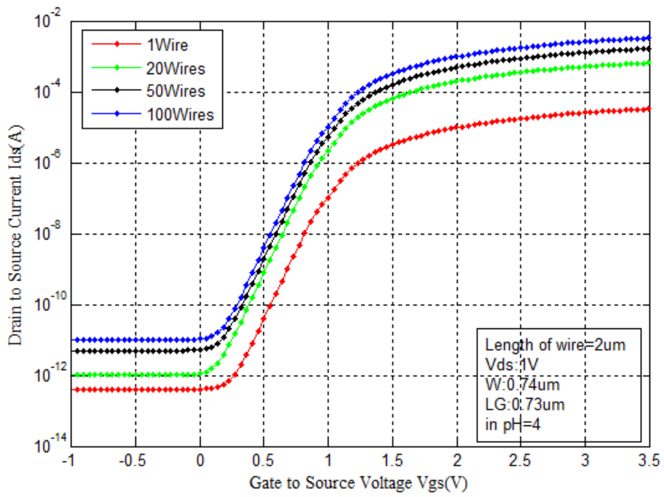

Fig4(b). Id(Vgs) characteristic of Si-nw-ISFETs, with a semi-logarithmic scale (Vds = 1 V).

3) **Influence Length of wire**

The influence of the length of the nanowires was low for the nanoMOSFETs, because of the strong resistance of the conducting channel to the resistance of the source-drain contacts (in the nanowire).

In the case of nanoISFETs, the gate control being totally surrounding, the conduction surface in the channel is increased and the resistance of the conductive channel is thus reduced. It turns out that the effect of the length of the wire is then no longer negligible and has a visible effect on the characteristics Ids (Vgs) as shwohn in Fig5.

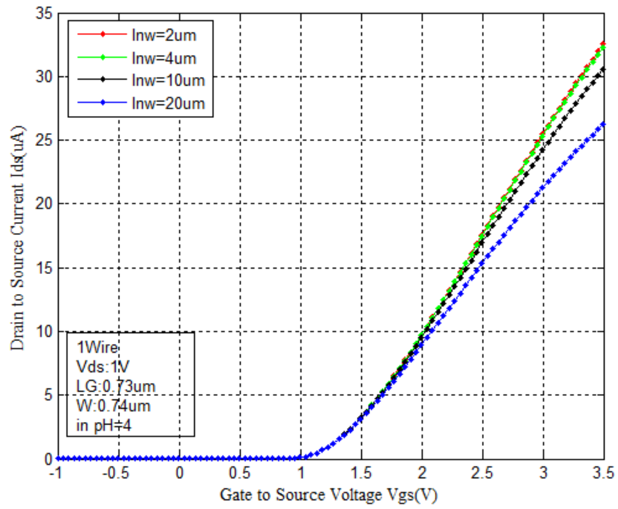

Fig5. Id(Vgs) characteristic of Si-nw-ISFETs, with a linear scale , different lengths of wire (Vds = 1 V).

4) **Influence of the solution pH**

Figure 8 shows the changes in the transfer curve Id(Vgs) as a function of pH. The influence of pH causes shift in the threshold voltage V_T of Si-nw-ISFET and the detection sensitivity is estimated to 52 mV/pH (Fig6).

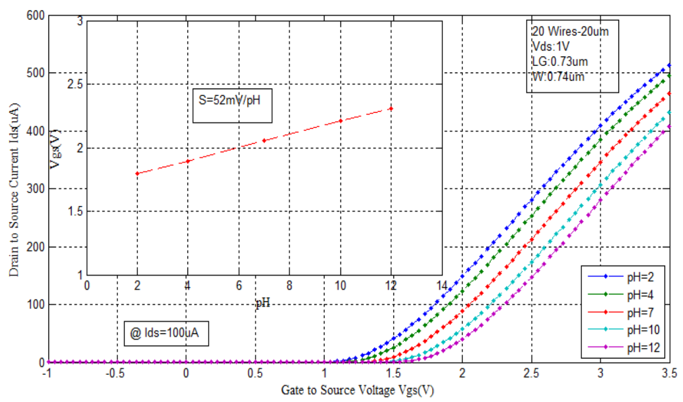

Fig6. Id(Vgs) characteristic of Si-nw-ISFET, with a linear scale, for different pH. (Vds = 1 V).

B. Model validation

To demonstrate the validity of the proposed model, the simulation results has been compared with the experimental data of a Si-nw-ISFET sensor. The Si-nw-ISFET device has been realized and characterized at the Laboratoire d'Analyse et d'Architecture des Systèmes (LAAS), in Toulouse, France. The Fig9 show that the fit is excellent for different of pH. The model parameters were obtained through a nonlinear regression process, by the least squares method. The table 1 listed the man parameters of the proposed model.

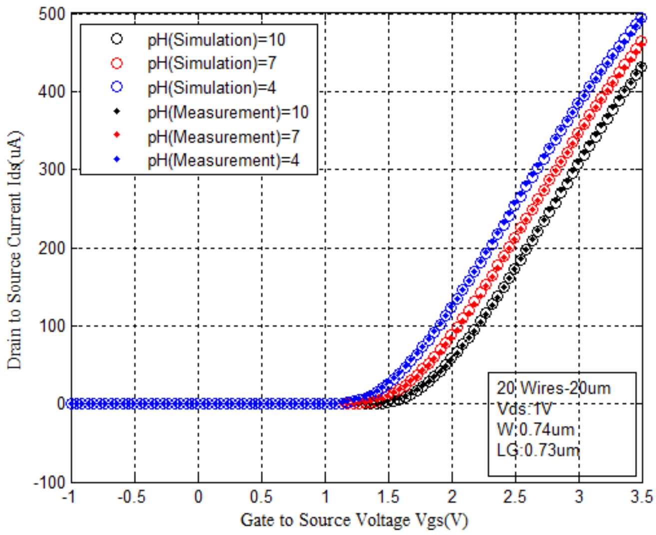

Fig9. Comparison between Simulation- Experience of the Id(Vgs) characteristic of Si-nw-ChemFET, with a linear scale, for three different pH. (Vds = 1V).

TABLE I. Extracted model parameters for Si-nw-ISFET

Parameters	Values
Length gate (µm)	0.73
width channel(µm)	0.74
Length of wire(µm)	20
number of nanowire	20
Rs of nanowire(Ω)	1.7 E4
µ0(cm3/V.s): Mobility	272.2724
θ (1/V): Mobility modulation	0.2462
CDL (F/cm2)	6.7961 E-5
Ns (cm-2)	6.7776 E14
Ka(mole/l)	1.5737 E-6
Kb (mole/l)	8.3652 E-11

IV. Conclusion

In this study, a theoretical model was developed to investigate the influences of man parameters of nanowire on response of Si-nw-ISFET sensor as the length of nanowire, the number of nanowire and the gate length. The simulations results show that :

- The effect of the length of the wire is no longer negligible and has a visible effect on the characteristics Ids (Vgs).
- The phenomenon modulation of the Ids observed with changing numbre of nanowire values. This phenomenon can be related to the transconductance that is inversely proportional to the gate length

Then, the theoretical model developed of Si-nw-ISFET was compared with the experimental data provided by the Laboratoire d'Analyse et d'Architecture des Systèmes (LAAS), in Toulouse, France . The simulation results show that this model can fit experimental results with good accuracy for different values of pH.

REFERENCES

[1] Bergveld, P. Development of an ion-sensitive solid-state device for neurophysiological measurements. IEEE Trans. Biomed. Eng. 1970, BME-17, 70–71

[2] Humenyuk, I. et al. Microelectronics Journal 37, 475-479 (2006).

[3] Hajji, B. et al. Microelectronics Reliability 40, 783-786 (2000).

[4] Temple-Boyer, P. et al. Sensors and Actuators B: Chemical 131, 525-532 (2008).

[5] Sant, W. et al. Sensors and Actuators B: Chemical 103, 260-264 (2004)..

[6] A. Lale et al. IEEE Nanotechnology Materials and Devices Conference (NMDC) 2016

[7] A. Lale et al.proceedings 2017, 1, 419, journal MDPI

[8] Naimi et al. Sensors and actuators B, 1019-1027 (2014)