



**SEWING**

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*System for European Water monitorING*

*Deliverable 10:  
Physical models of CHEMFETs*

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Project Co-ordinator: Politechnika Warszawska, Poland  
Partners: Politechnika Warszawska - PL, Instytut Technologii Elektronowej - PL., Technical University of Lodz - PL., Valtion Teknillinen Tutkimuskeskus - FI, Centre National de la Recherche Scientifique - F, MICROSENS - CH, Universitat Politecnica Catalunya - E, Institut fuer Wasservorsorge, Gewaesserekologie und Abfallwirtschaft - A, SYSTEVA - I.



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## DELIVERABLES SUMMARY SHEET

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Deliverable N°: 10. Physical models of CHEMFETs

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### Short Description:

Deliverable 10: Physical models of CHEMFETs.

Deliverable No 10 is based on the results obtained previously and presented in Deliverables No 7 and No 9. It is included in WP 3 "Sensor global modelling and testing". Taking into account technology of sensors for water analysis discussed in Deliverable 9 as well as requirements of the final system designers, it was decided to develop and implement two kinds of sensor models: physical and behavioural. Deliverable 10 is dedicated only to physical models. Behavioural models are reported in Deliverable 11.

Due to water monitoring requirements, we have elaborated models for both ISFET sensors, sensitive to hydrogen ions as well as CHEMFET sensors – dedicated to many other types of ions considered in SEWING project as common ions of water pollution. In CHEMFET case ion selective membranes containing some ionophore and a lipophylic salt (as described in the Deliverable 9) have been assumed. Physical basis for operation of ISFET and CHEMFET sensors have been studied and efficient physical models have been developed, analysed and verified by means of measurements. First verifications have been performed for  $\text{NO}_3^-$  and  $\text{NH}_4^+$  ions from a pilot fabrication. It should be underlined however, that delivered models are not ion-specific and can be applied to a large class of devices dedicated to any ions being considered in this project.

Although complicated physics based models can be potentially more accurate than simple ones, but they have turned out to be harder to use – due to more difficult identification of parameters and increased time of computer simulation. Hence we have proposed also physics based models of intermediate complexity. These models, after measurement based identification of their parameters, will be used for development of data fusion algorithms that are to process raw sensor measurement as to improve accuracy and reliability of ion measurements.

The detailed report attached to this document shows the following. 1) Physical models of ISFETs of different level of accuracy, also including thermal effects. 2) Physical models of CHEMFET devices that properly reflect sensitivity, selectivity, operating point and temperature dependence of real sensors that have been measured. Both full as well as simplified physical models have been proposed. 3) Rough identification (pre-extraction) of parameters for the proposed models have been proposed. Software has been created to efficiently store/search/retrieve/visualise measurement data and to perform optimisation based parameter extraction.

The results obtained so far are sufficient to advance other workpackages of the SEWING project, especially development of data fusion algorithms.

Limited number of sensors and amount of measurement data prohibited statistical characterisation of sensors and also a study of ageing effects – at this stage of our work. Further measurement and characterisation is planned so to estimate accuracy and lifetime of ISFET/CHEMFET based sensing of ionic activity in water.

Partners owning: TUL, Politechnika Warszawska

Partners contributed: TUL, Politechnika Warszawska.

Made available to: Mr. Mario Verdesse, Project Officer.



**Workpackage 3:**  
**Sensor global modelling and testing**

**Deliverable 10:**  
**Physical models of CHEMFETs**

**I - Introduction**

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Due to water monitoring requirements, we have elaborated physical and behavioural models for both ISFET sensors, sensitive to hydrogen ions and also for CHEMFET sensors – dedicated to many other types of ions considered in SEWING project as common ions of water pollution. First verifications have been performed for  $\text{NO}_3^-$  and  $\text{NH}_4^+$  ions from a pilot fabrication. It should be underlined however, that delivered models are not ion-specific and can be applied to a large class of devices dedicated to any ions being considered in this project.

In what follows we present models based on physical phenomena in: water containing some cations and anions at ISFET’s surface and in CHEMFET’s ion selective membranes (containing some ionophore and a lipophylic salt) deposited on the gate insulator. Physical bases for ISFET/CHEMFET sensor operation have been studied and efficient physical models have been developed, analysed and verified by means of measurements. Although complicated physical models are potentially more accurate than simpler ones, but they have turned out to be harder to use – due to more difficult identification of parameters and increased time of computer simulation. Hence we have proposed also physics based models of intermediate complexity. These models, after measurement based identification of their parameters, will be used for development of data fusion algorithms that are to process raw sensor measurement as to improve accuracy and reliability of ion measurements.

In what follows we show the following. 1) Physical models of ISFETs of different level of accuracy, also including thermal effects. 2) Physical models of CHEMFET devices that properly reflect sensitivity, selectivity, operating point and temperature dependence of real sensors that have been measured. Both full as well as simplified physical models have been proposed. 3) Rough identification (pre-extraction) of parameters for the proposed models

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## **II – Physical models of ISFET sensors**

In the Department of Microelectronics and Computer Science some of the H<sup>+</sup> sensitive ISFETs models were created. Most of efforts concentrated on steady state behaviour modelling for various environments however thermal and dynamic models of the ISFET system were also developed.

The physical modelling of H<sup>+</sup> sensitive ISFET concentrates on proper and accurate modelling of the phenomena that governs the process of the surface potential creation on the solid–liquid interface of the ISFET system. To model efficiently the H<sup>+</sup> sensitive ISFET the so-called “site-binding theory“ has to be applied as well as standard theory of electrochemistry. It assumes that sensor model can be related to modelling of the chemical double layer that exists on the border of the solid–liquid phases of the sensor-electrolyte system.

The following models were taken into consideration:

- 1) static model neglecting the presence of other than hydrogen ion in the measured solution
- 2) static model taking into account other than hydrogen ion (disturbing ions) that form its own sub-layers in the Helmholtz plane
- 3) dynamic model of the sensor with application of the overpotential theory
- 4) thermal model of the sensor system (taking into account the semiconductor part of the sensor, solution, phase borders and reference electrode thermal dependence)

Presented theoretical models will be parameterised to obtain the best possible accuracy with the measurements of real test structures provided by ITE and LAAS.

### **II.1 - Modelling of the transducing part of ISFET**

The transducing part of the ISFET transistor resembles the standard MOSFET structure, and is described in details in deliverable 11 part II.1. Therefore in this deliverable it is not going to be more extensively presented.

### **II.2 – Physical models of the surface potential of ISFET**

Physical modelling bases on the site-binding theory that assumes, that on the outer layer of the ion sensitive material the active sites exist. The ions from the solution react with these sites (hydration process of the ion-sensitive layer). This process changes the total charge adsorbed by the ion selective material of the gate which gives rise to the surface potential changes. This process influences the changes of the current in the channel of the transistor.

The sophisticated model of the double layer can be shown as follows. In figure 1  $\sigma_S$ ,  $\sigma_A$ ,  $\sigma_K$ ,  $\sigma_D$  represent the charge accumulated on the surface of the ion selective material, charge of the specifically adsorbed ions, adsorbed cations, charge accumulated in the diffuse layer respectively.  $\Psi_S$ ,  $\Psi_A$ ,  $\Psi_K$ ,  $\Psi_D$  represent corresponding potentials.

Model of H<sup>+</sup> sensitive ISFET can be treated as an entity consisted of two interconnected submodels. First of them refers to the semiconductor part of the sensor and the other refers to the chemical part (mainly to the double layer, reference electrode, solution etc.).

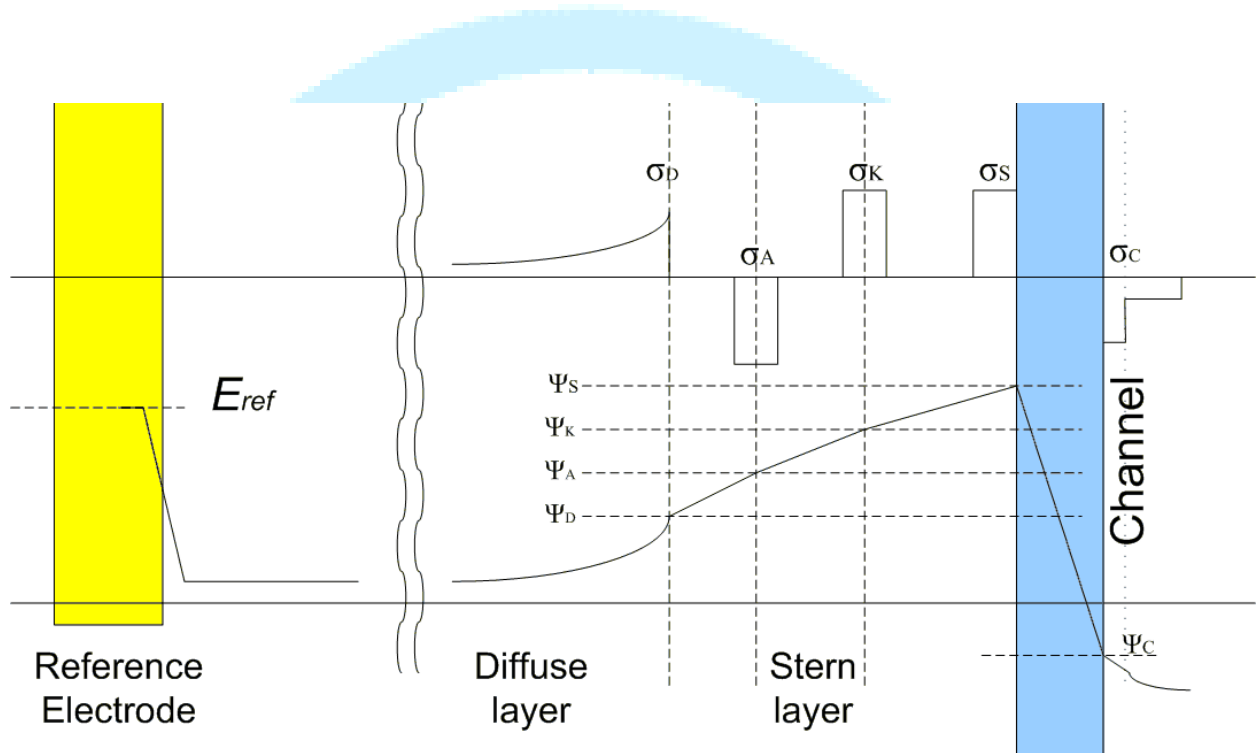


Figure 1: Schematic representation of the double layer (solution–ion sensitive material interface), charge and potential distribution.

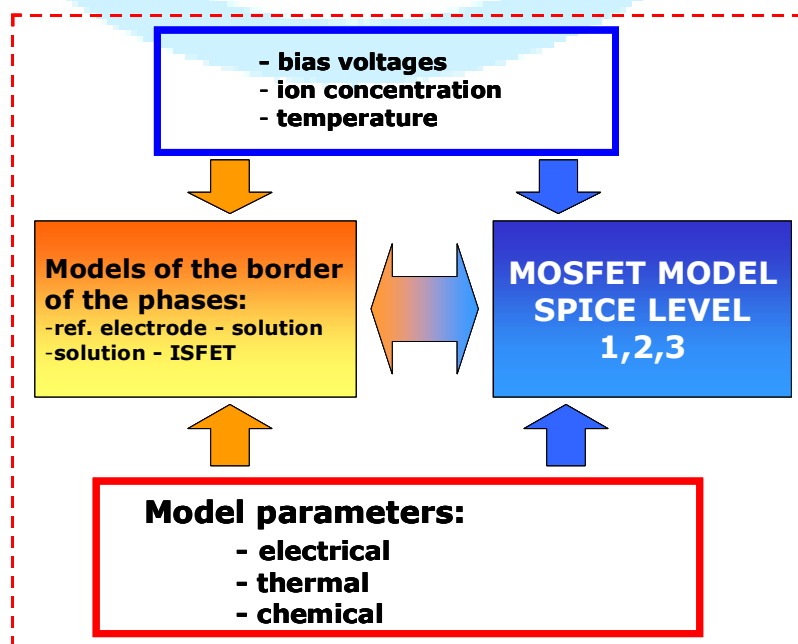


Figure 2: Schematic representation of the ISFET model.

For a sensor to be operational the biasing voltages have to be applied. For a model to be operational – some model parameters of chemical, electrical and thermal origin have to be determined (from measurement of physical sensors).

## II.2.1 - Modelling of the surface potential in the steady state conditions

Two static models of the sensor are presented. They were implemented in various simulation environment such as SPICE, VHDL-AMS and HDL-A. On that base of the model the library of different H<sup>+</sup> sensitive ISFETs can be built.

### II.2.1.a – Model LEVEL1

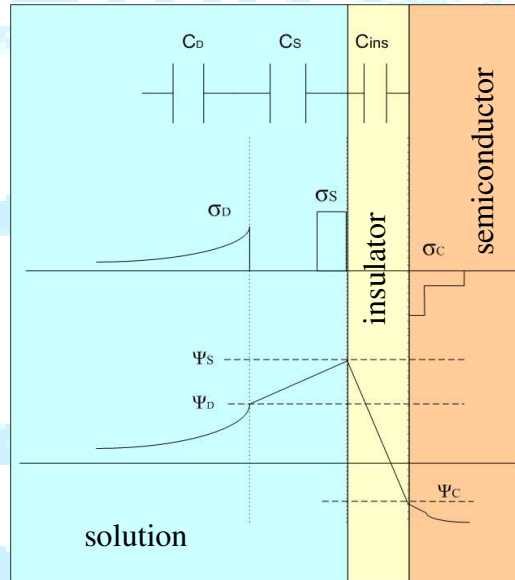


Figure 3: Simplified model of the system reference electrode – solution – transistor in the H<sup>+</sup> sensitive ISFET

First of the mentioned models (LEVEL 1) covers the ideal condition of work of the sensor. In measured solution only hydrogen ion are assumed to be present. This assumption simplifies the charge and potential distribution over the double layer model from the figure 1 by neglecting the presence of the sub layers of the Stern layer of the solid-liquid interface. The simplified structure of the system is presented in figure 3.

The most important equations characterising the model can be briefly written as follows:

$$\sigma_C + \sigma_S + \sigma_D = 0 \quad (1)$$

$$\Psi_S - \Psi_D = -\frac{\sigma_D}{C_S} \quad (2)$$

$$\Psi_C - \Psi_S = -\frac{\sigma_D}{C_{ins}} \quad (3)$$

The expression for  $\sigma_S$  – surface charge that drives the transistor current can be derived as follows:

$$\begin{aligned} \sigma_S = & q(N_{SIL} \cdot (\exp(-2.0\gamma \frac{q\Psi_S}{kT} - 4.6 pH) - K_{FS} K_{BS})) / (\exp(-4.6 pH - 2.0\gamma \frac{q\Psi_S}{kT}) + \\ & + K_{FS} \exp(-2.3 \cdot pH - \gamma \frac{q\Psi_S}{kT}) + (K_{FS} K_{BS})) + N_{NT} \cdot \exp(-\gamma \frac{q\Psi_S}{kT}) / (\exp(-\gamma \frac{q\Psi_S}{kT}) + K_N \exp(2.3 pH)) \end{aligned} \quad (4)$$

In (4) parameters  $N_{SIL}$ ,  $N_{NIT}$ ,  $K_{FS}$ ,  $K_{BS}$ ,  $K_N$  stand for the total number of silanol and nitride sites present on the ion sensitive area (in two site system) per unit area, ionisation constants of these sites respectively, while  $\gamma$  represents a fitting coefficient.

Simulation results of the surface potential dependence on pH value is presented in figure 4.

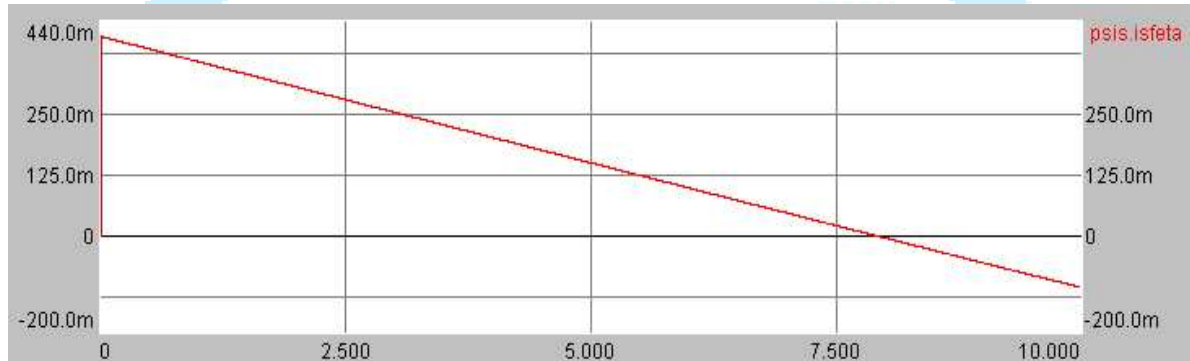


Figure 4: Surface potential dependence on pH

### II.2.1.b – Model LEVEL2

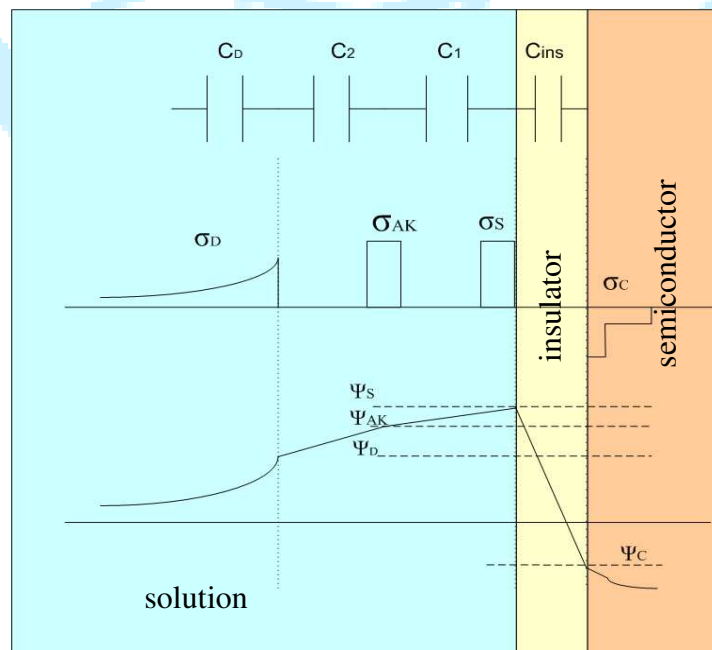


Figure 5: Model LEVEL2 of the system reference electrode – solution – transistor in the  $H^+$  sensitive CHEMFET

The second model (LEVEL2) is slightly more complicated. It assumes the presence of other than hydrogen ion in the measured solution that gives rise to the nonideal behaviour of the sensor. This preliminary assumption complicates the earlier presented model by introducing the single, common sublayer into the Stern layer. This sublayer is formed by the disturbing ions (cations and anions) present in the solution. Its presence can influence the output signal of the sensor.

The influence of the disturbing ion on the surface potential is shown on the figure 6. As it can be seen it flattens the surface potential curve in the regions of higher and lower hydrogen concentration in the solution.

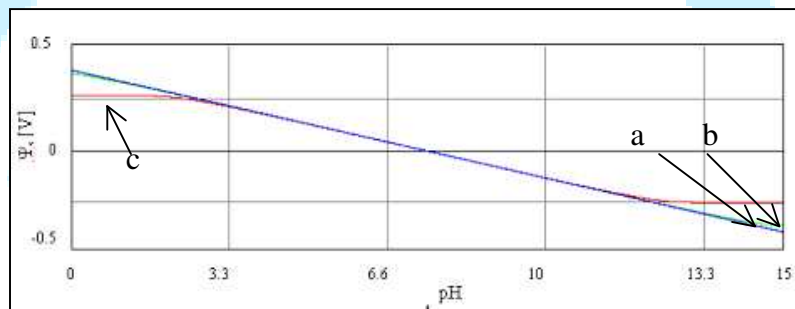


Figure 6: The surface potential curve v. pH with the concentration of disturbing cations and anions a)  $pK, pA = 5$ , b)  $pK, pA = 3$ , c)  $pK, pA = 1$

In the figure 7 and 8 the influence of the contents of the measured solution on the output curves and transfer curves of the sensor presented in figure 2 were presented. The test simulation were performed with condition of no disturbing ion present in the solution.

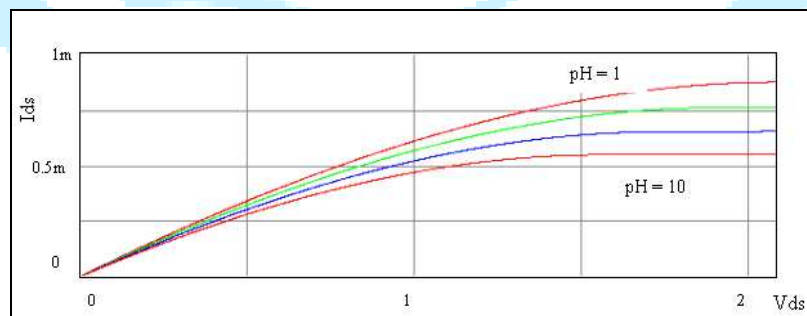


Figure 7: Influence of the contents of the solution (pH) on the output curves (from pH=1 through 4,7, and 10)

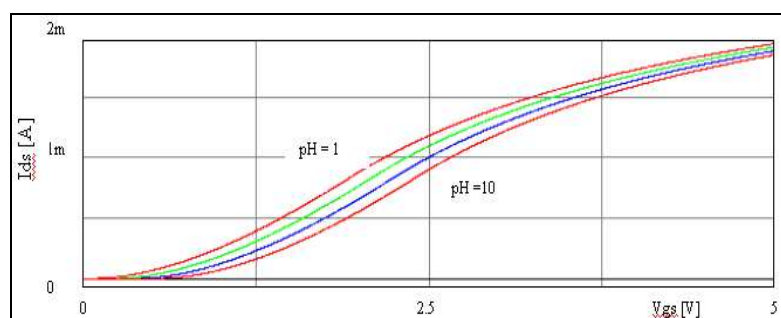


Figure 8: Influence of the contents of the solution (pH) on the transfer curves (from pH=1 through 4,7, and 10)

## II.2.2 - Physical modelling of the dynamic properties of the $H^+$ selective CHEMFET

Physical modelling of the dynamic behaviour of the  $H^+$  sensitive CHEMFET bases on the overpotential phenomenon. In this chapter the outline of the dynamic model is presented. The

dynamic behaviour is of second importance in case of chemical potentiometric sensor dedicated to water pollution monitoring due to the nature of changes of concentration of measured ion in the environment. However knowledge of the nature of the phenomenon (and accurate model) that rules the behaviour of the sensor can appear helpful and support the main process of ion measurements. Simulation indicates that response time on fast changes of pH is dependent on the starting value of pH as well as on the direction of changes.

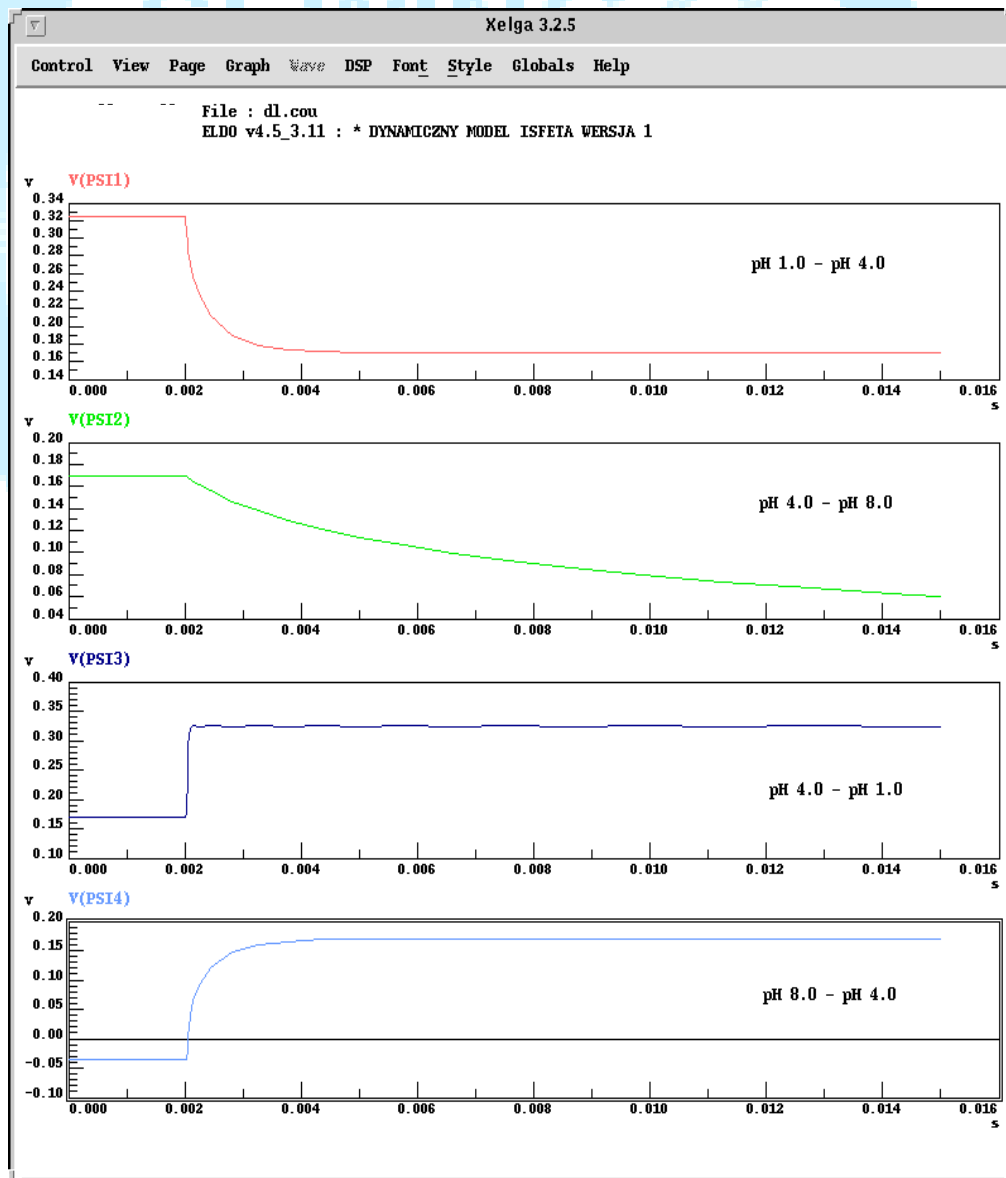


Figure 9: Dynamic responses on a rapid change of pH ( $pH = pH_0 1(t - 0.002)$ )

### **II.3 – Thermal modelling of the H<sup>+</sup> sensitive CHEMFET system**

Past measurement of the real structures manufactured by Institute of Electron Technology revealed the significant temperature dependence of the sensor. It is obvious, that to model the thermal behaviour of the sensor it is necessary to take into account all parts of the sensor system. Preliminary estimations show that including thermal dependence just to the semiconductor part of the sensor and neglecting the thermal influence on the other sensor

parts does not assure proper accuracy and therefore are insufficient for the overall sensor modelling.

In the proposed model additional thermal dependencies were applied to the four particular parts as it is presented in figure 10.

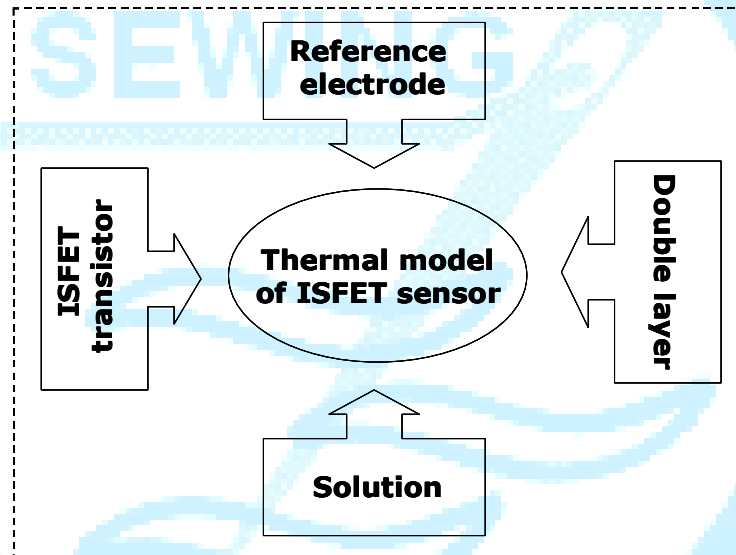


Figure 10: Schematic representation of the thermal modelling of  $H^+$  sensitive CHEMFET sensor

The temperature dependencies were implemented as follows. First, temperature changes reaction constants of the species with the ion sensitive area. We took into account also temperature of diffusion and Stern layers in the double layer. Semiconductor part of the sensor became temperature dependent by the effective mobility expression and Fermi potential. For the reference electrode the potential dependence on temperature dependence was taken into account with the aid of the Nernstian equation. Example results of the simulation are presented in the figure 11. Preliminary simulation have revealed that the strongest temperature influence shows dissociation constants as well as charge mobility in FET.

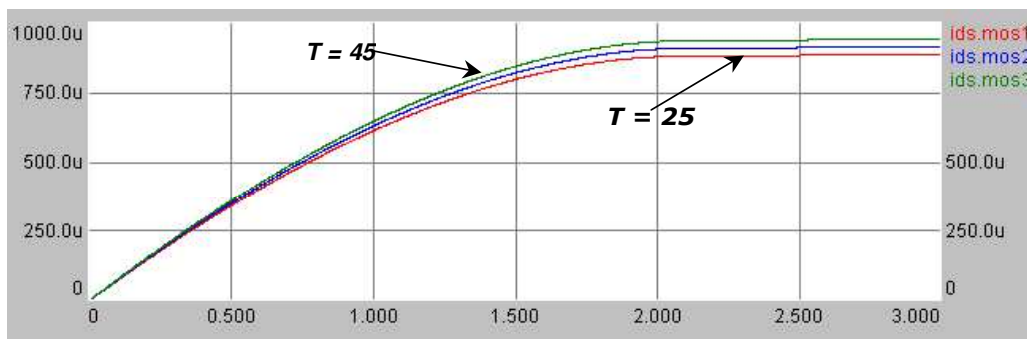


Figure 11: Temperature dependence simulation of the overall sensor system

### III – Physical models of CHEMFET sensors

In this section we outline a mixed-domain model of the CHEMFET device – as developed in the Institute of Electronic Systems. The model not only properly represents sensing of ionic activity in a tested aqueous solution for fixed operating point. It can also approximate well influence of operating point upon CHEMFET sensor responses. The CHEMFET devices are built upon a silicon structure of a MOSFET without a gate shown in Fig. 12. The gate insulator is directly covered with a hydrogel, containing an aqueous solution of the internal electrolyte. The hydrogel is in turn covered with a special ion-selective membrane, that directly contacts the tested aqueous solution, as sketched in fig 13. Ideally a chemical sensor should be specific, i.e. it should respond to a strictly specified (main) ion activity only. In reality potential drop between each electrolyte and membrane surfaces depends also on activity of other (interfering) ions.

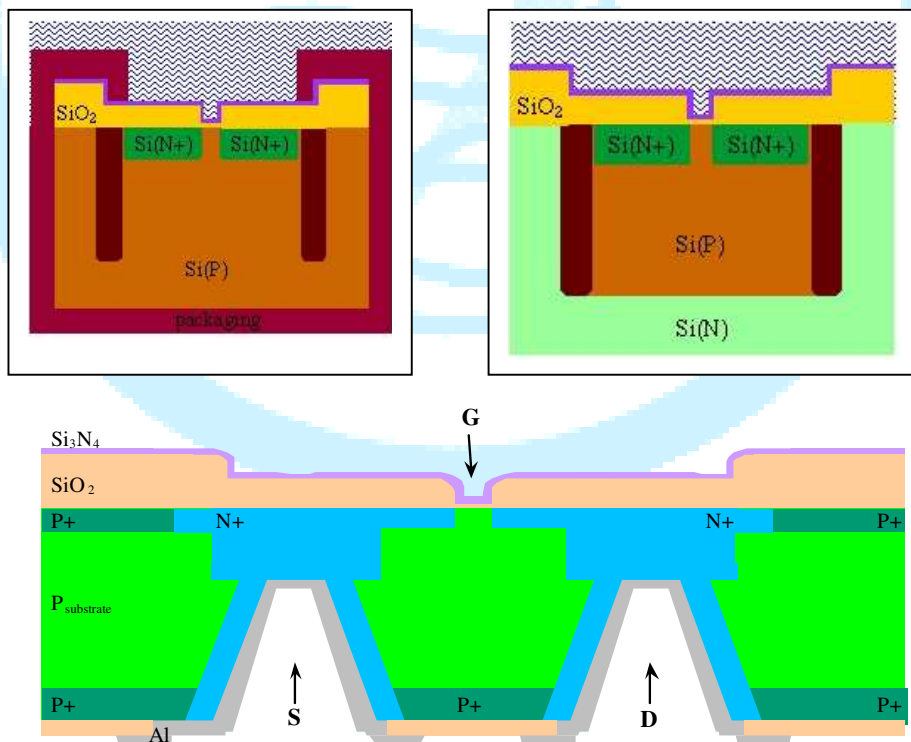


Figure 12. Two types of the CHEMFET construction from LAAS (top) and a backside contact construction from ITE (bottom).

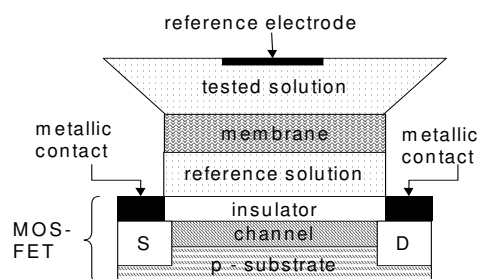


Figure 13. A schematic cross-section of the CHEMFET sensor structure

### III.1 – Advanced chemo-electrical models of CHEMFET sensors

In the CHEMFET sensor the output signal is a voltage  $V_{GR}$  between the solution bulk (precisely: the reference electrode dipped in the electrolyte) and an ISFET insulator surface. This voltage consists of the reference electrode surface voltage  $V_R$ , the ISFET surface voltage  $V_{FET}$  and the voltage  $V_{BR} = E_B - E_{BR}$  across the membrane, i.e.  $V_{GR} = V_R(T) + V_{FET}(T) + V_{BR}(T)$ .

For the reference electrode we assume  $V_R = V_{R0} + \alpha_R \Delta T$  and typically  $\alpha_R = 0.1 mV/^\circ C$ . As for chemo-electrical effects in CHEMFET devices their physical modeling is based on the Van den Berg theory. It takes into account membrane surface phenomena described by: 1) the Boltzmann Law, 2) selective complexation of ions by ligands in the membrane and 3) association of these complexes with the lipophylic salt molecules. This yields a model with the following technological parameters: ligands concentration  $\bar{a}_{Ltot}$ , the lipophylic salt concentration  $\bar{a}_{Ytot}$ , nonideality index  $n$  and moreover division constants  $k_{di}$ , complexation coefficients  $\beta_i$ , association constants  $k_{ai}$  for each ion (and anti-ion - the superscript A) involved. Instead of these parameters, difficult in identification, we prefer normal (scaled) parameters listed in Table 1.

Table 1. Normal parameters of the CHEMFET physical model

Parameter	Name	Relation to technological parameters	Typical values (interfering)
$K_j$	Intrinsic selectivity	$(k_{dj} \beta_j) / (k_{d0} \beta_0)$	$(5.6 \cdot 10^{-5})$
$E_{ofs}$	Intrinsic offset	$n \psi_0 \ln(k_{d0} \beta_0)$	0.19
$n$	Nonideality index	$N$	1.1
$k_{aj}$	Association constants	$k_{aj}$	3200 (100)
$a_{Ltot}$	Ligands concentration	$a_{Ltot}$	$10^{-3}$
$a_{Ytot}$	Lipophylic salt concentration	$a_{Ytot}$	$5 \cdot 10^{-4}$
$b_j$	Complexation inverts	$1 / \beta_j$	$10^{-9}$ ( $10^{-5}$ )
$K_j^A$	Normalized constants for anti-ions	$k_{dj}^A k_{d0} \beta_0$	$10^{-3}$
$a_{0R}$	Main ion activity in the reference electrolyte	----	$10^{-2}$

Let  $e_B = \exp \frac{E_B - E_{ofs}}{n \psi_0}$ ,  $\psi_0 = nkT / q$  (the electro-thermal voltage),  $E_B$  be the potential

of the membrane surface,  $C_0 = b_0 a_0 + \sum_{j=1}^m b_j K_j a_j$ ,  $C_1 = a_0 + \sum_{j=1}^m K_j a_j$ ,  $C_3 = C_1 + C_2 \bar{a}_{Ltot}$ ,

$C_2 = k_{a0} a_0 + \sum_{j=1}^m k_{aj} K_j a_j$ ,  $C_A = \sum_{j=1}^m K_j^A a_j^A$  and  $a_j$  be the  $j$ th ion activity. Then the physical model of the border between the membrane and the electrolyte takes the form:

$$\frac{-\bar{a}_{Ltot} C_1}{C_1 + e_B} + \frac{\bar{a}_{Ytot} (C_1 + e_B)}{e_B + C_3} - \frac{C_0}{e_B} + C_A e_B = 0 \quad (5)$$

In the same manner as  $E_B$  also a potential  $E_{BR}$  can be calculated from (5) formulated for the border between the membrane and the reference electrolyte which is free of interfering ions and activity its main ions is given as  $a_{OR}$ .

Great advantage of this model is its technological and temperature dependent character. Its drawback is implicit, complicated structure. Potential precision of this model cannot be exploited in practice - due to low accuracy of experimental identification of its parameters. Hence in engineering practice simplified models are preferable.

### III.2 – Simplified chemo-electrical models of CHEMFET sensors – SNE model

Efficient, explicit physical model for CHEMFET systems simulation has been obtained from (5) by neglecting infinitesimal influence of the 3<sup>rd</sup> and 4<sup>th</sup> component. This gives a, so called, super-Nikolski-Eisenmann (SNE) model:

$$e_B = C_1 \left[ \frac{\bar{a}_{Ltot}}{2\bar{a}_{Ytot}} \left( 1 + \sqrt{1 + 4\bar{a}_{Ytot} \frac{C_2}{C_1}} \right) - 1 \right] . \quad (6)$$

Its accuracy w.r.t. the full model (5) for the typical data from Table 1 has been plotted in Fig. 14. This model determines very well the useful range of small and medium ion concentration, where discrepancy between (5) and (6) is smaller than 0.3% of the range. The high-concentration knee, which is a result of anti-ions influence, can be modelled by (5), as shown in Fig. 3, but is not included in (6). Fortunately in up-to-date good quality CHEMFETS this effect is shifted to extremely high, impractical concentrations, and so for environment monitoring applications the SNE model is quite sufficient.

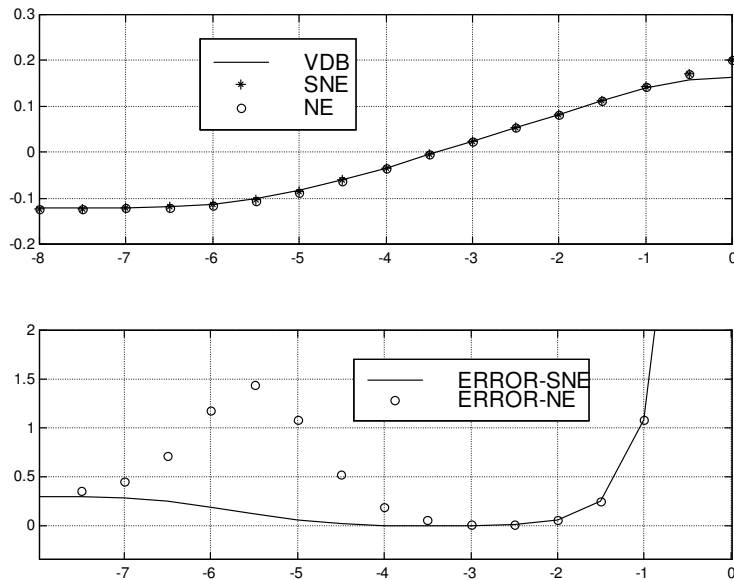


Figure 14. Accuracy of the SNE model (5) and the further discussed behavioural NE model

### III.3 – Electrical models CHEMFET sensors

To reduce influence of the internal MOSFET properties upon the CHEMFET sensor response typically the operating point  $U_{DS}$  and  $I_D$  is fixed by a biasing circuitry of the sensor. For such a mode of operation the CHEMFET device can be represented by the chemo-electrical model where the chemical part is not dependent on the electrical part, so the MOSFET device can be viewed as separable from the chemo-electrical transducer, where the ionic activity is converted into  $V_{GR}$  according to models described in III.1 or III.2.

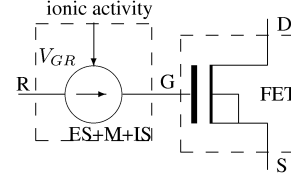


Figure. 15. Separable CHEMFET model

As a compromise between simplicity and accuracy, a depletion MOSFET model described by Merckel was adapted. It contains 7 parameters joined in Table 2. For use as a separable CHEMFET model one should replace  $U_{GS}$  with  $U_{RS} + V_{GR}$ , where  $U_{RS}$  is the reference electrode-source voltage and  $V_{GR}$  models the transducer activity. This model distinguishes 3 ranges of  $U_{GS}$  voltage:

1. For  $U_{GS} < V_{OFF}$  :  $I_D = 0$

2. For  $V_{OFF} \leq U_{GS} \leq V_{FB}$  - depletion region.

(a) If  $U_{DS} \leq V_{DSS1} = V_E \left( \sqrt{1 + \frac{2U_{GS} - V_{OFF}}{V_E(1+\delta)}} - 1 \right)$  (linear):  $I_D = \beta \cdot \left( U_{GS} - V_{OFF} - U_{DS} \frac{1+\delta}{2} \right) \cdot U_{DS}$

(b) Otherwise (saturation region):  $I_D = I_{DSS1} \cdot \left( 1 + \frac{U_{DS} - V_{DSS1}}{V_E + V_{DSS1}} \right)$ , where  $I_{DSS1}$  is calculated from (a) for  $U_{DS} = V_{DSS1}$ .

3. If  $U_{GS} \geq V_{FB}$  and  $U_{GS} - V_{FB} \geq U_{DS} \geq 0$  (fully enhanced), let  $U_{GF} = U_{GS} - V_{FB}$ ,  $r = r_0 / (1 + \theta \cdot U_{GF})$ , then:  $I_D = \beta \cdot \left[ \left( U_{GP} - U_{DS} \frac{1+\delta}{2} \right) \cdot U_{DS} + (r-1) \cdot \left( U_{GF} - \frac{U_{DS}}{2} \right) \cdot U_{DS} \right]$ .

4. Otherwise (partly enhanced).

(c) If  $U_{DS} \leq V_{DSS2} = V_E \left[ \sqrt{1 + \frac{2}{1+\delta} \cdot \left[ \frac{U_{GP}}{V_E} - \frac{r-1}{2} \left( \frac{U_{GF}}{V_E} \right)^2 \right]} - 1 \right]$  (linear):

$$I_D = \beta \cdot \left[ \left( U_{GP} - U_{DS} \frac{1+\delta}{2} \right) \cdot U_{DS} + (r-1) \frac{U_{GF}^2}{2} \right].$$

(d) Otherwise (saturation):  $I_D = I_{DSS2} \left( 1 + \frac{U_{DS} - V_{DSS2}}{V_E + V_{DSS2}} \right)$ ,  $I_{DSS2}$  calculated from (c) for  $U_{DS} = V_{DSS2}$

Joint fitting of Merckel model transfer and output electrical characteristics to measurements for 7 activity levels of the main potassium ion variable in the range  $[10^{-6}, 10^{-1}]$  mole/l with interfering sodium ions 0.1 mol/l can be observed in Fig. 5. The composite model exhibits maximum relative error of 4.9%. For the narrower range  $[10^{-6}, 10^{-2}]$  mol/l the error was only 3%. The model has been positively verified for a depletion mode MOSFET-based CHEMFET device.

Table 2 Electrical parameters of the CHEMFET sensor

Parameter	Name	Typical value
$\beta$	Transconductance	1.26 [mS/V]
$V_{OFF}$	Offset voltage	-2.28 [V]
$V_{FB}$	Flat bands voltage	-0.215 [V]
$V_E$	Early voltage	32.7 [V]
$\delta$		0.181
$\theta$		$2.92 \cdot 10^{-3}$ [V <sup>-1</sup> ]
$r_0$		1.4

For rational design of the CHEMFET sensor it was necessary to develop a model which does not place constraints on biasing and includes a subtle dependency of sensor response  $VGR$  not only on ions but also on the operating point  $ID$ ,  $VDS$ . We can see, that a separable CHEMFET model could be true under two conditions: 1) the FET should have at least floating conducting gate, that would provide equipotentiality of the “external” gate insulator surface, looking from the substrate, 2) potential of the gate should not depend on phenomena inside transistor, but be completely, determined by electrical field in electrolytes and the membrane and so dependent on electrolyte contents.

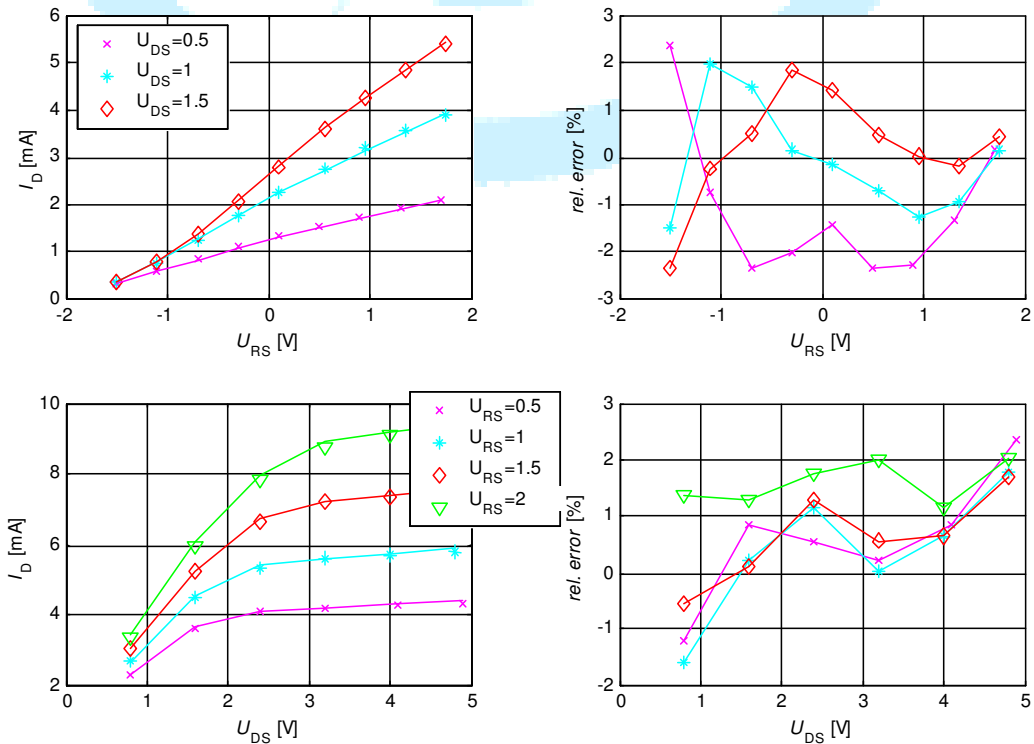


Figure 16. MOSFET transfer and output characteristics fitting

In practice CHEMFETs are made of gateless FET structures, where the equipotentiality of the gate insulator surface is not provided by conduction of electrons in the gate material, but by movement of mobile ions of the internal. Second, changing gate surface potential involves movement of charge on both surfaces of the gate insulator. Since charge in the semiconductor depends on electric field due to  $U_{DS}$  voltage, so the gate surface potential generally also

depends on  $U_{DS}$ . Detailed measurements show that for small values of activity sensor output does depend on FET drain current, and so the separable model is not accurate. Variations of voltage due to change of drain current is about 20 mV for this device. Since maximum slope of the response is approximately 52mV per decade of activity change, the observed ambiguity of sensor output response due to variation of the operating point is significant. It is interesting to note, that the variation decreases to 3mV for  $U_{DS} = 1$  V and below 2mV for  $U_{DS} = 1.5$  V. Similar values were found for other devices. It seems that operating point influences chemical model parameters significantly. Small  $U_{DS}$  value results in worst fit and strongest influence of  $I_D$  upon model parameters. Moreover we have observed strong correlation between significant variations of sensor voltage and linear mode of FET operation. These observations contradict opinions, which advocate small biasing voltage  $U_{DS}$ . The above presented findings do not contradict opinions, which consider CHEMFET based sensors a competitive technology for implementation of low cost portable instruments, but it raises a warning regarding selection of operating point for a depletion type FET structure.

Due to considerable complication and so low efficiency of quantitative modelling of the reported phenomena, based on unified charge-based description of the whole CHEMFET with the membrane, tested and reference electrolytes, in this project we rather prefer a more efficient behavioural approach (Deliverable 11).

#### **IV - Conclusions**

At the reported stage of the project SEWING the following works have been done and the following problems solved:

- 1) Two physical models (LEVEL1 and LEVEL2) of  $H^+$  sensitive ISFET static behaviour were presented. They represent different complexity and covers ideal and to some extent non ideal work of the sensor. These models together with the semiconductor part model can be used by optimisation based parameter extraction procedures.
- 2) The physical, large signal model of the ISFET sensor has been developed and presented.
- 3) The extended thermal model of ISFET was presented that covers the thermal dependencies of four particular parts of the sensor system (reference electrode, solution, semiconductor etc.)
- 4) Creation and implementation of mathematical models of the CHEMFET device based on understanding of its physics. These models are based on a Van den Berg theory that considers such phenomena as sensor sensitivity, selectivity, offset and temperature dependence. Since the full model (see III.1) is too complicated, to improve simulation efficiency and adapt model accuracy to engineering needs - a simplified SNE model (see III.2) has been proposed. These two models enable data fusion from sensors during monitoring of different ions. Further model simplification will be possible in behavioural approach.
- 5) Development of parameter identification techniques for these models. The first one is rough, based on analysis of formulae (5) and (6). The second one is based on the optimisation based model fitting.
- 6) As an aid in modeling a research software has been created to efficiently store/search/retrieve/visualise measurement data and to perform optimization based parameter extraction. More details about this software can be found in Deliverable 11.