Sensing with FETs
- once, now, future -

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Once – bioelectricity, electrophysiological recordings –
(ISFET was not invented as chemical sensor)

(a) Monophasic potential, recorded with an ion sensitive field effect device. (b) Biphasic recording, originating from a similar device which was (temporarily) not sensitive for ions. Both registrations from the flexor tibialis of a Locust.
The Ion Sensitive Field-Effect Transistor (ISFET) is a special potentiometric sensor.

Why special?
- Unlike other potentiometric sensors, absolutely no galvanic contact exists between the solution and the silicon sensor chip

The ISFET potentiometric sensor functions essentially different:
- Information is transferred via an electric field (FET)
- Charge is the source of any (static) electric field
- The nature of this charge is ions (IS)

| charge from ions in the chemical world | predictable behaviour of charge in the electrical world | mirror |
Once – operational principle of the ISFET-

- From an electronic point of view:
  ISFET = MOSFET
  (Metal Oxide Semiconductor FET)
Once – operational principle of the ISFET-

**ISFET = MOSFET** - some theory

\[ I_D = \frac{C_{ox}\mu WL}{2} \left\{ V_{GS} - \left( \frac{\Phi_M}{q} - \frac{\Phi_S}{q} + 2\phi_B - \frac{Q_B}{C_{ox}} \right) - \frac{1}{2} V_{DS} \right\} \cdot V_{DS} \]

\[ I_D = \frac{C_{ox}\mu W}{L} \left\{ V_{GS} - \left( V_{ref} - \psi_0 - \chi^{sol} - \frac{\Phi_S}{q} + 2\phi_B - \frac{Q_B}{C_{ox}} \right) - \frac{1}{2} V_{DS} \right\} \cdot V_{DS} \]

\( \psi_0 \) is pH-sensitive. Why?
The pH sensitivity of an ISFET

The amphoteric equilibrium reactions at the oxide surface

- The nature of the ionic charge in the chemical world (mirrored in the electrical world)

\[
\text{SiOH} \Leftrightarrow \text{SiO}^- + H_B^+
\]

\[
\text{SiOH}_2^+ \Leftrightarrow \text{SiOH} + H_B^+
\]
The pH sensitivity of an ISFET

\[
\frac{\partial \psi_0}{\partial p H_B} = -2.3 \frac{kT}{q} \cdot \alpha
\]

\[
\alpha = \frac{1}{2.3kT C_{dif}^2 + q^2 \beta_{int}} + 1
\]

- Parameter \( \alpha \) is a dimensionless sensitivity parameter, varying between 0 and 1, depending on the intrinsic buffer capacity, \( \beta_{int} \), of the oxide surface and the differential double-layer capacitance, \( C_{dif} \).

- If \( \alpha \) approaches 1, the ISFET shows Nernstian sensitivity of -59 mV/pH at 298 K.

- This is the case for a high value of the intrinsic buffer capacity, which is a function of 3 material parameters of the oxide:
  - the acid and base equilibrium constants of the oxide surface groups,
  - the total density of available surface sites.

- Remember:

\[
I_D = \frac{C_{ox} \mu W}{L} \left\{ V_{GS} - \left( V_{ref} - \psi_0 - \chi_{sol} \frac{\Phi_s}{q} + 2\phi_B - \frac{Q_B}{C_{ox}} \right) - \frac{1}{2} V_{DS} \right\} \cdot V_{DS}
\]
The pH sensitivity of an ISFET  

**Experimental verification**

- Theoretical and experimental pH response for both SiO\(_2\) (left) and a Al\(_2\)O\(_3\) (right) gate oxide ISFETs

The theoretical (solid curve) and experimental (dashed curve) total pH responses of two types of ISFETs: SiO\(_2\) gate oxide at the left graph, Al\(_2\)O\(_3\) gate oxide at the right graph.
The ISFET – instrumentation -

Electronic read-out
  • simple, but smart circuit

U_{out} \psi_0 = f(pH)

Less than €2,- circuit

The principle of the ISFET-amplifier circuit.
The ISFET – in practice -

Photographs of some ISFETs
From ISFET to CHEMFET

Reinhoudt
Some results of CHEMFETs

Brzozka Warsaw University of Technology, Poland

Torbicz Institute of Biocybernetics and Biomedical Engineering of the Polish Academy of Sciences, Poland
Advanced application of an ISFET

Case study: coulometric sensor-actuator systems

Concept:

From uni-directional to bi-directional data flow
Advanced application of an ISFET

Case study: *coulometric sensor-actuator systems* for acid/base titration

Implementation:

Actuator: local pH control by water electrolysis

\[
\begin{align*}
2\text{H}_2\text{O} & \leftrightarrow 4\text{H}^+ + 4\text{e} + \text{O}_2 \\
2\text{H}_2\text{O} + 2\text{e} & \leftrightarrow 2\text{OH}^- + \text{H}_2
\end{align*}
\]

at the anode

at the cathode

Sensor: pH-sensitive ISFET
**Advanced application of an ISFET**

Case study: *coulometric sensor-actuator systems for acid/base titration*

Measurement set up:

No reference electrode is necessary, due to the dynamic mode of operation and the differential measurement set up.

Olthuis et al.,
Sensors and Actuators, Volume 17, Issue 1-2, 1989, P. 279-283
Advanced application of an ISFET

Case study: coulometric sensor-actuator systems for acid/base titration

Typical coulometric titration - measurement result

![Graph showing ISFET ampl. output vs. time](graph)

- [NaOH]=2 mM, \(i_{\text{act}}=10\ \mu\text{A}\)

- End-point of the titration easily detectable
- Time \(t_{\text{end}}\) contains the concentration information
Advanced application of an ISFET

Case study: coulometric sensor-actuator systems for acid/base titration

Results of a series of measurements both in HNO₃ and HAc:

\[
\frac{\partial \sqrt{t_{\text{end}}}}{\partial C_{\text{acid}}} = \frac{F \sqrt{\pi D_{\text{acid}}}}{2 j_c}
\]
**Advanced application:** on-line monitoring of fermentation with ISFETs – realized device

Si Nanowires as FET sensors

- exploring the sensing limitations of silicon nanowires.
- label-free detection.
- Si-NW sensors are nanoscale versions of ISFET sensors.
- carefully study the sensing limitations, critical device characteristics and interface behavior.

Songyue Chen et al.,
Shortest possible

Conclusion

• the ISFET is still very much alive