ISFET
Ion Sensitive Field Effect Transistor

Using a FET to measure the pH of a liquid

- In a dilute aqueous solution the pH give a measure of the concentration of hydrogen ions in the solution

\[ pH \approx -\log_{10} \left( \frac{[H^+]}{mol/l} \right) \]

This shows that the pH is related to the concentration of hydrogen ions in the liquid

<table>
<thead>
<tr>
<th>Substance</th>
<th>pH</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lemon juice</td>
<td>2.4</td>
</tr>
<tr>
<td>Cola</td>
<td>2.5</td>
</tr>
<tr>
<td>Vinegar</td>
<td>2.9</td>
</tr>
<tr>
<td>Orange</td>
<td>3.5</td>
</tr>
<tr>
<td>Beer</td>
<td>4.5</td>
</tr>
<tr>
<td>Acid Rain</td>
<td>&lt;5.0</td>
</tr>
<tr>
<td>Coffee</td>
<td>5.0</td>
</tr>
<tr>
<td>Tea</td>
<td>5.5</td>
</tr>
<tr>
<td>Milk</td>
<td>6.5</td>
</tr>
<tr>
<td>Pure Water</td>
<td>7.0</td>
</tr>
<tr>
<td>Blood</td>
<td>7.34 – 7.45</td>
</tr>
<tr>
<td>Seawater</td>
<td>7.7 – 8.3</td>
</tr>
<tr>
<td>Hand soap</td>
<td>9.0 – 10.0</td>
</tr>
<tr>
<td>Bleach</td>
<td>12.5</td>
</tr>
</tbody>
</table>

Info from Wikipedia
pH measured using glass electrode

1 a sensing part of electrode, a bulb – membrane of conductive glass – made from a specific sensitive glass composition
2 sometimes the electrode contains a small amount of AgCl precipitate inside the glass electrode
3 internal solution, usually 0.1M HCl for pH electrodes
4 internal electrode, usually silver chloride electrode (Ag/AgCl in KCl of known constant composition)
5 body of electrode, made from non-conductive glass or plastics.
6 reference electrode, usually Ag/AgCl
7 junction with studied solution, usually made from ceramics or capillary with quartz fiber.

Some insight into sensing pH

Liquid to be measured

Known constant composition electrolyte

Glass sensing membrane

e.g. SiO₂ (silicate)

buffers the ion concentration in a thin layer near the membrane

(and thus keeps pH constant in that region)

Ag/AgCl metal rod

electrode
Some insight into sensing pH

Glass sensing membrane
Liquid to be measured  Known constant composition electrolyte  Ag/AgCl metal rod
Constant and known potential difference.

Reaction of H⁺ with membrane imposes a surface potential dependent on the amount of H⁺ available = pH

Note: buffer keeps pH constant near surface -> H⁺ diffusion from liquid towards interface
How can we measure $\phi_s$?

**Glass sensing membrane**
- Liquid to be measured
- Known constant composition electrolyte
- $\Delta \phi$

By making a closed circuit via a liquid and metal interface -> reference electrode

A liquid can be connected via a membrane-liquid (electrolyte)-metal electrode systems
How can we measure $\phi_s$?

- **Glass sensing membrane**
  - Liquid to be measured
  - Known constant composition electrolyte
  - $\Delta \phi$

- **None ion reactive membrane**
  - Liquid to be measured
  - Known constant composition electrolyte
  - $\Delta \phi$

- $\Delta \phi \propto 2 \phi_s$

**Why not stick to this?**

- Bulky electrode
- Miniature versions are not stable
- Fragile electrodes

**Solution:** Ion Sensitive Field Effect Transistor (ISFET)
Field Effect Transistor

Connecting the ionic world to the electronic world

- No glass thus robust
- Small and highly integratable because compatible with CMOS
- The shape can be adapted for various applications
- Fast response
- Easy manipulation
- Can be stored in dry state
- Easy cleaning (tooth brush + soap!)
- Good sensitivity: 56 - 58 mV/pH
- Good pH range: 2 - 12

![Field Effect Transistor Diagram]

MOSFET
ISFET

Reference electrode
Field Effect Transistor

MOSFET

\[
I_{DS} = \frac{\mu C_{ox} W}{L} \left( (V_{GS} - V_{th}) V_{DS} - \frac{V_{DS}^2}{2} \right)
\]

\[
V_{th} = \frac{\Phi_m - \Phi_s}{e} - \frac{Q_1}{C_{ox}} - \frac{Q_B}{C_{ox}^2} - 2\phi_F
\]

Note: \(\phi_F\) defined as in “Short channel effects” handouts (determines the sign)

Field Effect Transistor

What has changed is the gate set-up. As a consequence the threshold voltage expression will change in the factor that concerns the gate contact: \(\Phi_m\)
Field Effect Transistor

What is the new expression of $\Phi_m$?

Focus on gate area only:
What is the new expression of $\Phi_m$?

Potential difference between liquid and reference electrode
$E_{\text{ref}}$

Potential difference between liquid and oxide surface
Field Effect Transistor

What is the new expression of $\Phi_m$?

Potential difference between liquid and reference electrode $E_{ref}$

Potential difference between liquid and oxide surface

Surface dipole potential of the solution $\chi_{sol}$

Surface potential which results from the chemical reaction $\psi_o$

$$I_{DS} = \frac{\mu C_{ox} W}{L} \left( V_{GS} - V_T \right) \left( V_{DS}^2 - \frac{V_{DS}^2}{2} \right)$$

$$\Phi_m = E_{ref} + \chi_{sol} - \psi_o + \frac{-\Phi_s}{e} - \frac{Q_i}{C_{ox}} - \frac{Q_f}{C_{ox}} + 2\phi_F$$

Chemical reaction at SiO$_2$ surface

Solution

Reaction with H+ of the solution

Thus due to the reaction process a certain amount of charge will appear at the SiO$_2$ surface
SiO$_2$->SiOH surface is amphoteric thus can take but can also give H dependent on pH of solution

Thus dependent on pH we will have a positive or negative charge density at the oxide – liquid interface.

Thus dependent on pH there will be a shift in the threshold voltage via a change in the surface potential: $\psi_0$. 
In FET language:
The chemical reaction at the surface of the oxide will change the charge density on the oxide (similar to applying a gate voltage). Thus that means that the induced charge density in the channel of the FET will change. As a consequence the current $I_{DS}$ will change in function of the pH at the interface of the SiO$_2$ surface.

Note: there is lots of charge (H+) redistribution & diffusion happening in the liquid.
ISFET

SiO2 isn’t that good, better reactions with H can be obtained using Si3N4, Al2O3, and Ta2O5.

One can make the ISFET sensitive to other ions by adding an ion-selective membrane on top of the oxide.

One can add other membranes e.g. an enzyme trapping membrane on top of the oxide layer in order to make an enzyme sensor.

Functionalise the oxide surface with molecules chains that trap specific species. E.g. an antigen immobilised on the surface can trap a virus for which this antigen is active.

Controlled attachment of organic molecules can enhance/change functionality.

-> chemFETs
-> bioFETs
ISFET

Problems include T drift, absorption of liquids, ...

Futuristic approaches using nanowires: surface area to volume ratio in nanowire is large, this means that whatever happens at the surface will have a huge impact on the current through the nanostructure.

Fig. 1. Nanowire-based detection of single viruses. (Left) Schematic shows two nanowire devices, 1 and 2, where the nanowires are modified with different antibody receptors. Specific binding of a single virus to the receptors on nanowire 2 produces a conductance change (Right) characteristic of the surface charge of the virus only in nanowire 2. When the virus unbinds from the surface the conductance returns to the baseline value.

Electrical detection of single viruses
Patolsky, Zheng, Hayden, Lakadamyali, Zhuang, and Lieber
PNAS September 28, 2004 vol. 101 no. 39 14017–14022

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