The sensors for the intelligent micro washing system

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1. The problem

In existing washing systems a constant amount of washing powder is put in the machine. The machine follows a pre-defined washing program with constant processing steps. The user selects the accurate program needed for his particular laundry.
This method has some disadvantages. Because the washing powder must be able to deal with all possible soils a major amount of all components is included in the powder. For the same reason, the washing programs are matched to the worst case. This implementation does not match the nowadays aims for saving the environment. It unnecessarily takes a lot of energy and detergents. An improvement of the washing system is needed to make it more efficient.
The first improvements at the Unilever Research Laboratories concerned the energy problem and a reduction of the environment pollution. A lot of the energy necessary to fasten the washing process is used to heat the water. The first research items concerned the washing at lower temperatures. The results are some new accelerator components.

The second step in the research involves the integration of machine and product in order to make the process more efficient. The assumption is that it is possible to lower the energy consumption and the amount of water and powder without losing the effectiveness of the washing program. This will require an adaptation of both the detergent supply and machine. To avoid the development of a product specific machine (which is a bad idea because of marketing considerations) a new concept was proposed known as the "intelligent (bio)catalytic micro washing system".

2. Intelligent micro washing system

The washing system to be developed is a system that will be added to a washing machine. It first measures some washing parameters, secondary evaluates them and finally adapts the washing process. The system contains a micro controller so human

knowledge can be implemented in the decisions the system makes. The aim is to enlarge the efficiency of the process.
The system must be located in a separated box so it can be applied on both existing and new machines. No intense or long lasting cooperation with machine companies will be necessary.

3. The washing system to be measured

A washing process is a combination of physical and chemical activities controlled by the electronic part of a washing machine. Normally the control logic processes a pre-defined program of washing activities. The user can choose one of a small number of programs.
The user must supply the following things [1]:
- Dirty laundry
- Detergent
- Tap water
- Electric supply

The washing machine returns:
- Clean laundry
- Rinsing water

The detergent consists of actives (ions, etc.), builders, bleach, enzymes, rinse conditioners and additives (pH adjuster for example).

4. Implementation

The sensors needed can be divided in chemical and physical types. A first summation can be:
- Physical:
  - Temperature sensor
  - Conductivity sensor
  - Dynamic surface tension sensor
- Chemical:
  - pH-sensor
  - Bleaching activity sensor
  - Soil in the system

These are all known devices, evaluated in previous research projects and described in literature. The power of this part of the system must be in the reduction of area by combining the sensors and integrating them on one chip.

The measured parameters will give the controller a reason to adapt the process. An adaptation can be chemical and physical also:
- Physical:
  - Temperature adaptation (heating)
  - Mixing the water and chemicals by rotating the container with the laundry
  - Pumping off or adding water
- Chemical:

- Adding detergents

The interface of the sensors with the controller can be made in two ways:
- The sensors can be part of complete separate devices (figure 4.1a). Some devices like ISFETs require an electronic circuitry for proper operation. The controller only has to sample the final measured value. This method gives less possibilities to integrate different sensor functions on one device and requires a larger space.
- The sensors can be devices to which the controller has to apply signals. Another signal can be sampled then from which a desired parameter can be calculated (figure 4.1b).

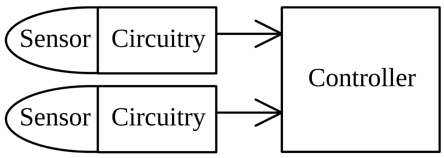


Figure 4.1a

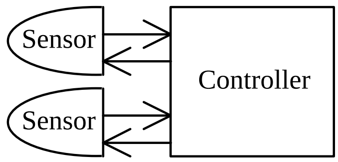


Figure 4.1b

As an example a conductance measurement can be done on two ways. First a circuitry can be build which converts the conductance value to an equivalent electrical voltage. The controller only has to sample this voltage. On the other hand the controller can apply a current itself and sample the voltage. The controller can now calculate a value for the corresponding conductance.

5. Temperature sensors

In the final sensor array a number of semiconductor devices will be present, for example the pH- and other chemical sensors will be ISFET-based. From literature [2] we know that a pn-junction has a temperature dependent behaviour. In order to combine sensors this semiconductor temperature sensor might have good possibilities. A V-I characteristics of a forward-biased diode can be described by the equation [3]:

$$I = \frac{KT^{r}}{\mathrm{h}} \cdot e^{\frac{qV - \mathrm{f}_{g}}{kT}} \qquad (5.1)$$

in which
- K is a constant for the junction
- r is a constant depending on the semiconductor and impurity concentration and is related to the temperature dependence of the mobility of the minority carriers
- h the ionisation factor
- f_g the bandgap energy at 0 K.

The diode voltage follows from (5.1) and is:

$$V = \frac{\mathrm{f}_{g}}{q} + \frac{kT}{q}\left[\ln\left(I\right) - \ln\left(\frac{KT^{r}}{\mathrm{h}}\right)\right] \qquad (5.2)$$

in which the second ln-term can be neglected. the theoretical temperature coefficient a becomes:

$$a = \frac{dV}{dt} = \frac{k}{q}\ln(I) \qquad (5.3)$$

The characteristics of a diode depend on the structure of the junction which can vary a lot from type to type. So an accurate calibration of the temperature dependence is required. Better results can be obtained with transistors or transistor pairs.
The emitter current I_e in a bipolar junction transistor consists of a diffusion, a surface leakage and a recombination current. The collector current I_c mainly consists of the diffusion current, the other two components of the emitter current are drained away by the base. The temperature dependence of the V-I characteristics looks like that of the diode but the constants K and r are related different:

$$V_{be} = \frac{f_g}{q} + \frac{kT}{q}\left[\ln(I_c) - \ln\left(\frac{KT^r}{h}\right)\right] \qquad (5.4)$$

As an indication f_g/q varies between 1.12 and 1.19 eV and r between 3 and 5 for commercially available devices [3]. With two measuring points the voltage difference depends linearly on temperature:

$$\Delta V_{be} = V_{be1} - V_{be2} = \frac{kT}{q}\ln\left(\frac{I_{c1}}{I_{c2}}\right) \qquad (5.5)$$

Now the output voltage is proportional to the absolute temperature (PTAT sensor). Implementing equation (5.5) in a sensor requires two measurements. By applying two matched transistors with different operating points a complete one-measurement PTAT temperature sensor can be obtained [2]. Figure 5.1 shows the principle.

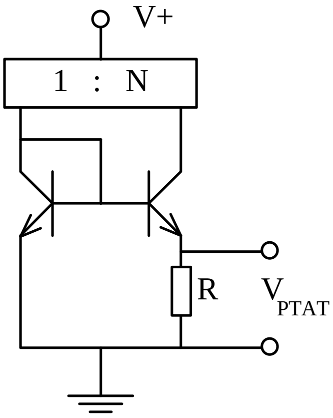


Figure 5.1: A PTAT temperature sensor

A relation for the temperature dependency can be calculated from equation (5.1). Writing (5.1) as:

$$I_c = I_s \cdot e^{\frac{qV_{be}}{kT}} \tag{5.6}$$

with

$$I_s = \frac{KT^r}{\eta} \cdot e^{-\frac{\phi_g}{kT}} \tag{5.7}$$

the output voltage becomes:

$$V_{PTAT} = V_{be1} - V_{be2} = \frac{kT}{q} \ln\left(\frac{I_{s1}}{I_{s2}} \cdot N\right) \tag{5.8}$$

with N the ratio of collector currents. This voltage is proportional to the temperature for a wide range.

6. The pH sensor

As pH sensor the ISFET will be useful. The ISFET resembles the MOSFET a lot except that the solution to be measured is between the insulator (SiO_2) and the gate electrode (figure 6.1).

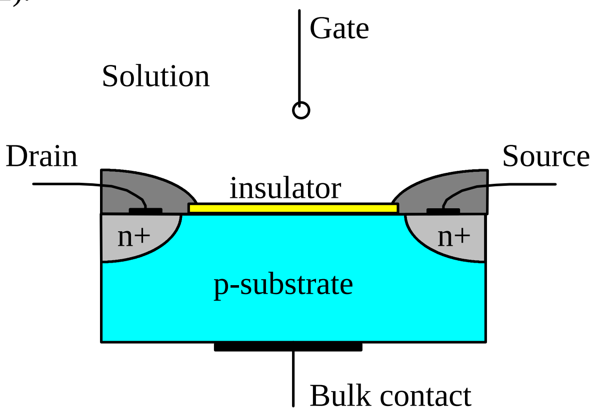


Figure 6.1: The ISFET

The ISFET satisfies the same equations as the MOSFET. In strong inversion and saturated operation the drain current I_{DS} is:

$$I_{DS} = \mu \cdot C_{ox} \cdot \frac{W}{L}\left[(V_{GS} - V_T) \cdot V_{DS} - \tfrac{1}{2} V_{DS}{}^2\right] \tag{6.1}$$

where V_{DS} and V_{GS} are the drain-source and gate-source potential respectively and V_T the threshold voltage. The parameters μ (the electron mobility), C_{ox} (the square oxide capacity) W and L (width and length of the channel) are constants for the configuration. The threshold voltage however is dependent on the interface potential of the surface between the electrolyte and the insulator, which is proportional to the pH. The complete dependence of the threshold voltage on the pH is a linear one.

$$V_T = A - B \cdot (pH_{pzc} - pH) \qquad (6.2)$$

In this equation the factors A and B are constants containing a large number of chemical and physical factors [4].

To measure the threshold voltage the ISFET must biased with a constant drain current and supplied with a constant drain-source voltage. A circuit that satisfies this conditions is drawn in figure 6.2. The gate source voltage is now proportional to the threshold voltage according to equation 6.1.

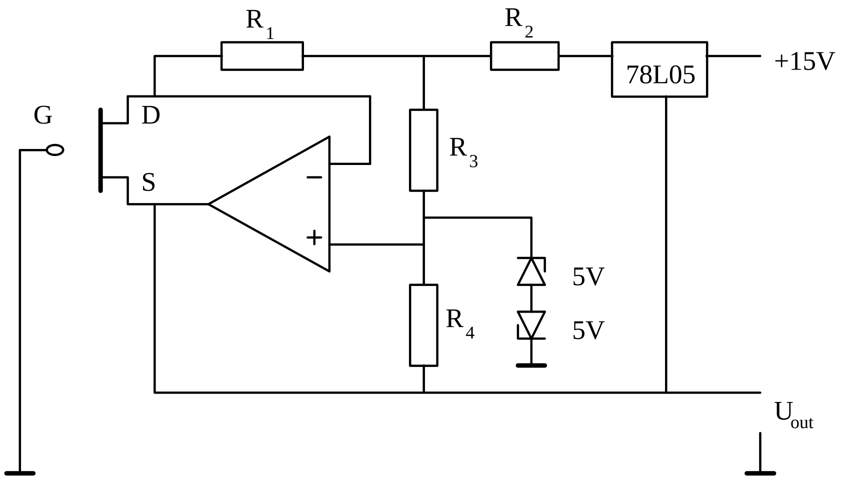


Figure 6.2: The ISFET amplifier

The sensitivity of the total system becomes:

$$\frac{\mathrm{d}V_{GS}}{\mathrm{d}pH} = -59\,\mathrm{mV/pH} \qquad (6.3).$$

As mentioned before, it is also possible to connect the D/A-converters of the micro controller to the drain and source and let the controller find out the accurate operating point itself. This makes the system more flexible and geometrical smaller. A disadvantage is that the measure time will increase.

7. The conductivity sensor

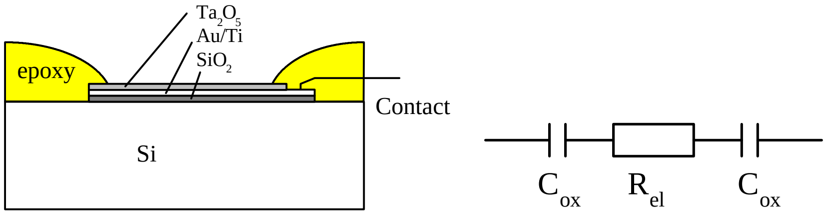
In conductivity measurements a current is led through the solvent and the corresponding voltage drop is being measured resulting in a resistance R_{el}. The conductivity σ of the liquid can now be calculated using the cell constant K_c.

$$R_{el} = \frac{1}{\sigma} \cdot K_c \qquad (7.1)$$

The problem is that with normal metal electrodes an overpotential is generated when the current is applied which results in a difference between the measured impedance and the desired resistance of the solvent.
Here are a number of possibilities to eliminate this problem.

Ta_2O_5 electrode [5]

By adding a Ta_2O_5 layer on a gold electrode the generation of undesired potentials at the solid/liquid surface is minimised. The only problem is that a series capacitance of the Ta_2O_5 layer is introduced. Figure 7.1a shows a realisation of a structure using this layer and figure 7.1b gives the equivalent electrical circuit with two Ta_2O_5 layer capacitances (C_{ox}) and one solvent resistance.



[a] Structure [b] Electrical equivalent

Figure 7.1: The Ta_2O_5 electrode

Two measure the resistance R_{el} of the solvent two operational modes were found in literature [6]. In the oscillator mode, the conductivity of the solvent results in a certain frequency of an oscillator. In the pole mode, a series inductor results in the real electrical resistance of the liquid at the resonance frequency of the circuit.

Single ISFET method [7]

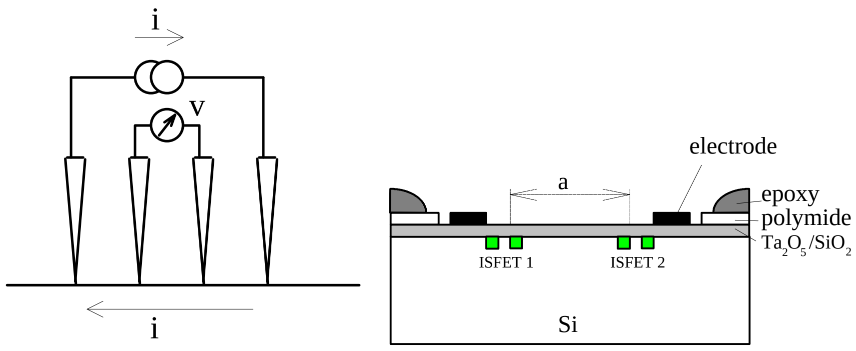
By evaluating the small signal behaviour of an ISFET system, it was found that the transfer function looks like a low pass filter with a cut-off frequency of:

$$f_{-3dB} = \frac{1}{2\pi R_{el}\left(C_{GD} + C_{GS}\right)} \quad (7.2)$$

with C_{GD} and C_{GS} the gate to drain and gate to source capacitors. From this frequency the electrical resistance R_{el} of the solvent (and so the conductivity) can be calculated. This method gives a linear relation between the concentration and the cut-off frequency [7].

Four point configuration using ISFETs [8]

In a four point method two electrodes are used to generate a current through the electrolyte. These electrodes are not critical: their overpotentials will not affect the measurement. Two other electrodes are used to sense a potential difference in the liquid. If no current flows through the electrodes, the measured potential is the actual liquid potential (figure 7.2a).



[a] Theoretical [b] Implementation with two ISFETs

Figure 7.2: Four point method

In figure 7.2b an implementation on a silicon wafer is given. The two black electrodes are platinum and supply the current. The two ISFETs are sensing the electrolyte potential with their "gates", separated by a distance a. By using a differential circuit a reliable measurements from 0.5 up to 100 mM KCl were reported [8]. The advantage of this method is that no reference electrode is needed.

The next table summarises the methods described above.

Table 7.1: Summary of the evaluated conductivity sensing methods

Method	**Range**	**Frequency**
Ta_2O_5 electrode, oscillator mode [6]	0.5 - 100 mM KCl	10 - 27 kHz
Ta_2O_5 electrode, pole mode [6]	0.2 - 100 mM KCl	» 50 kHz
Single ISFET	10 - 100 mM KCl	20 - 400 kHz
Four point conf. with ISFETs	0.5 - 100 mM KCl	1 kHz

8. The dynamic surface tension sensor

Alex Volanschi is working on a surface tension sensor. His sensor is based on producing gas bubbles in a cavity while counting the number of them by monitoring the overpotential.
His work will be studied and possibilities for integration with other sensors will be evaluated. A problem will be that the bubbles will cause a liquid flow that might disturb other measurements.

9. Combining sensors

The ISFET contains some pn-interfaces that might be used to perform the temperature analysis. In figure 9.1a a realisation of an ISFET is drawn with the bulk as channel material. The heavily negative doped drain and source areas both can be used as one side of the diode, the p-substrate is the other one. This pn+ type diodes (or np+ diodes) resemble the metal semiconductor diode.

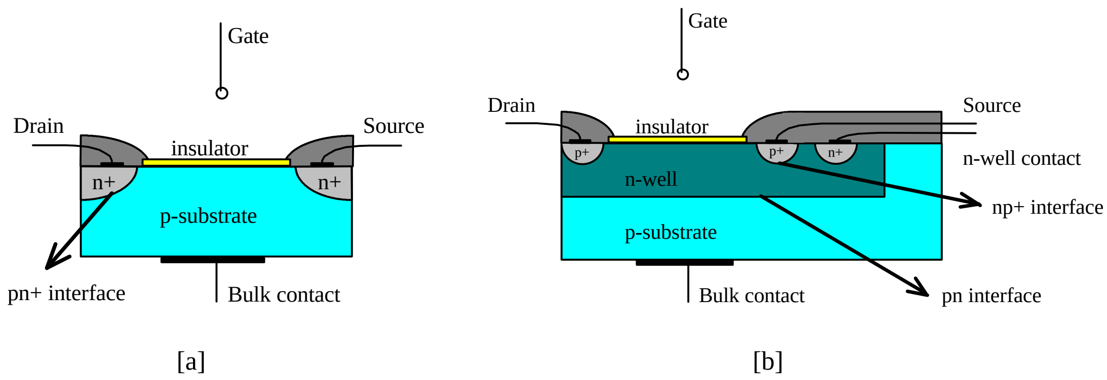


Figure 9.1: Diode interfaces in ISFETs

In case that the ISFET is located in a n-well (figure 9.1.b) two diode junctions are present:
- The interface between the p+ source and the n-well contact is a np+ diode
- The junction between the well and the substrate acts as a diode. This junction can be electronically accessed by the n-well contact and the bulk contact.

In the configuration without a well there is one bipolar mode accessible (remember that for temperature sensing a bipolar transistor was needed). This is drawn in figure 9.2a. Here the bulk functions as the base of the transistor and the drain and source as emitter and collector.

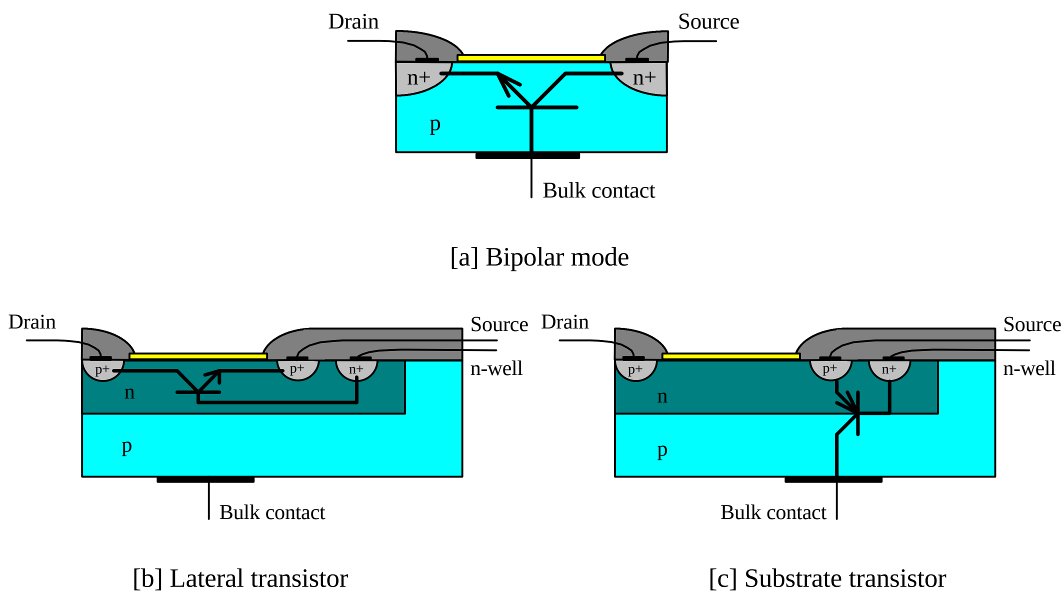


Figure 9.2: Bipolar modes in ISFETs

Two bipolar transistor modes are present in the ISFET structure with a well (figure 9.2b and 9.2c). The first one is the lateral bipolar mode and resembles the previous one the most: both are p+np+ transistors. The second one is the substrate transistor which is a p+np type accessible by source, n-well and bulk contact.
The problem with this bipolar modes of a FET is that they are using areas in which the doping profile is unpredictable.

MOSFETs have another mode known as weak inversion. In this mode the gate-source voltage is lower than the threshold voltage which results in an exponential behaviour of the drain current. This resembles the bipolar junction transistor and is the opposite of the normal strong inversion mode which has a square relation. In the weak inversion mode the MOSFET can be used to replace the BJTs in the PTAT circuit of figure 5.1.
With an ISFET the behaviour in weak inversion mode is hard to predict because of the pH sensitivity which is only defined for strong inversion mode. On first sight this option gives less possibilities than the previous described bipolar modes.

A conductivity measurement can be done using the ISFET in a higher frequency range. This is the method referred before as single ISFET method. The available ISFET can also be used as one of the two probes in the four points method.

Other sensors can be made from an ISFET by adding a special membrane to the oxide. Especially some chemical sensors will be realised by adapting the ISFET. It should be considered to use one of them as the second probe in the four points method for conductivity sensing.

10. References

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