Microfluidic Design of Neuron-MOSFET Based on ISFET

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Abstract: In this Paper we suggest a device which combines the operation of a neuron- MOS [1] [3] and an ISFET [2]. An ISFET is an ion-sensitive field effect transistor used to measure ion concentrations in a solution; when the ion concentration changes, the current through the transistor will change accordingly. A voltage between substrate and the oxide surfaces arises due to an ions sheath. The surface concentration of the -OH groups of the gate materials varies in the aqueous solutions due to pH value. The neuron-MOSFET was first proposed by Shibata and Ohmi in 1991. It contains a conventional MOSFET and a gate electrode which is electrically floating and N-input gates capacitively coupled to the floating gate. The effective gate potential is a function of both the potentials applied and the coupling capacitances. More the coupling capacitance, more the effect of the applied potential on the gate and the output potential. The suggested device contains multiple microchannels that are of varying size and are used to induce a potential on the floating gate. The microchannels (which act as multiple gates) can be arranged to cause flow of charge between the drain and the source of the MOSFET similar to a logic 'and' and logic 'or' operation.
Using COMSOL Multiphysics™ simulation tool the suggested device was simulated.

Keywords: Neuron MOSFET, ISFET, Microchannel, Poiseuille flow, Poisson- Boltzmann equation, Electrical double layer

1. Introduction

Biomedical engineers exploited the possibilities of the chip technology to develop silicon based sensors, to be incorporated in the tip of a catheter (since about 1970). The ISFET sensor is one of the most well-known examples. The ISFET is a type of potentiometric sensor i.e. the electrical potential difference, $\Delta\varphi$, at a solid/liquid interface as function of the ion concentration to be determined is measured. The suggested device has the capability of measuring the output potential based on the ionic concentration of not one but many different ionic solutions. To achieve this, the concept of ν-MOSFET is used. Neuron- MOSFETs were suggested for image processing and smoothing based on capacitive coupling.

In the suggested device, different ionic solutions are made to pass through capillaries on surface of which they form the double layer. This layer consists of ions having a particular charge. The potential of this layer is related to the ionic concentration. This potential is then transferred by capacitive coupling onto the gate of the MOSFET which amplifies the potential for measurement and for further processing if needed. The effect of a particular solution on the output potential can be controlled by manipulating the size of the capacitor formed between the microchannel and the gate.

The Electrical Double Layer (EDL) represents the interface between a solid surface (polarized electrode) and an electrolyte. The charged surface attracts nearby counter-ions and repels co-ions present in the solution. In microsystems, the same electrostatic phenomenon is also present around charged nanoparticles (biomolecules, latex beads…) immersed into an electrolyte: they experience electrostatic interactions which give rise to a counter-ion cloud.

RC circuit models [5] are widely used by electrochemists for representing the EDL. However, in microsystems where applied electric fields can be very strong because of very small dimensions, this approximation fails. Despite the explosive growth of multi-scale modeling for microfluidics, where the continuum is usually coupled to Molecular Dynamics techniques, coupled continuum was investigated based on Poisson-Boltzmann (PB) equation. It is interesting to represent the EDL using COMSOL Multiphysics software application because it is strong coupling to macroscopic equations (Navier- Stokes in our case) is possible.

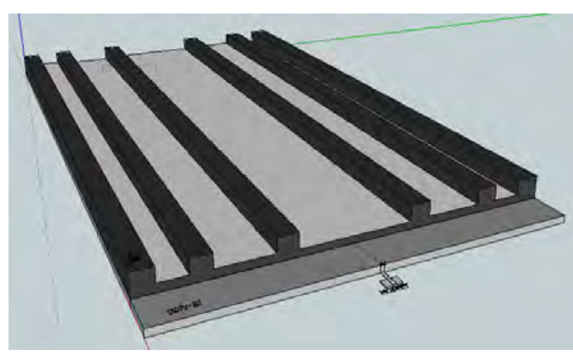

Figure 1: 3-Dimensional structure of proposed device

2. Theory

The operation of an ISFET can best be described by comparing it with its purely electronic analogue, the MOSFET (Metal Oxide Semiconductor Field Effect Transistor).

The metal gate of the MOSFET of Figure 2(a) is replaced by the metal of a reference electrode, whilst the liquid in which this electrode is present makes contact with the bare gate insulator (figure 2(b)).

For both devices the following equation is valid for the non-saturated region (below pinch-off):

$$I_d = \beta(V_{gs} - V_T - \frac{1}{2}.V_{ds}).V_{ds} \qquad (1)$$

$$\beta = \mu.C_{ox.}\frac{W}{L} \qquad (2)$$

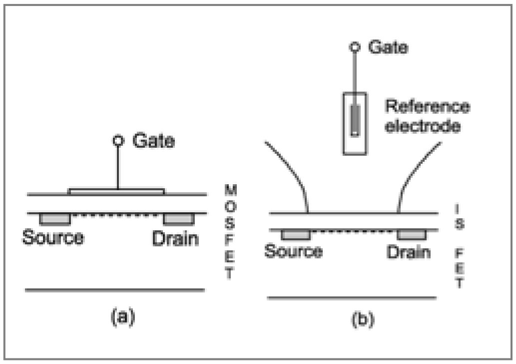

Figure 2: Schematic diagram of (a) MOSFET (b) ISFET [2]

The threshold voltage V_T [10] is given by:

$$V_T = V_{FB} - \frac{Q_d}{C_i} + 2.\varphi_F \qquad (3)$$

The floating gate potential, assuming the substrate is grounded is represented as:

$$\phi_{FG} = Q_{FG0} + \frac{\sum_{i=1}^{i=N} C_i.V_i}{\sum_{i=0}^{i=N} C_i} \qquad (4)$$

The above equation states that the floating gate potential is determined as a linear sum of all input signals weighted by the capacitive coupling coefficients

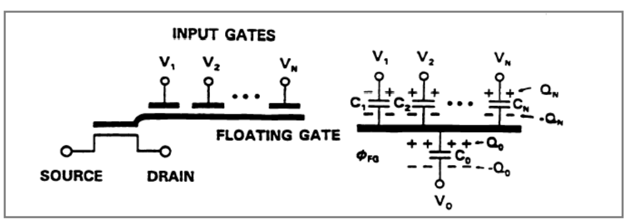

Figure 3: A schematic of a Neuron- MOSFET

2.1. The Poisson-Boltzmann equation

The Poisson-Boltzmann (PB) theory [5] predicts that the surface potential decreases exponentially in the EDL. In the double layer, the inner layer (called the *compact layer*) which is in contact with the electrode and where ions are absorbed on to the surface due to high electrostatic interactions. Outside the compact layer, there is the *diffuse double layer*.

This is the screening phenomenon of the surface charges by the counter-ions. In the PB equation, ions are supposed to be point like charges, the ionic solution is supposed to be a dilute solution (so the ions do not interact with each other) and the solvent (water) is considered as a continuum dielectric of permittivity. $\varepsilon = \varepsilon_{r.}\varepsilon_o$

The charges of the surface induce an electric potential ψ(V) in the electrolyte which acts on each species of ions. Each ion concentration distribution c_i (ions/m3) is given by the Boltzmann distribution where electrostatic ($z_i e\psi$) and thermal (kT) energies balance each other:

$$c_i = c_i^{\infty}.e^{\frac{-z_i e\psi}{kT}} \qquad (5)$$

c_i^{∞} is the ion i concentration in the bulk (n_i being the number of ions i in the electrolyte formula, c_∞ is the bulk concentration), T is the temperature (K) and Boltzmann constant. The proton charge- e and z_i is the ion i charge number.

The non-linear Poisson-Boltzmann (PB) equation can be written as:

$$\vec{\nabla}.(-\varepsilon\vec{\nabla}\psi) = \sum_i z_i e c_i^{\infty}.e^{\frac{-z_i e\psi}{kT}} \qquad (6)$$

On the electrode E, the potential ψE corresponds to the following surface charge density

When moving away from the polarized electrode, the potential decreases exponentially with a characteristic length called the *Debye length*

$$\kappa^{-1} = \sqrt{\frac{\varepsilon kT}{2z^2e^2c^{\infty}}} \qquad (7)$$

2.2. Navier-Stokes Equation

The *Navier–Stokes equations,* describe the motion of fluid substances. These equations arise from applying Newton's second law to fluid motion, together with the assumption that the fluid stress is the sum of a diffusing viscous term (proportional to the gradient of velocity), plus a pressure term . The Navier– Stokes equations dictate not position but rather velocity. A solution of the Navier– Stokes equations is called a velocity field or flow field, which is a description of the velocity of the fluid at a given point in space and time. Once the velocity field is solved for, other quantities of interest (such as flow rate or drag force) may be found.

$$\rho_m\frac{DU}{Dt} = -\nabla P + \rho_m g + \eta\nabla^2 U + \frac{\eta}{3}\nabla(\nabla.U) \qquad (8)$$

Poiseuille's Flow [9]

A classic, and simple, problem in viscous, laminar flow involves the steady-state velocity and pressure distributions for a fluid moving laterally between two plates whose length and width is much greater than the distance separating them. The flow is driven by a pressure gradient in the direction of the flow, and is retarded by viscous drag along both plates, such that these forces are in balance. Let there be a uniform pressure gradient in the x-direction

$$\frac{\partial P}{\partial x} = -K(constant) \quad (9)$$

With these assumptions, the Navier-Stokes equation becomes

$$\frac{\partial^2 U_x}{\partial y^2} = \frac{-K}{\eta} \quad (10)$$

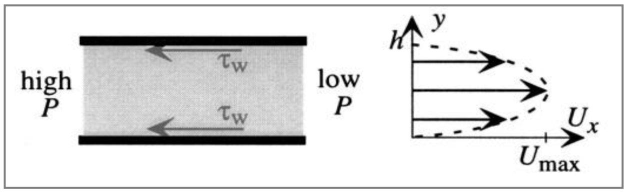

Figure 4: Poiseuille Flow

The lumped-element model for Poiseuille flow can be expressed in both the mechanical and fluidic domains. In that case, the pressure gradient must be expressed in terms of the pressure drop between the ends ΔP spaced by a length *L*.

$$K = \frac{\Delta P}{L} \quad (11)$$

The relation between flow and pressure drop is then

$$\Delta P = \frac{12\eta L}{W h^3} Q \quad (12)$$

3. Simulation and Results

Model Used: ***Fluid Flow using Incompressible Navier- Stokes***

Pressure applied for a desired velocity of 1 cm/s. Velocity profile at inlet pressure of 239.34 Pa (assuming No Slip conditions)

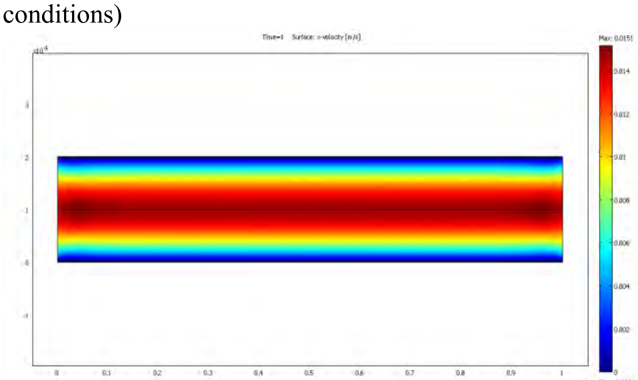

Figure 5: Surface plot of x-direction velocity

The result obtained confirms that the velocity profile is parabolic in nature (Figure 4) with almost zero (exactly zero in case of zero slip) at the boundary.

Model Used: ***PDE, Coefficient form (for Anion)***

The channel was simulated for an aqueous solution of Potassium Chloride (KCl).

Concentration profile: The bulk concentration was assumed to be 10mg/L.

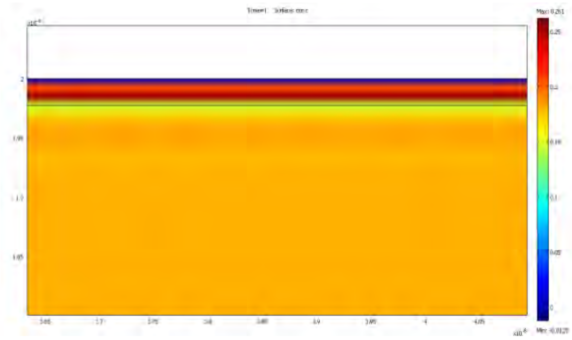

Figure 6: Surface plot of Concentration

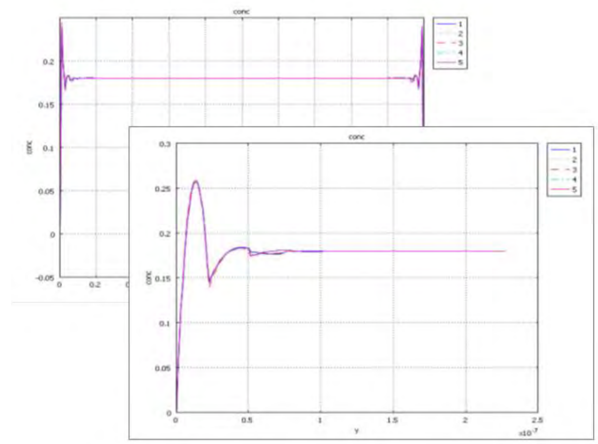

Figure 7: Graph showing variation of concentration in Electrical Double Layer (Rear- the complete plot, Front- enlarged section)

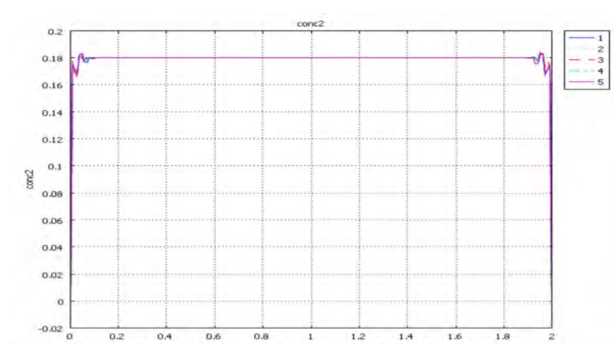

Figure 8: Concentration profile of counter-ion

It can be seen from the concentration profile that the concentration of the ions is very high around the boundaries and equal to bulk concentration towards the inside of the capillary. The graphs above show that the overall solution remains neutral, for the concentration of the counter ion decreases around the boundary and increases in the diffuse layer completing the double layer structure.

Model Used: ***Electrostatics (emes) (MEMS module)***

A potential of the order of a few mV is obtained on the boundary of the microchannel as a result of the redistribution of the ions.

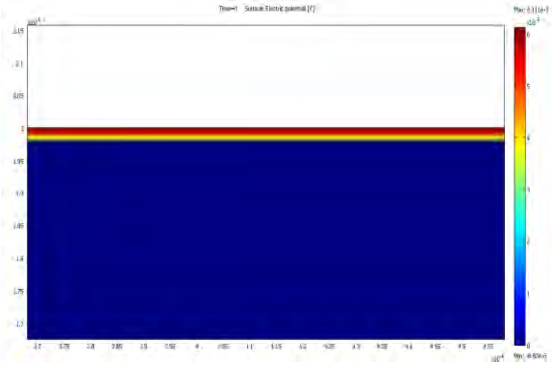

Figure 9: Surface plot of potential in the Electrical Double Layer

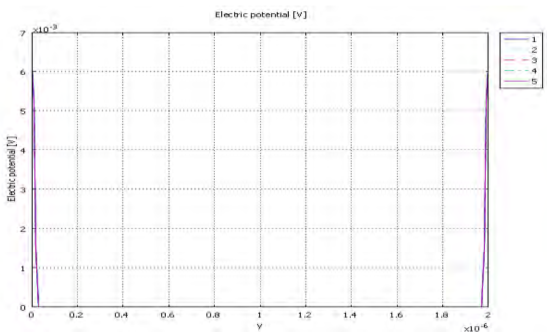

Figure 10: Graph of potential along the cross- section of the microchannel

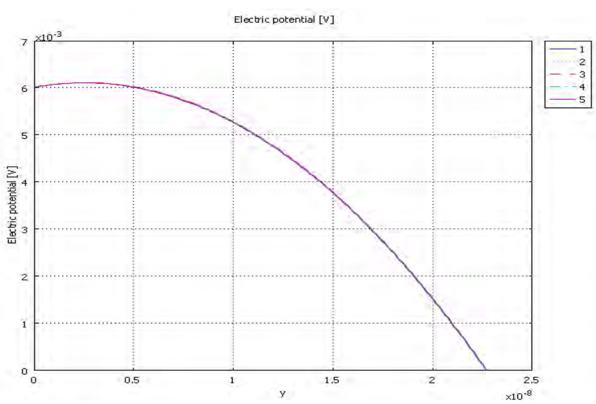

Figure 11: Graph showing potential in the Electrical Double Layer

The surface of the channel was in contact with Si_3N_4 which was assumed to be a linear dielectric. It induced an opposite charge (negative in our case) on the contact surface causing an opposite charge (positive in our case) on the surface of Si_3N_4 in contact with poly-Silicon. 5 such channels of different cross-section width were in contact with poly-Silicon acting like a υ-MOSFET.

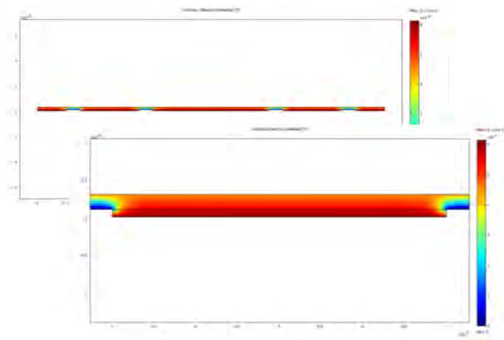

Figure 12: Surface plot of Si3N4 dielectrics in contact with poly- Si (Rear- the complete plot, Front- enlarged section)

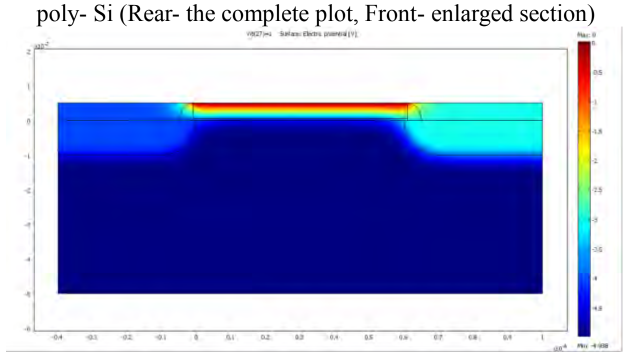

Figure 13: Potential in a MOSFET

The MOSFET was simulated using the example from the COMSOL Multiphysics™ Library and the output potential was observed.

4. Conclusion

The microchannel simulated satisfied the Navier-Stokes Equations. The concentration gradients for the ions confirmed the formation of the double layer. The potential gradient was generated by the rearrangement of the ions. The potentials of the microchannels when capacitively coupled to a floating gate were indeed a function of the potential applied and the coupling capacitance.

5. Applications and Future Prospects

The suggested device modifies the basic ISFET structure to perform a mathematical operation by choosing appropriate coupling capacitances. Device helps in triggering an electrical output when the ion concentrations of more than one ions reaches a desired level. The electrical output can be refined and amplified by using additional circuitry.

The ability of a fluid to act as a coolant enhances the capabilities of the device. The design simulated was a basic structure. As an extension of the project one can try optimizing the shape and size of the microchannel and the concentration of ions. A circuit performing a logic operation, depending on voltage applied to the gates (and hence on the concentration of the ions) can be developed.

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