Sensors based in suspended gate field effect transistors for pH measurements

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Abstract. This work presents a new pH sensor based on the architecture SGFET (Suspended Gate Field Effect Transistor). The pH variations are obtained using the threshold voltage and the transfer characteristics shift of the SGFET. To evaluate the accuracy and reliability of the pH sensor, pH variations were measured directly in the solution using both the SGFET and a commercial pH-meter.

1. Introduction
The usual glass pH-meter are often being replaced by Ion Sensitive Field Effect Transistors (ISFET’s). Since Bergveld [1] first employed the field effect transistor in neuro-physiological measurements in 1970, ISFET’s have been developed into a new type of chemical sensing electrode. Many theoretical and experimental studies have been published describing the behavior of this chemical-sensing electronic device [2,3].

The sensitivity of ISFETs can be increased by using a suspended gate at a sub-micrometric distance from the channel of the transistor [4]. This sub-micrometric distance allows the field effect to increase the sensitivity by more than 7 times the Nernstian sensitivity [5]. This new technology is called Suspended Gate Field Effect Transistor (SGFET) and was originally developed by Janata [6]. Other variations of the structure followed after the SGFET, such as Hybrid SGFET [7] and Floating Gate FET [8]. These first structures were developed only with the goal of fixing the usual reference electrode of ISFETs because the suspended gate was too far from the transistor channel to benefit from the field effect.

In this paper, technological improvements of the ISFETs structure are studied with the goal of obtaining practical, simple to use and highly sensitive pH-meters. This work presents different ways of polarizing SGFET’s and the relative pH sensitivity of each method. Using the results of polarization tests the architecture of an array-based micro-system has been developed and tested.

1.1. SGFET process and electrical principle
Figure 1 shows a scheme of a P-type SGFET just before removing the Undoped Sicila Glass (USG) sacrificial layer. Low-doped N type silicon wafers with <100> orientation were used as

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substrates. The drain and source wells come from boron nitride diffusion at 1100°C with a 1µm SiO$_2$ as protective layer. The channel is then oxidized at 1100°C so that the SiO$_2$ thickness is kept at 70 nm. After that, the channel oxide is protected by a 50 nm Si$_3$N$_4$ LPCVD (Low Pressure Chemical Vapour Deposition) layer deposited at 600°C. On the silicon nitride layer, a 500 nm USG sacrificial layer is deposited by Plasma-Enhanced Chemical Vapor Deposition (PECVD) at 350°C, followed by a 50 nm silicon nitride layer which acts as isolation layer for the bottom of the suspended gate.

![Figure 1](image1.png)  
**Figure 1.** Scheme of the structure of P type SGFET before releasing of the USG sacrificial layer.

Gate and drain source contacts are then obtained by adding a 500 nm thick P-type polysilicon layer amorphously deposited at 550°C and crystallized during 12h at 600°C. A last 50 nm of a nitride layer protects the top of the gate. Vias are opened in this silicon nitride layer to make the contacts with Al path. All surface metal layers are protected with oxide layers such as BPSG (Boro Phosphorous Silica Glass) and nitride (PECVD) to avoid direct electrical leakage during the use in a liquid environment. The last step of the process is the release of the gate by HF etching of the USG sacrificial layer. A Scanning Electron Microscope view of the final structure is shown in Figure 2.

For this architecture, the principle of ph-meter measurement is based in the concentration of charges in the gap between channel and gate. The concentration of H$^+$ or OH$^-$ in the gap influences the threshold voltage ($V_T$) of the SGFET as shown in equation 1,

$$V_T = \phi_{MS} + 2\phi_F + \frac{Q_{ss}}{C_{ox}} - \frac{1}{C_{ox}^e} \int_{0}^{e_{ox}} \chi_p(x)dx$$  

(1)

Where $\phi_F$ is the Fermi potential in the bulk of the n-type semiconductor, $\phi_{MS}$ is the difference in the work function between the metal and the semiconductor, $Q_{ss}$ is the density of charges in the effective gate oxide, $C_{ox}$ is the total capacitance between the gate and the semiconductor, $e_{ox}$ is the thickness of the insulat and $\chi_p(x)$ is the charge in the insulator at a distance x from the gate.

2. pH measurements

In a p-type SGFET, the absolute value of $V_T$ (threshold voltage) increases as the pH decreases. In the experiments presented in this paper, adding small amounts of the basic solution varied the pH of the acid solution. After waiting a few seconds, the transfer characteristics of the SGFETs were measured. Figure 3 shows the transfer characteristics and the trans-conductance of a P-type ISFET for different pH values.
Figure 3. Transfer characteristics $I_{ds}=f(V_{gs})$ and trans-conductance ($g_m$) of P-type SGFET in different pH solutions with $V_{ds}=-0.3$ V.

The trans-conductance was calculated using the transfer characteristics. The sensitivity of the SGFET sensors was calculated using the $V_{gs}$ values for the maximum trans-conductance. A sensitivity of approximately 630 mV/pH was obtained. This value is much higher than those reported in literature for usual pH-meters. Actually, the sensitivity of usual pH-meters is limited by the theoretical Nernstian response of 59 mV/pH at 20°C.

Figure 4 shows the transfer characteristics for solutions with different pH values. Figure 5 shows the trans-conductance obtained from the transfer characteristics. A sensitivity of 650 mV/pH is obtained from the linear relationship between $V_{gs}$ and pH, shown in figure 6. This result demonstrates the high sensitivity and reliability of SGFET’s sensors.
3. Conclusion
An SGFET sensor that functions as a fully electronic pH-meter has been developed using standard microelectronics technology. The detection principle is based on the field effect mechanism of a MOSFET. The system reacts to the shift of the gap capacitance due to pH variation. The measurements demonstrated the simplicity of the method used to bias the sensor and to analyze the output signal. It has been shown that a pH variation could be detected with a good sensitivity of approximately 650 mV/pH. Finally, the method presented has good reliability and sensitivity.

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