

Nano-porous poly-silicon gated ion selective field effect transistors

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ABSTRACT

We report a novel nano-porous polysilicon gate ion selective field effect transistor with dramatic improvement in its sensitivity as a pH-meter. The gate region is converted into a nano-porous structure, increasing the effective area of the transistor capacitance and consequently, transistor current shows much higher sensitivity to pH variations. By applying a constant current source, a voltage shift of 150 to 450 mV/pH is measured which is beyond the sensitivity of regular ISFET devices. This higher value is attributed to the 3-dimensional geometry of the nano-porous structure to adsorb H^+ or OH^- in electrolytes. A simple model is proposed to describe the transistor behavior.

Keywords: nano-porous poly silicon, IS-FET, pH-meter.

I. INTRODUCTION

Ion selective field effect transistors (ISFET) are electronic devices that have important role in the development of chemical sensors[1-5]. Generally, ISFET is analogous to an ordinary MOSFET transistor where the metallic gate is replaced by a sensitive membrane and a reference electrode[6,7]. The SiO_2 surface contains reactive $SiOH$ groups, which can be used for covalent attachment of organic molecules and polymers[8]. The most important use of ISFETs is as pH meters. The adsorbed charge layer on the sensitive membrane causes a shift in the threshold voltage and the pH sensitivity is limited to values around 59mV/pH because of the Nernst law [9].

In this paper we present a novel ISFET structure where the gate region is covered with a nano-porous polysilicon layer and acts as a charge transfer medium to the underneath gate-oxide layer. Using this approach the effective area of the transistor increases quite dramatically and the accumulated charge on the transistor depends on the "ion" concentration (pH) in the liquid. The highly doped nano-structured polysilicon layer acts as a matrix of nano wires which transfers the absorbed charges (ions) onto the underlying gate-oxide layer. This in turn leads to a significant rise in the transistor current which is not observed in standard ISFET devices.

II. EXPERIMENTAL

Fig. 1 describes the schematic of the pH meter and the nano-porous structures on the gate oxide layer. pH-meters were fabricated using N-MOS transistors on P-type $\langle 100 \rangle$ -oriented silicon wafers with channel length and width of 50 and 400 μm , respectively. A thermally grown silicon dioxide with a thickness of 130nm is used as the gate dielectric material. The thickness of the polysilicon layer, deposited on the oxide layer, is about 1 μm . After defining the source and drain regions with a diffusion process, a tri-layer of PECVD-deposited SiO_2 , Si_3N_4 and SiO_2 passivates the whole structure. The key feature of this device is the formation of nano-porous structures right on the gate region, which is accomplished using a hydrogen-assisted reactive ion etching with a mixture of hydrogen and oxygen and a trace value of SF_6 in a highly programmable fashion. Details about this process are found elsewhere [10].

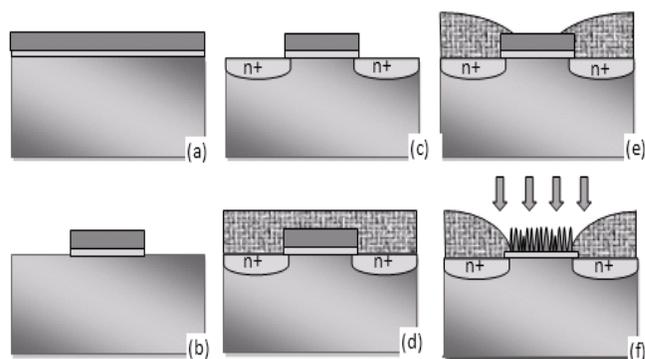


Figure 1: The fabrication process of pH meter and the evolution of the nano-porous layer on the gate oxide. (a) poly-silicon and oxide growth, (b) patterning the gate region, (c) source/drain diffusion, (d) passivation of source and drain regions and (e) patterning the passivation layer and finally (f) nano-porous silicon formation.

Fig. 2 collects several SEM images of the nano-porous poly silicon films on the oxide layer, indicating the formation of highly porous features. The cross-sectional views of the nano-porous structures are seen in parts (a) and (b) of this figure, confirming the presence of a highly porous layer with holes of the order of 50nm. Arrows in part (a) shows

the interface between nano-porous polysilicon and the gate oxide layer. Fig. 3 shows the AFM image of the layers, further corroborating the nano-porosity of the poly silicon layer.

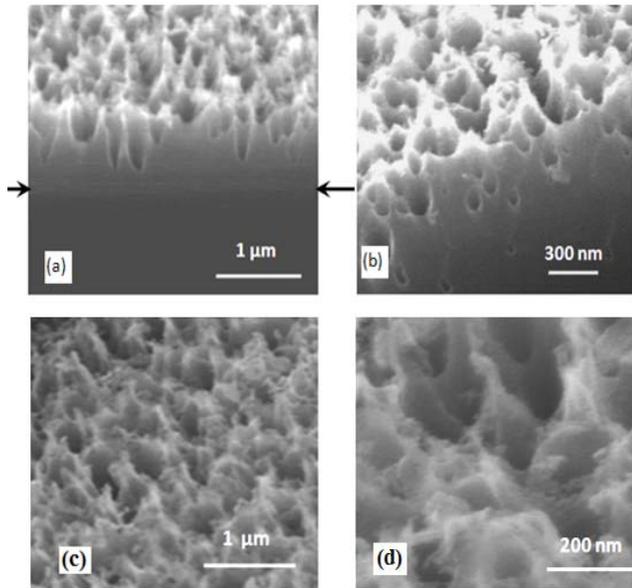


Figure 2: SEM images of the nano-porous poly silicon films on the oxide layer (a) and (b), SEM images of the cross-sectional views of the nano porous structure, evidencing the porosity down to the gate oxide. Arrows in (a) show the interface. (c) and (d) surface images of nano-porous structure at different magnifications.

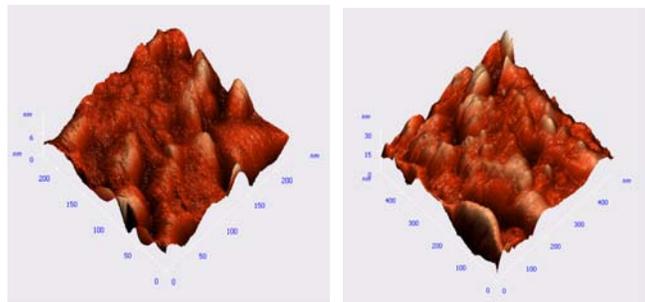


Figure 3: The AFM investigation of the nano-porous silicon layer, confirming deep and nanometric porosity formation.

III. DISCUSSIONS

The electrical characteristics and the response of such transistors to various ion concentrations have been obtained using a Keithley 2361 parameter analyzer unit. For testing the regular planar ISFETs, the drain voltage is constant while the gate voltage is swept. Fig. 4 shows the schematic of the measurement setup, where drain and source are kept in a constant voltage and gate voltage is swept from low voltage to higher values. The level of ion concentration in the electrolyte has a significant effect on the threshold voltage shift and consequently on the source-drain current.

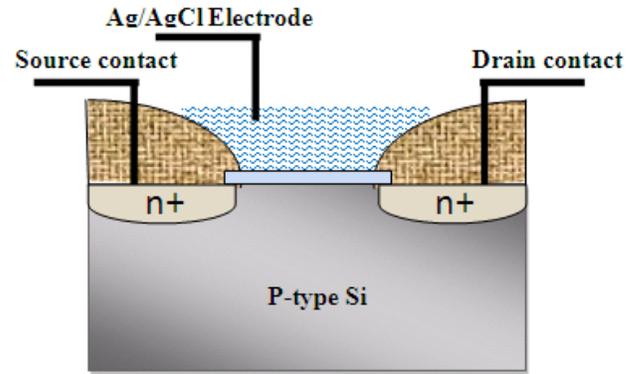


Figure 4: The schematic of the measurement setup. At constant Drain and Source voltage, the voltage of reference electrode is swept.

Figure 5 represent the results of regular ISFET pH meters for three pH values of 2 to 4. In this figure, the drain current has been plotted against the gate reference electrode voltage (I_d-V_g), showing a threshold voltage shift of 37 (mV/pH) as the sensitivity of our regular structures in constant current. It must be born in mind that the results presented in this figure belong to a regular structure where the samples are made without a nano-porous layer and the values obtained for this structure is close to the values reported on standard ISFET devices.

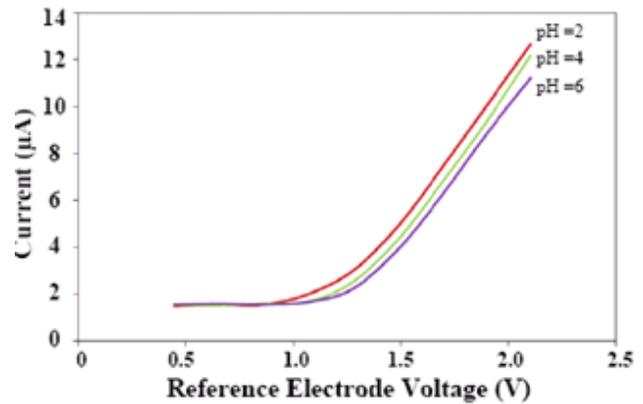


Figure 5: The schematic of the measurement setup and typical results of regular ISFET devices for three different pH values. The I_d-V_g characteristic shows a threshold voltage shift and sensitivity about 37 mV/pH.

The output characteristics of the transistors do show standard saturation as observed in all MOSFET devices. Fig. 6 shows the result of the I_d-V_d characteristics of IS-FET-pH meter with nano porous poly silicon on top of the gate oxide. These measurements have been achieved at an electrode reference voltage of 4V. Please observe the significant separation of the transistor current-voltage characteristics because of pH variations.

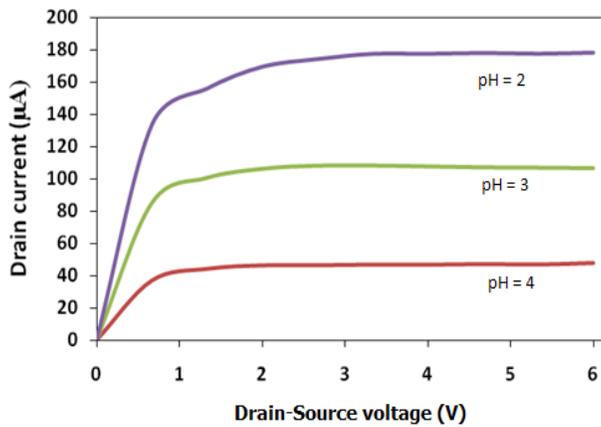


Figure 6: Output characteristics of nano-porous structure, for three pH values with an electrode reference voltage of 4V, evidencing a well-operating transistor behavior.

The transfer characteristic of the device, as the device response to the ion concentration, is obtained by plotting the source/drain current with respect to the reference electrode voltage at various pH values and provided in Fig. 7 and 8. These figures show the results of samples, prepared using nano-porous layers with 1µm and 500nm thicknesses respectively. If a constant current source is applied onto the drain side as applied in regular ISFETs, a remarkable shift in the voltage is observed. Dashed-lines in Fig. 7 and 8 show the span of the “gate-source” voltage as a result of different pH values.

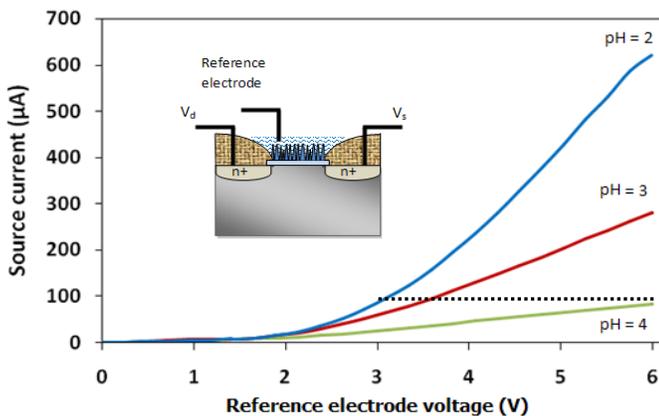


Figure 7: Transfer characteristics of nano-porous structure pH sensor with an initial poly silicon thickness about 1µm, for three pH values. The horizontal line shows how significant the voltage shift could be. Inset shows the schematic of the measurement setup.

In the fabricated ISFETs, we take advantage of nano-porous structure of polysilicon to realize higher sensitivities as opposed to standard plain gates. As shown in Figure 9 such porous structure increase adsorption surface, while effectively transmit adsorbed ion effects to underlying SiO₂

layer. We believe that the adsorbed ions on nano-porous features cause an electric field which extends the depletion region in these structures. Existence of a depletion region yields an extra accumulation of positive ions at the interface between the gate oxide and nano-porous features. As a result, the effect of multi-layer charges is transmitted onto the gate capacitance, which in turn raises the channel inversion layer and leads to a much higher current in transistor terminals. This mechanism works based on charge concentration rather than threshold voltage shift where the effective area becomes a critical parameter.

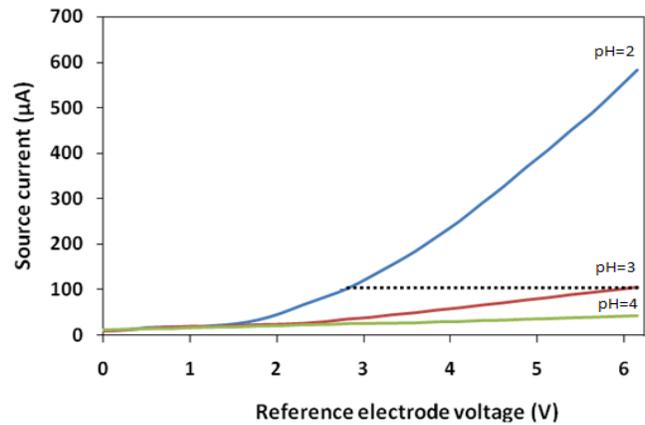


Figure 8: The result of the transfer characteristics measurement of a nano-porous pH sensor with an initial poly silicon thickness about 500nm. The horizontal line shows how significant the voltage shift could be. Compared with the data in Fig. 7, one can see a more significant sensitivity to higher values of pH.

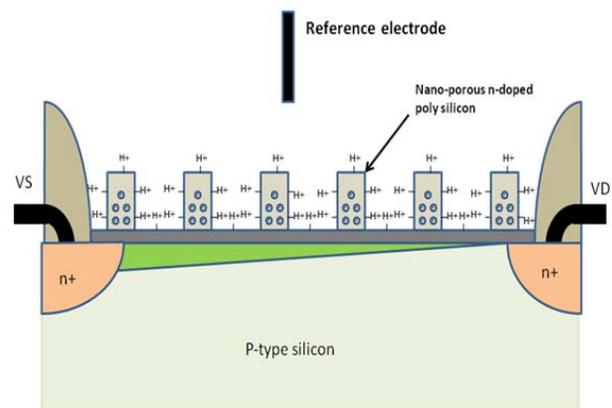


Figure 9: As shown in the schematic, the adsorbed ion on the surface of the nano-porous features leads to an increase in the electric field which leads to an increase in the charge accumulation in the inversion layer and consequently a rise in the transistor current.

Eqn. (1) describes the transistor current. The main difference is the presence of a porosity factor ($f(Q)$) which is affected by the pH concentration and leads to a strong

variation of the current-slope as opposed to regular ISFETs where only threshold voltage varies;

$$I_D = \mu (W/L) (\epsilon_{ox}/t_{ox}) f(Q) (V_{GS} - V_{th})^2 \quad (1)$$

Here I_D , V_{GS} and V_{th} are drain current, gate voltage and threshold voltage, respectively. In addition, μ , W , L , ϵ_{ox} and t_{ox} are mobility, width, length, permittivity and oxide thickness of the gate region. Details about model and the porosity factor will be presented. For regular ISFETs the value of $f(Q)$ is unity whereas for the nano-porous structures this value can be as high as 100 depending on the porosity as well as the ion concentration.

IV. CONCLUSION

In summary, a significant improvement in the ISFET pH-meter performance was achieved by means of a layer of nano-porous polysilicon as sensitive surface without any complexity increase in the fabrication process. This layer increases the adsorption of charge and surface area, and as a result higher charge inversion in the channel of the transistor and higher sensitivity is observed. This device with its unique sensitivity can be used in bio-sensing applications where concentration of bio-objects is very low. On the other hand, this sensitive layer can play the roll of filtering or trapping membrane in bio-applications, thanks to its porous structure.

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