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Suspended-Gate Polysilicon Thin Film Transistor as Generic Structure for Highly Sensitive Charged Ambience Sensors

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Abstract

Suspended-Gate Polysilicon Thin Film Transistors, namely SGTFT, are fabricated at a maximum temperature of 600°C on glass substrate. When using sub-micronic gap, high field effect induces large shift of the transfer characteristics due to any charge variation inside the gap. The device is used in measurements of pH of different solutions with high sensitivity (~250 mV/pH), 4 times the theoretical Nernstian response and the usual value given by the known transducers. This high sensitivity, un-reached until now, is explained by the charge distribution induced by the high applied field. Application of the device is extended to DNA recognition with high and rapid answer. Whatever the application, SGTFT is sensitive to charge variation. Selectivity can be insured by the detection principle that is based on the couple DNA/complementary DNA in the case of DNA recognition or antibody / antigene in the case of proteins.

Keywords: electronic detection, suspended-gate TFT, sensitivity, pH measurements, NDA recognition, charge detection

1 Introduction

Suspended-gate-field-effect-transistor based sensors are extensively investigated since ever the work of Janata [1]. Different variations of the structure (Hybrid SGFET [2], Floating Gate FET [3]) were introduced to improve the performance. All these structures use the work function variation as sensitive parameter. Then, their sensitivity is limited to the Nernstian response. We show here the possibility to increase highly the sensitivity by introducing a field effect as additional parameter.

Used device is a completely polycrystalline silicon air-gap Thin Film Transistor that we realized previously. The device fabrication uses a low temperature surface micro-machining process [4]. Besides the low temperature advantage, the important particularity of the process is the possibility to fix the gap at any value that can be much lower than 1 µm. In such low gap, the field effect due to the applied gate voltage is so important that it can influence the charge distribution in the ambience and then the adsorption phenomenon and the work function variation.

This air-gap TFT device was used in gas detection with very high sensitivity. Depending on the active layer, oxidizing as well as reducing gas were detected. The shift of the transfer characteristics was 2V for 1 ppm of NO_2 and 6V for 100 ppm of NH_3 with short response time [5].

Here, application of this device is extended to the detection of solution pH first. High sensitivity is shown when sensing pH of different solutions. The very high pH sensitivity, some times the theoretical Nernstian response, is then explained for the first time by highlighting the field effect. Next, application of the device in DNA recognition with enough rapidity and sensitivity is demonstrated.

2 Polysilicon air-gap TFT process

The structure of the air-gap thin film transistors, that to be dipped in different solutions is shown in Figure 1. The fabrication process includes 8 masks and the maximum temperature is 600 °C, which is compatible with glass substrates.

First, the substrate, Corning 1737, is covered with 500nm thick Low Pressure Chemical Vapor Deposition (LPCVD) silicon nitride deposited at 600 °C. This film acts as diffusion and contamination barrier. Then a 350 nm thick layer of silicon is deposited by LPCVD at 550 °C and 90 Pa. The first 200 nm of this layer is deposited undoped by using only pure silane gas and successively without breaking the vacuum, just by switching on the diborane opening valve, the last p-type doped 150 nm are deposited. This structure is *in situ* crystallized under vacuum in the deposition reactor at 600°C. The doped up-layer is plasma etched to define source and drain regions.

Then 70 nm thick silicon dioxide and 45 nm thick silicon nitride films are successively deposited in order to passivate the channel. Silicon dioxide is deposited at 450°C by Atmospheric Pressure CVD (APCVD) and silicon nitride as previously.

There after, 500 nm thick polycrystalline germanium sacrificial layer is deposited by LPCVD at 550°C and patterned to form the regions of the drain and source contacts and the bridge anchors. Next, 45 nm thick silicon nitride film is deposited as previously. This layer and the previous silicon dioxide / silicon nitride stack of layers are patterned simultaneously to open the drain and source windows. Then, 500 nm thick boron doped polysilicon and 45 nm thick silicon nitride films are successively deposited and patterned to form the gate (bridge). The boron doped film is amorphously deposited by LPCVD at 550°C and then post-crystallized *in-situ* at 600°C.

Afterwards, 500 nm thick aluminium film is deposited and patterned to form the source, drain, and gate pads. The contacts wires are insulated using a photoresist. Then the sacrificial germanium layer is easily wet etched using hydrogen per oxide (H_2O_2). Moreover, its etch selectivity versus all other materials used in the process is very high. H_2O_2 does not etch any more silicon, SiO_2, and Si_3N_4.. A scheme of the cross-section of the final SGTFT structure is shown in figure 2. Figure 3 is a Scanning Electron Microscope up-view of the structure

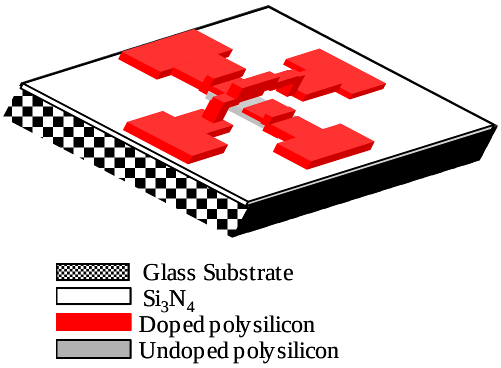

Figure 1: Structure of SGTFT.

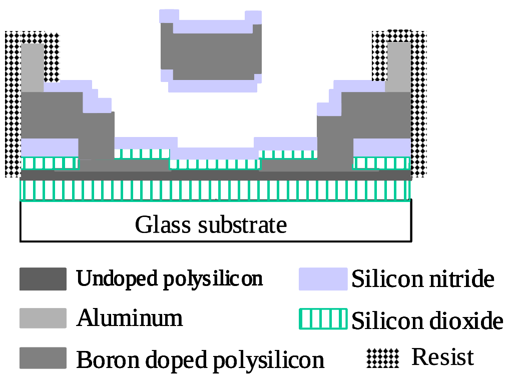

Figure 2: Schematic Cross Section of SGTFT Structure used in liquid detection

3 Results

3.1 Air-gap TFTs as pH sensor

Previous structure is checked as pH sensor. Followed procedure consists first on plotting transfer characteristics of transistor that are dipped in highly de-ionised water (DI). Then transistor is dipped in solution with a fixed pH and transfer characteristics is replotted. There after, transistor is rinsed in DI during 5 minutes. Afterwards, transistor is dipped in a solution with another pH and transfer characteristics is plotted. The procedure is then renewed for different pH values.

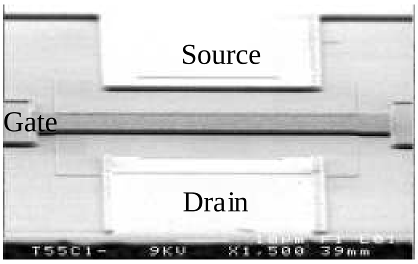

Figure 3: Scanning Electron Microscope up-view of the structure

Figure 4 shows transfer characteristics, drain-source current Id versus gate-source bias Vgs, plotted at different increasing pH values. Parallel shift of the characteristics is observed. Threshold voltage of this p-type transistor decreases when pH value increases. This is consistent with a decrease of H^+ charges content at high pH.

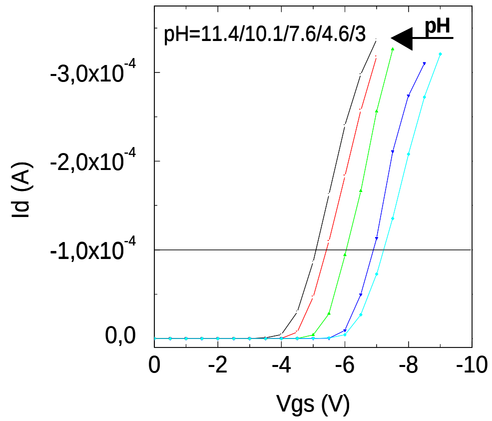

Figure 4: Transfer characteristics at different pH value increasing from 3 to 11.4

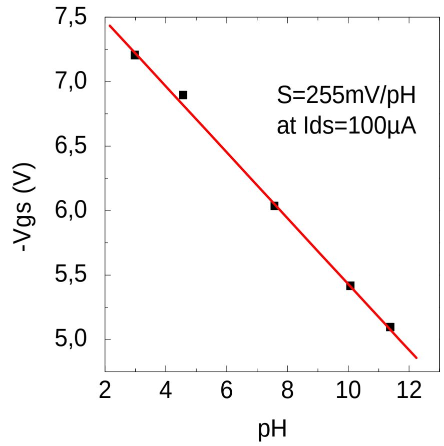

Figure 5: Gate voltage at a drain current Ids of 100µA as a function of pH. The slope of the linear plot gives a sensitivity of 255mV/pH

The gate voltage Vgs that gives a drain current Ids value of –100 µA is plotted as a function of pH in figure 5. It varies linearly with pH. The slope of the linear plot gives a sensitivity of 255mV/pH. This sensitivity is well higher than the usual Nernstian response. It may be remember that the Nernstian theoretical sensitivity is 59 mV/pH at 20°C.

Then, present sensitivity is more than 4 times the Nernstian sensitivity. In comparison, the usual glass electrode pH meter or the known ISFET (Ion Sensitive Field Effect Transistors) present a sensitivity just lower than the Nernstian value.

3.2 Field effect as main origin of the high sensitivity

3.2.1 Qualitative description of the field effect

To understand the origin of the very high sensitivity, the effect of the field between the gate and the semiconductor can be considered. Due to the low gap, 500 nm here, electrical charges in the air-gap are submitted to very high field. Particularly, positive charges, H^+ for example, accumulate on the bottom of the bridge when negative gate voltage is applied. Desertion of H^+ from the surface of the silicon nitride gate insulator leads to reduced voltage needed to create the channel of the p-type transistor. Then, the effect of the field is to reduce the threshold voltage. In usual ISFET, the field effect is very low. Solution that is initially neutral on any point, stays neutral. Only charges that can be in vicinity of the silicon nitride adsorb and then shift the threshold voltage.

So, in the present device, shift of the threshold voltage is due to the field effect that induces new charge distribution in the air-gap and also to the charge adsorption at the surface of silicon nitride.

The threshold voltage V_{TH} of SGTFT can be expressed by:

$$V_{TH} = \Phi_{MS} + 2\varphi_F + \frac{Q_{SC}}{C} - \frac{1}{Ce_{ox}} \int_0^{e_{ox}} x\rho(x)dx \qquad (1)$$

where Φ_{MS} is the difference between the work function of the gate material and the semiconductor, φ_F is the Fermi level position in the semiconductor versus the mid-gap, Q_{SC} is the space charge in the semiconductor, C is the total capacitance between the gate material and the semiconductor, e_{ox} is the thickness of the insulator that is the stack of air-gap, Si_3N_4 and SiO_2 here, ρ(x) is the charge in the insulator at a distance of x from the gate.

Any variation of the ambience in the air-gap leads to a variation of the total charge in the insulator and a possible variation of its distribution. Moreover some chemical reactions at the inner surface of the gap can occur leading to a variation of Φ_{MS}.

Usually only the last variation is considered in ISFET. However when a high field due to the very low gap is present, the distribution of the charge in the ambience varies leading to a variation of ρ(x). Moreover the high field can influence the adsorption by pushing the charges on the surface.

All these effects lead to a variation of Φ_{MS} but also of the last term in the V_{TH} expression. Then, V_{TH} variation can be very large if the effects of a high field are considered.

3.2.2 Experimental evidence of the field effect on the sensitivity

To illustrate, the effect of the high field on the pH sensitivity, SGTFTs are fabricated by using 0.8 µm air-gap that is larger than the previous 0.5 µm one. Figure 6 shows the linear plot of Vgs versus pH for this SGTFT. The sensitivity, 90 mV/pH, is much lower than the previous 255 mV/pH. Then, the large field effect can occur only with very high fields. Little bit higher air-gap leads to large decrease of the sensitivity. Then, the beneficial effect of the high field on the sensitivity is experimentally evidenced.

3.2.3 Experimental evidence of the effect of the new charge distribution induced by the high field.

In the previous qualitative description paragraph, the high sensitivity was explained from both the adsorption as in usual ISFET and the effect of the new charge distribution induced by the high field. It is possible to separate experimentally these both effects by using salt solutions that do not change the pH and do not introduce an adsorption at the surface. Salt solutions of KCl and NaCl and basic solution KOH are prepared with exactly the same concentration. pH does not change when using salt solutions as KCl and NaCl. When plotting transfer characteristics of SGTFT that is dipped in these solutions, only effect of the field on the charge distribution will be observed. In the presence of KOH, pH change and then both effects of the new distribution of charges inside the gap and of the adsorption will be observed. Figure 7 shows the transfer characteristics of SGTFT dipped in DI water and in solutions of KCl, NaCl and KOH with the same concentration.

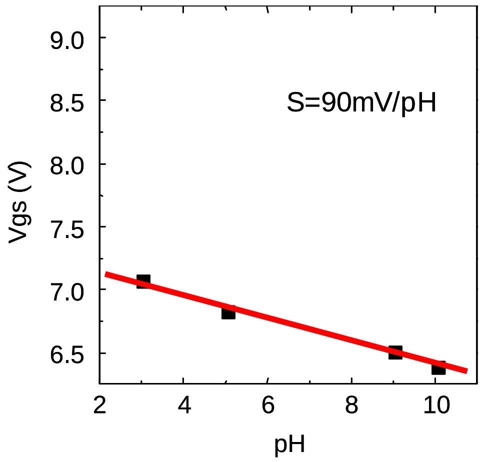

Figure 6: Gate voltage as a function of pH for 0.8 µm air-gap SGTFT. The slope of the linear plot gives a sensitivity of 90mV/pH

Similar shift of the characteristics is shown in presence of KCl or NaCl with the same concentration. This shift is only due to the distribution of charges induced by the field inside the gap. V_{TH} shift is induced by the variation of the last term of equation (1). Same charge content gives same shift.

With same concentration KOH solution, extra shift is observed. It can be due to the pH of KOH and then to the charges that adsorb at the surface of silicon nitride (first term in equation (1)). Then in presence of KOH the shift is due to both the charge distribution and the adsorbed charge. Both origins contribute to the high pH sensitivity of the present device.

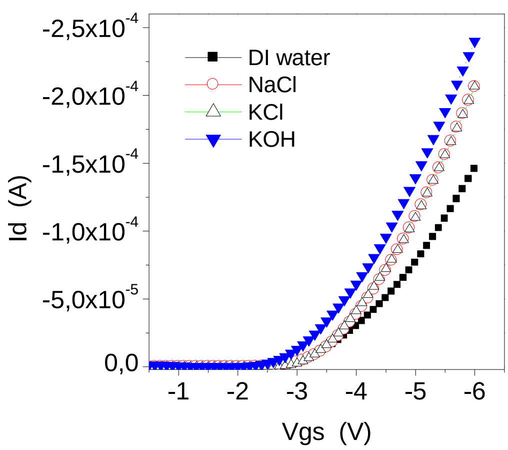

Figure 7: Transfer characteristics when SGTFT is dipped in DI water, and in solutions of NaCl, KCl or KOH. These 3 solutions have the same concentration.

3.3 Air-gap TFTs as biological sensor

Air-gap TFTs are then able to detect any charge variation inside the gap with high sensitivity, some times the usual value, thanks to the high field effect. It can be considered as generic structure to sense any chemical product that is linked to charge variation. As an example, we show here that it can be used as biological sensor, particularly, in specific DNA (Desoxyribo Nucleic Acid) sequence detection. DNA detection becomes now a major scientific and economic priority.

DNA recognition is based on the couple DNA-complementary or not complementary DNA that induces charge variation. Then our charge sensitive air-gap TFTs (or SGTFT) can be used in this application. Specificity is insured by the hybridisation.

To detect the charge variation induced by the DNA presence, DNA have to be bounded to the inner surface of the gap. This needs to functionalize the silicon nitride surface. So, Si_3N_4 surface is activated by diving transistors in a solution of glutaraldehyde. Then, it is ready to bound DNA.

An amino-substituted oligonucleotide, ODN, is grafted on this functionalised surface. Transfer characteristics of SGTFT, dived in Phosphate Buffered Saline (PBS) solution, are plotted to detect the grafted ODN. The presence of the grafted ODN is confirmed by the positive shift of the SGTFT transfer characteristic (Figure 8). Positive shift of P-type transistors means presence of negative charge that is ODN charge in this case.

Next, hybridisation with non complementary DNA (5nM concentration) is checked by its effect on transfer characteristics. Transfer characteristic does not shift as shown in Figure 8; that means that no charge variation is induced by the add of non complementary DNA. Hybridisation does not occur with non complementary DNA.

So hybridisation with complementary DNA (5nM concentration) is checked. Figure 8 shows large 0.4V positive shift of the transfer characteristics, induced by the hybridisation of complementary DNA. The present shift is very large in comparison with previous results obtained using ISFETs [6,7]. Typically, The shift is in the range of one hundred or less mV when using such ISFETs.

Hence, present SGTFT structure is shown as very sensitive and direct DNA transducer.

The present example of DNA detection opens the way to use the SGTFT device in protein detection. The detection principle of protein is based on anti-body / anti-gene reaction. In this understanding, it is similar to DNA recognition where charge variation can be detected.

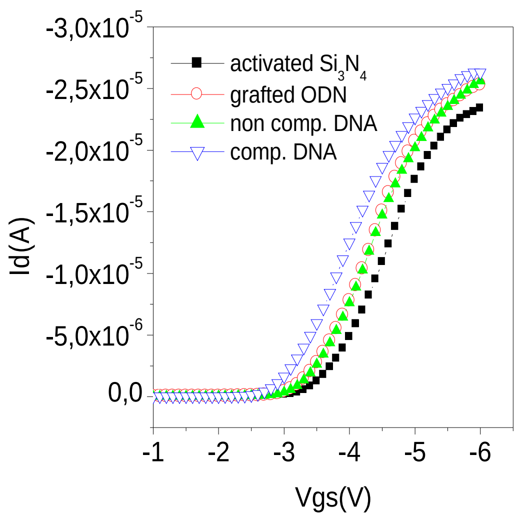

Figure 8: Transfer characteristics when SGTFT is dipped in PBS after activation of Si_3N_4 by glutaraldehyde, after grafting of ODN, after hybridisation trying of nom complementary and complementary DNA. Positive shift shows the presence of negative charge.

4 Conclusion

Suspended-Gate TFTs with sub-micron gap showed their ability to detect with very high sensitivity any charge variation inside the gap. This sensitivity is some times the usual value given by the known transducers.

Through different experiments, this high sensitivity is explained form charge distribution inside the gap due to the high field effect. New distribution contributes to the shift of the transistor characteristics. Moreover, the high field increases the eventual adsorption at the surface by pushing or removing charges.

pH sensitivity reached 250 mV/pH that is 4 times the usual theoretical Nernstian response or the experimental response of the known pH meters.

DNA recognition with high and rapid answer is proven. It opens the way to other biological applications as protein detection.

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