FINFET WITH FULLY PH-RESPONSIVE HFO_2 AS HIGHLY STABLE BIOCHEMICAL SENSOR

S. Rigante[1], M. Wipf[2], A. Bazigos[1], K. Bedner[4], D. Bouvet[1], and A.M. Ionescu[1]
[1]Nanoelectronic Devices Laboratory, EPFL, Lausanne, Switzerland
[2]Department of Physics, University of Basel, Switzerland
[4]Laboratory for Micro- and Nanotechnology, Paul Scherrer Institute, Switzerland

ABSTRACT

In this work, highly scaled FinFETs (Fin Field Effect Transistors) are proposed as both sensing and circuit units of a lab-on-a-chip platform. The FinFET-based sensors with an HfO_2 gate oxide demonstrate full pH-response with $\Delta V_{th} \approx 56$ mV/pH. High readout sensitivity $S_{out} = \Delta I_d/I_d \approx 43\%$ is achieved in combination with excellent device electronic properties, i.e. SS = 77 mV/dec and $I_{on}/I_{off} = 1.5\times10^6$. High long-term stability is proven over 4.5 days with a drift in time limited at 0.14 mV/h

INTRODUCTION

Challenges of SiNW-based sensors

In the last decade, SiNWs have shown their potential as label-free sensors [1]. With respect to other emerging technologies they provide a real-time and direct signal when a change in charge at the surface occurs. According to the read-out, the variation of the surface potential can be detected as a variation of either the threshold voltage, V_{th}, or drain current, I_d, but no other transduction is needed. Despite their evident efficiency, the integration with CMOS ICs is still a challenge. To achieve such integration the research should focus on the optimization of the device architecture and power supply constraints. Commonly, single SiNWs are designed with rather large width and reduced thickness ($H_{SiNW}/W_{SiNW} < 1$) [2-5] and high voltage are applied, especially at the back-gate [3,4]. The device reliability and its long-term stability are rarely addressed. High-k dielectric materials, such as AlO_3 and HfO_2, have already been investigated and demonstrated to provide pH response close to the Nernst limit of $\Delta V_{th} \approx 59$ mV/pH [5].

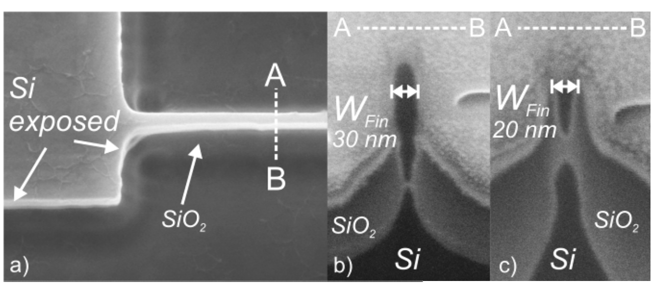

Figure 1: SEM top view of a FinFET detail (a) and wire cross-sections by FIB: Si vertical fin with W_{Fin} = 30 nm, H_{Fin} = 85 nm (b) and W_{Fin} = 20 nm, H_{Fin} = 65 nm (c).

In this work, we propose FETs (Field Effect Transistor) which feature an HfO_2 gate oxide and a Double-Gate (DG) architecture for optimized channel control, sensitivity and stability. Such devices are known as FinFETs and their excellent electronic properties are well known in nanoelectronics [6]. Figure 1 shows SEM (Scanning Electron Microscope) images of the FinFET implemented as sensing units: (a) is a top view of the Si-Fin at the anchor point with its contact pad, (b) and (c) are cross-sections obtained by FIB (Focused Ion Beam) showing the vertical fins with W_{Fin} = 30 nm and W_{Fin} = 20 nm, respectively, and aspect ratio $H_{Fin}/W_{Fin} > 3$. In previous works, we published preliminary implementations of the FinFET as ionic sensor [7, 8]. Herein, we present the latest sensing platform after having additionally achieved: (i) full pH response based on HfO_2 gate oxide, (ii) highly stable long-term reliability and repeatability.

Device and Microfluid Platform Development

The FinFETs were fabricated using a local SOI technology on Boron doped Si-bulk wafers [7, 8]. Fin widths from 15 to 40 nm and $H_{Fin}/W_{Fin} > 3$ have been achieved. Source and drain contacts were implanted with a Phosphorous dose $\approx 10^{16}/cm^2$ at 30 keV, aimed at reaching a contact doping level $N_a = 10^{20}$-$10^{21}/cm^3$ and expected penetration depth of 150 nm. The fin surface was covered by 8 nm of HfO_2 deposited by ALD (Atomic Layer Deposition). In order to prevent any surface degradation the use of highly concentrated HF acid (Hydrofluoric) solution and high power O_2-plasma was avoided after ALD.

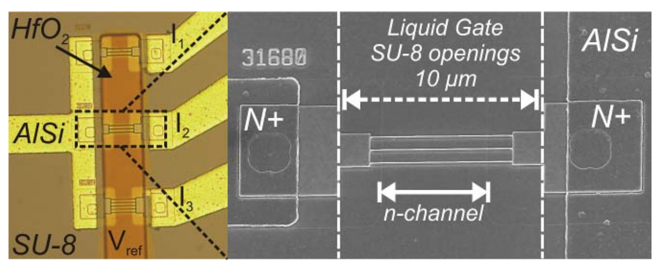

Figure 2: Optical image of the sensors with independent outputs and SU-8 openings over the sensing channels (left); SEM detail of a three SiNW FinFET (right).

The metal connections were fabricated by a lift-off process of AlSi with 1% Silicon to avoid Al diffusion at the junctions. To limit the contact with the liquid at the Si surface, SU-8 openings were patterned next to the sensor channels, as shown in Fig. 2 (left). The correct superposition of the liquid opening and doped regions (Fig.2, right) allow the n-channel to conduct when the solution is biased at the proper potential. Liquid and metal gate FinFETs are both available on the same die, as represented in Fig. 3.

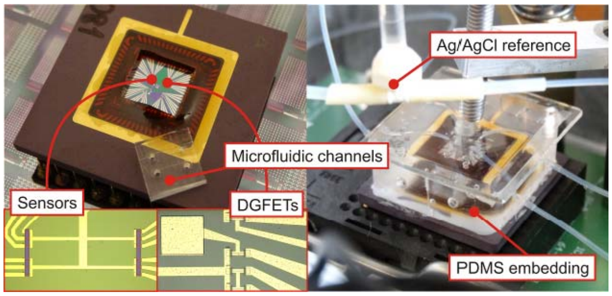

Figure 3: Die-chip carrier assembly with FinFET sensors and transistors; a PDMS cube is patterned with microchannels at its bottom (left); sensing platform with PDMS embedding and Ag/AgCl reference electrode (right).

Once the die was diced out form the wafer, it was connected to the chip carrier by ball-bonding with Au wires. For the assembly of the microfluidic platform, PDMS microchannels were aligned with respect to the SU-8 openings and liquid Epoxy fixed them at chip carrier. The channels were then connected by PTFE tubes and a full PDMS embedding seals the whole system (Fig. 3).

MEASUREMENTS

pH Sensing

To perform pH measurements in a liquid environment the PTFE tubes were connected to a tubing pump and a valve selector system. The liquid potential was controlled by an Ag/AgCl flow through reference electrode included in the tubing. The first pH measurement was meant to evaluate the device threshold voltage shift, ΔV_{th}, at different pH values. The FinFET drain current, $I_{d,}$ was measured at constant source and drain voltage, V_{ds} = 80 mV, and back-gate potential, V_b = 0 V. The liquid potential, V_{ref}, was swept from 0.5 to 2.5 V, through the reference electrode at fixed pH = 3. The resulting $I_d(V_{ref})$ transfer characteristic is illustrated in Fig. 4 on the left Y-axis. The liquid gate devices exhibit the same good electrical behavior as for the metal gate devices. Prior to liquid measurements, metal gate FinFETs were characterized, achieving excellent electrical properties of SS = 77 mV/dec and I_{on}/I_{off} $=1.5\times10^6$ for W_{Fin}= 30 nm, H_{Fin}= 80 nm and L_{Fin}= 10 µm. The right Y-axis of Fig. 4 shows the $I_d(V_g)$ corresponding to the same FinFET fabricated with a metal gate. For comparison, we set $V_{ref} = V_g + \Delta V_{sol}$, with ΔV_{sol} = 0.75 V. The liquid gate FinFETs performs a less steep Subthreshold slope, SS = 180 mV/dec. Highly probably, this is due to the higher I_{off} current level, which may depend on different measurement set-up conditions, resulting higher leakage currents. Afterward, the valve selector system was used to exchange the solutions at different pH values. Steady-state measurements were performed between $3 \leq pH \leq 9$ and the rest $I_d(V_{ref})$ transfer characteristics are also reported in the Fig. 4 on the left Y-axis.

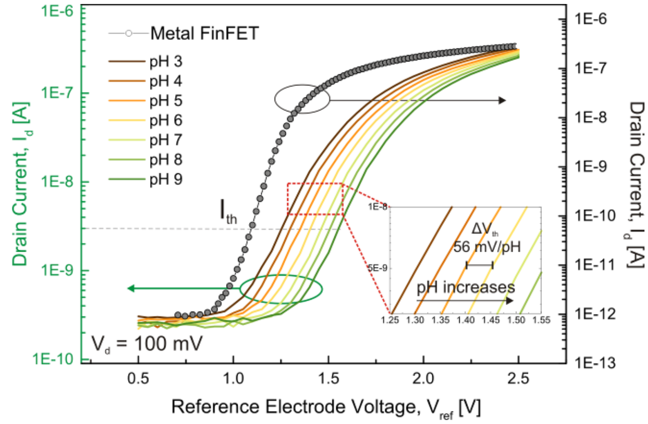

Figure 4: $I_d(V_{ref})$ characteristic for a 3 SiNW metal (right Y-axis) and liquid gate (left Y-axis) FinFET at V_d = 100 mV, V_b = 0 V. The FinFET sensor characteristics have been obtained for $3 \leq pH \leq 9$ with the inset showing the curve shift $\Delta V_{th}/pH$ due to the surface potential variation at different pH values.

For the data analysis, we can differentiate between the intrinsic sensor sensitivity, S = V_{th}/pH, and the readout sensitivity, $S_{out} = \Delta I_d/I_d$. While the former only depends on the oxide surface the second one is linked to the SS of the FETs as well. For all pH transitions, S ≈ 56 mV/pH is achieved. The fabricated FinFETs finally present a full pH sensitivity and, as a consequence, sensitivity with respect to other chemicals is suppressed [5,8]. Afterwards, V_{ref} was fixed at 1.5 V and I_d measurements vs. time were performed and reported in Fig. 5.

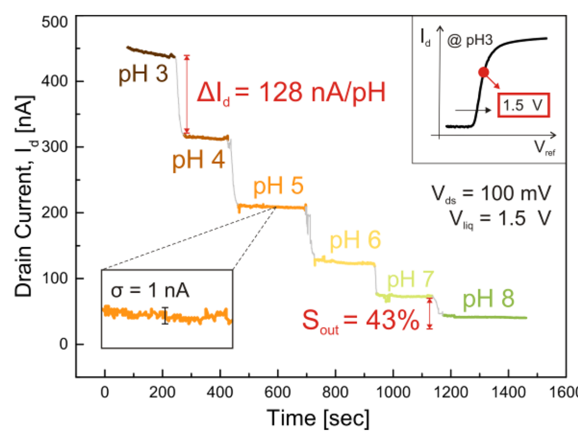

Figure 5: Measured Drain Current I_d, for a 5 SiNW FinFET sensor during a time period of 25 minutes for $3 \leq pH \leq 9$ with reference electrode V_{ref} = 1.5 V and V_{ds} = 100 mV.

The devices achieved a high current variation with a maximum $\Delta I_d/I_d$ = 43% for the transition pH 7→8 and averaged $\Delta I_d \approx 80$ nA/pH for $3 \leq pH \leq 8$. At a different bias, V_{ref} = 2 V, the sensor provided a maximum $\Delta I_d \approx 271$ nA/pH but the relative current variation does not exceed

$\Delta I_d/I_d$ = 28%. Studying in overall the current transitions we can assume a negligible background noise, with $\Delta I_d/\sigma_{\Delta Id} > 60$. Tables 1 and 2 summarize the data obtained at $V_{ref} = 1.5$ and $V_{ref} = 2$ for each transition. The characterization of time-dependent measurements is important for fast kinetic reactions and small surface potential variation. Steady-state measurements could entail hysteretic effects affecting the detection of small ΔV_{th}. According to the type of measurement the point of biasing can be adjusted for high ΔI_d or $\Delta I_d/I_d$.

TABLE 1: FinFET performances as pH sensor, $V_{ref} = 1.5$ V

	FinFET, $V_{ref1} = 1.5\ V_{@ph3}$					
pH	3→4	4→5	5→6	6→7	7→8	3-8
S_{out} [%]	29	33	40	40	43	≈ **31%**
ΔI_d [nA]	128	105	85	50	32	≈**80 nA/pH**
$\Delta I_d/\sigma_{Id}$	45	88	85	71	80	≈ **61**

TABLE 2: FinFET performances as pH sensor, $V_{ref} = 2$ V

	FinFET, $V_{ref1} = 2\ V_{@ph3}$					
pH	3→4	4→5	5→6	6→7	7→8	3-8
S_{out} [%]	9	7.5	22	15	28	≈ **14%**
ΔI_d [nA]	130	100	271	148	232	≈**176 nA/pH**
$\Delta I_d/\sigma_{Id}$	27	31	117	123	300	≈**99**

Long Term Stability

The threshold voltage V_{th} was monitored for 4.5 *days*, keeping the liquid environment at constant pH = 6. Every 30 minutes the system pumping was automatically activated to renew the liquid on top of the sensors. After a stabilization time of several minutes the $I_d(V_{ref})$ characteristic was traced by sweep of the reference electrode. The V_{th} was then extracted at the same I_d = 2 nA and plotted, as shown in Figure 6. The FinFETs behaved in an extremely stable way with a drift of $\delta V_{th}/\delta t \approx 0.14$ mV/h for multiple wire FinFETs, with different fin thickness, T_{Fin} = 30 nm for D_1 and T_{Fin} = 20 nm for D_2.

The presented data also describe the measurement repeatability. The V_{th} measurement was, in fact, acquired more than 200 times. Assuming the intercept of a population of data equal to the mean V_{th} for a specific device, its standard deviation $\sigma_{Vth} \approx 0.8$ mV is an indicator of the V_{th} fluctuation, independent from the time drift.

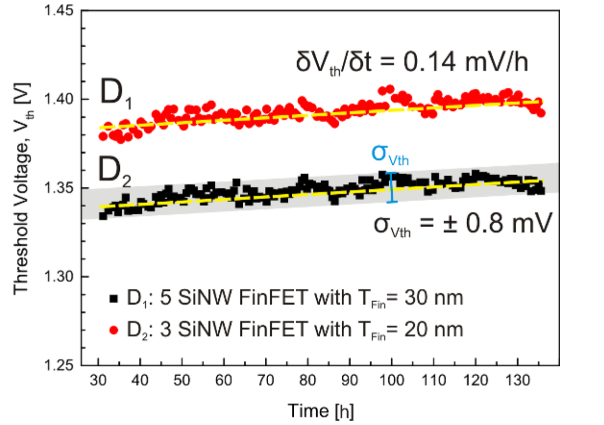

Figure 6: Long-term stability measurement over 4.5 days; the threshold voltage V_{th} is monitored for different FinFET sensors at constant pH = 6.

Moreover, we have compared two identical FinFETs, D3 and D4, located at two different positions of one die, measured through channel A (CH A) and channel B (CH B), respectively. The devices are expected to have the same V_{th}. By subtracting the two V_{th} sets of data, a residual $\Delta V_{th} \approx 0.6$ mV with its corresponding standard deviation $\sigma_{\Delta Vth} \approx 1$ mV is obtained, as shown in Figure 7.

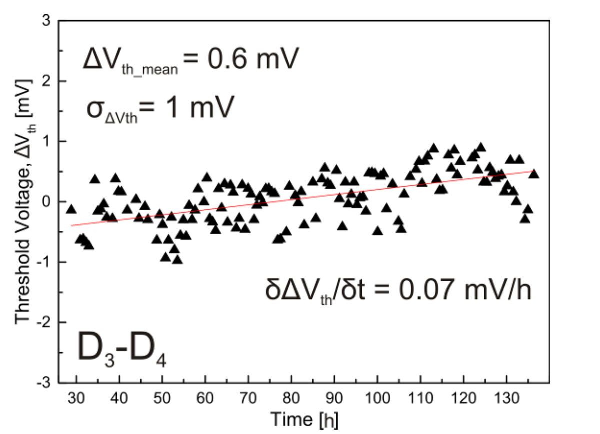

Figure 7: Result of the subtraction of the date set of V_{th} for two identical FinFETs located at two different positions on the same die.

The reliability of the FinFETs and the fabrication process was then demonstrated at the die level. A small drift in time, $\delta\Delta V_{th}/\delta t \approx 0.07$ mV/h was also observed for the relative ΔV_{th}. These data have proven two important sensor properties, stability and reliability at single sensor and wafer/die level.

CONCLUSIONS

Herein, we have demonstrated the advantages of implementing FinFETs as sensing units. The same FinFET architecture has been implemented as both sensing and circuit device with excellent outputs. We have optimized the FinFET structures to achieve good electronic proprieties, i.e. high SS and I_{on}/I_{off}. The surface oxide quality for full pH response has been drastically improved [8]. Boosting both electronic and sensing properties have resulted in pH sensors with state-of-the-art features: (i) high current variation with readout sensitivity of $S_{out} \approx 31\%$, $\Delta I_d \approx 176$ nA/pH and signal to noise ratio S/N > 60 [2-4, 9], (ii) extremely low power consumption with $P_{sens} < 0.1$ µW and low voltage supply [3,4] and (iii) enhanced long-term stability [2]. Moreover, the FinFETs, thanks to a precise process and their well-defined geometry, have been proved reliable by comparing same entities at different positions.

In conclusion, the presented sensing platform based on high-stability, low-power FinFETs on Si-bulk can be implemented for efficient chemical label-free sensing towards non-invasive simultaneous monitoring of human physiological signals (pH and other biological entities). The use of scalable high-k dielectric FinFETs for both applications is in accordance with the material constraints which come along Moore's Law of scaling, in contrast to other SiNW-based sensors, and paves the way towards sensing integrated circuits.

ACKNOWLEDGEMENTS

The presented work has been financially supported through the Swiss Federal Program Nano-Tera "NanowireSensor" under contract reference 611_61.

REFERENCES

[1] F. Patolsky, C. M. Lieber, "Nanowire Nanosensors", Mater. Today, vol. 8, pp. 20-28, 2005.

[2] I. Park, Z. Li, A. P. Pisano, R. S. Williams, "Top-Down Fabricated Silicon Nanowire for Real-Time Chemical Detection", Nanotechnol., vol. 21, pp. 15501-15510, 2010.

[3] N. Elfstrom, A. E. Karlstrom, J. Linnros, "Silicon Nanoribbons for Electrical Detection of Biomolecules", Nano Lett., vol. 8, pp. 945-949, 2008.

[4] S. K. Yoo, S. Yang, J.-H. Lee, "Hydrogen Ion Sensing Using Schottky Contacted Silicon Nanowire FETs", Trans. On Nanotech., vol. 7, pp. 745748, 2008.

[5] A.Tarasov, M. Wipf, R. L. Stoop, K. Bedner, "Understanding the Electrolyte Background for Biochemical Sensing with Ion-Sensitive Field-Effect Transistors", ACS Nano, vol. 6, pp. 9291-9298, 2012.

[6] J.-P. Colinge, "FinFETs and Other Multi-Gate Transistors", Springer, 2008.

[7] S. Rigante, P. Scarbolo, D. Bouvet, M. Wipf, A. Tarasov, K. Bedner, A. M. Ionescu, "High-k dielectric FinFETs towards sensing integrated circuits," ULIS 2013, vol. 73, pp.19-21, 2013.

[8] S. Rigante, M. Wipf, A. Tarasov, D. Bouvet, K. Bedner, R. L. Stoop, A. M. Ionescu, "Integrated finfet based sensing in a liquid environment", TRANSDUCERS & EUROSENSORS XXVII 2013, vol. 681, pp. 16-20, 2013.

[9] Y. Cui, Q. Wei, H. Park, C. Lieber, "Nanowire Nanosensors for Highly Sensitive and Selective Detection of Biological and Chemical Species", Science, vol. 293, pp. 1289-1292, 2001.

CONTACT

*S.Rigante; sara.rigante@epfl.ch.