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High-k Dielectric FinFETs for Ion and Biological Sensing Integrated Circuits

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Abstract

In recent years, sensing applications of nanoelectronics have become increasingly prevalent in many fields. Silicon Nanowires (SiNWs) have already been successfully exploited for sensing, although high sensitivity, integration and low power consumption are still challenging. This work presents an advanced electronic device, namely an n-channel fully depleted FinFET on bulk silicon, as novel label-free ion and biological sensor. This innovative approach paves the way for integrated and CMOS compatible sensing circuits in which the sensor and the driver transistor are the same structure.

1) FinFETs-Technological Development[1][2]

A challenging fabrication process of sub-50 nm FinFETs using a local SOI technique on p-type bulk silicon has been developed. Thanks to Si_3N_4 spacers, vertical silicon fins are detached and isolated from the bulk by the growth of SiO_2 to limit bulk electrical contributions.

- E-beam Lithography on a HSQ-Si_3N_4 layer
- Deep Reactive Ion Etching of Si_3N_4
- Transfer of vertical fins into the Si-bulk by RIE
- Si_3N_4 spacers creation by LPCVD and DRIE
- Wet Oxidation → formation of 350 nm SiO_2
- Si_3N_4 spacers etching by Hot Phosphoric acid
- Ion Implantation (N+) and RTA
- Fin surface exposure by DIP HF etching
- ALD deposition of HfO_2 or Al_2O_3
- Contact vias by Ar Ion Milling
- AlSi1% metallization
- SU-8 channels

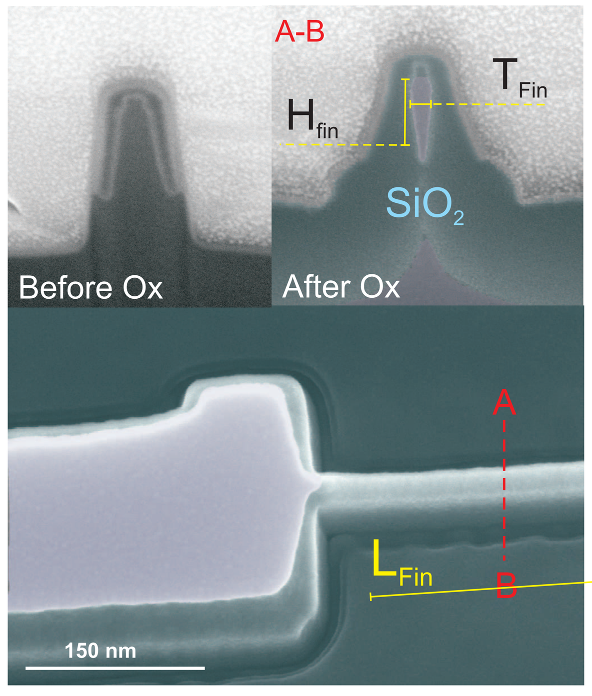


Figure 1: (top) SEM cross-section of vertical fins before and after wet oxidation; (bottom) SEM top view of a SiNW and its anchoring pad.

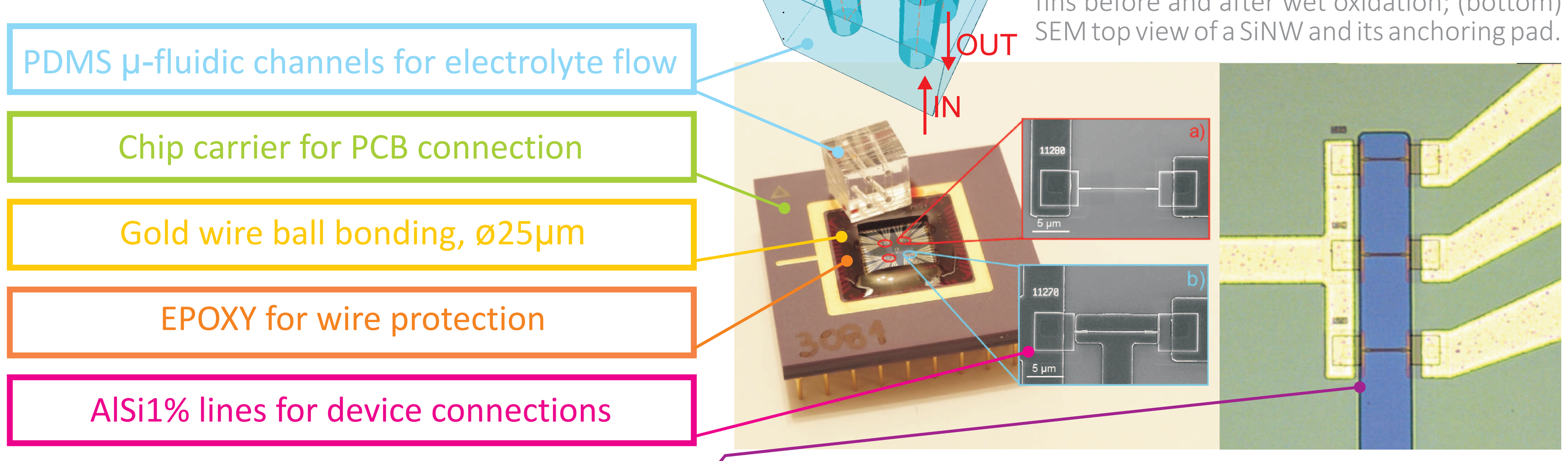


Figure 2: (left)Silicon chip with sensors (a) and metal gate FinFETs (b) embedded in a chip carrier with PDMS microfluidic channels; (right) optical microscope top view of single FinFETs with AlSi1% connections and SU-8 openings.

[1] based on the Finite Element Analysis design presented in S. Rigante et al., Microelectron. Eng., (2011), 88, 1864-1866
[2] S. Rigante et al, ULIS2013

2) Sensing FinFETs-Liquid Environment[3]

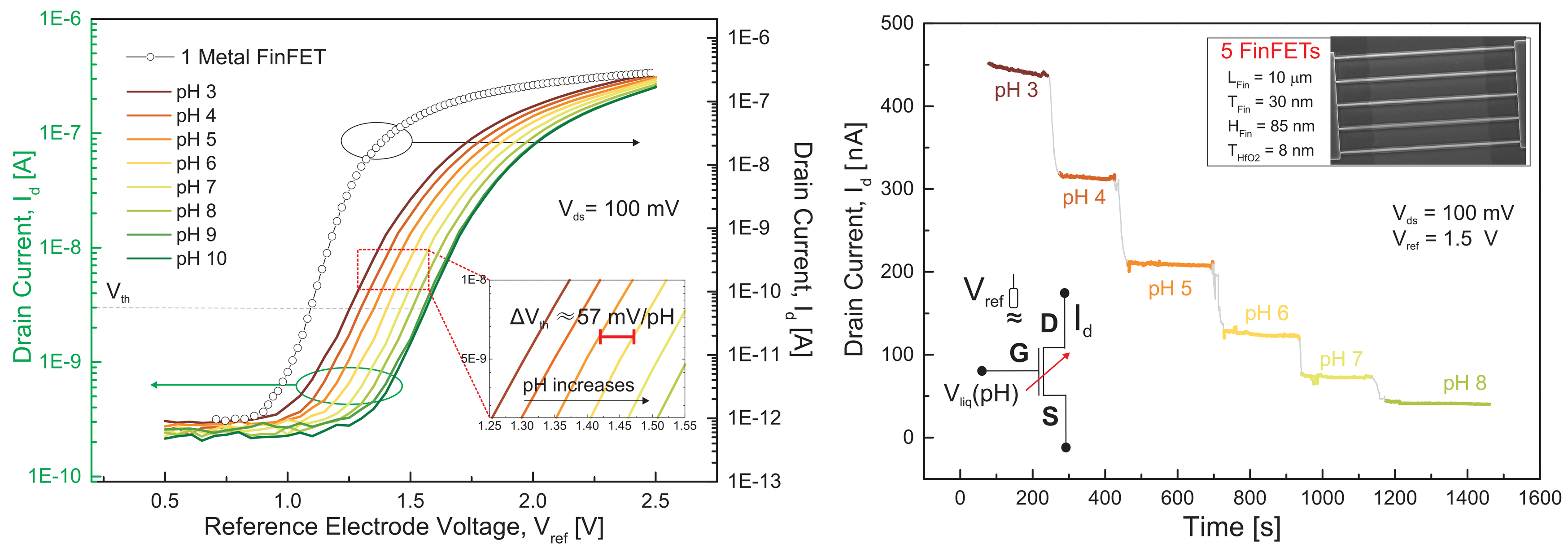


Figure 3: (left) Measured I_d-V_g characteristic for a metal gate FinFET (right Y-axis) in comparison to I_d-V_{ref} (left Y-axis) obtained with a reference electrode iin different pH solutions for a FinFET sensor; (right) current variation ΔI_d, while the device is exposed to solutions of pH values from 3 to 8 over time.

The FinFET sensors with HfO_2 on the surface are characterized in a liquid environment. A tubing pump and a valve system are used to exchange different pH solutions. The liquid potential is controlled by a flow trough reference electrode which can be swept or kept fixed. Time dependence measurements are performed to study current variations when a sensing event occurred at different biasing conditions.

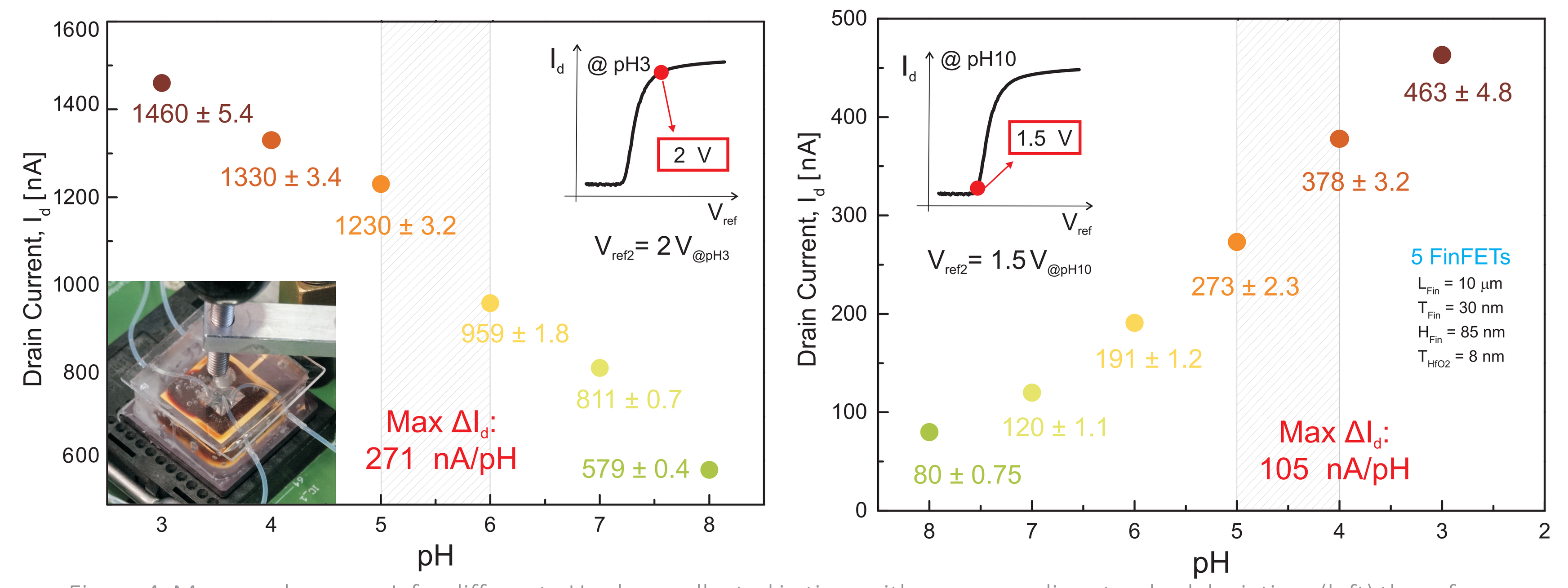


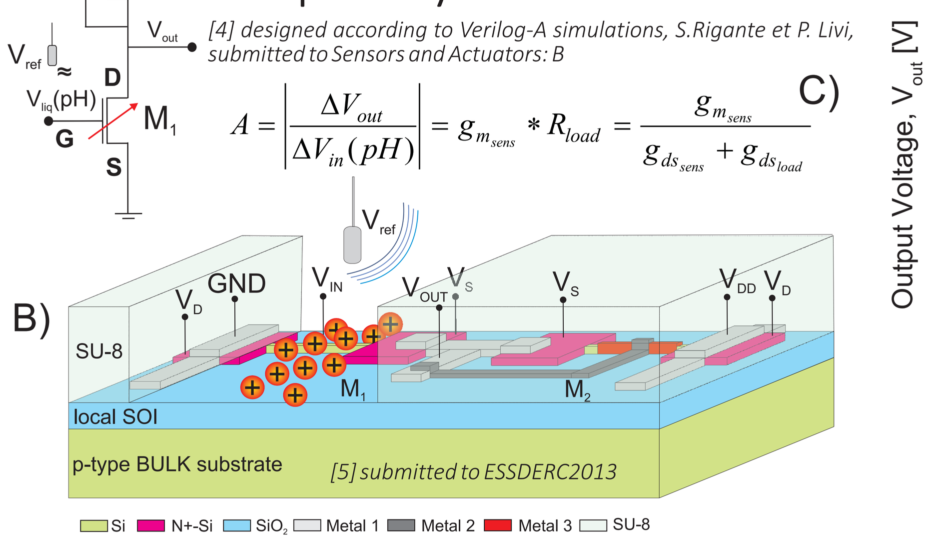
Figure 4: Measured average I_d for different pH values collected in time with corresponding standard deviation; (left) the reference electrode is fixed at 2 V and the pH is changed from 3 to 8; (right) the reference eletrcode is fixed at 1.5 V and the pH is changed from pH 8 to 3. All measurement have been performed n 5 parallel FinFETs with T_{Fin} = 30 nm, H_{Fin} = 85 nm and L_{Fin} = 10 μm.

[3] S. Rigante et al, TRANSDUCER2013

4) Sensing Inverters-Liquid Environment[4][5]

A simple architecture with one FinFET connected as load and another one as driving sensor can provides a readout gain of 6.3 with a ΔV_{th} readout of 175 mV/pH. With respect to the standard current readout this simple connection can provide a linear voltage-to-voltage input-output correlation. Multiple connections of these stages could lead to sensing frequency readout.

[4] designed according to Verilog-A simulations, S. Rigante et P. Livi, submitted to Sensors and Actuators: B



$$A = \left|\frac{\Delta V_{out}}{\Delta V_{in}(pH)}\right| = g_{m_{sens}} * R_{load} = \frac{g_{m_{sens}}}{g_{ds_{sens}} + g_{ds_{load}}}$$

[5] submitted to ESSDERC2013

Figure 6: (A) circuit schematic of the FinFET amplifier with a metal gate FinFET connected ad depletion load and sensing FinFET as driver; (B)sketch of the pH sensor exposed to H⁺ solution and reference electrode, connected to a metal gate FinFET protected by an SU-8 layer; (c) equation for voltage gain.

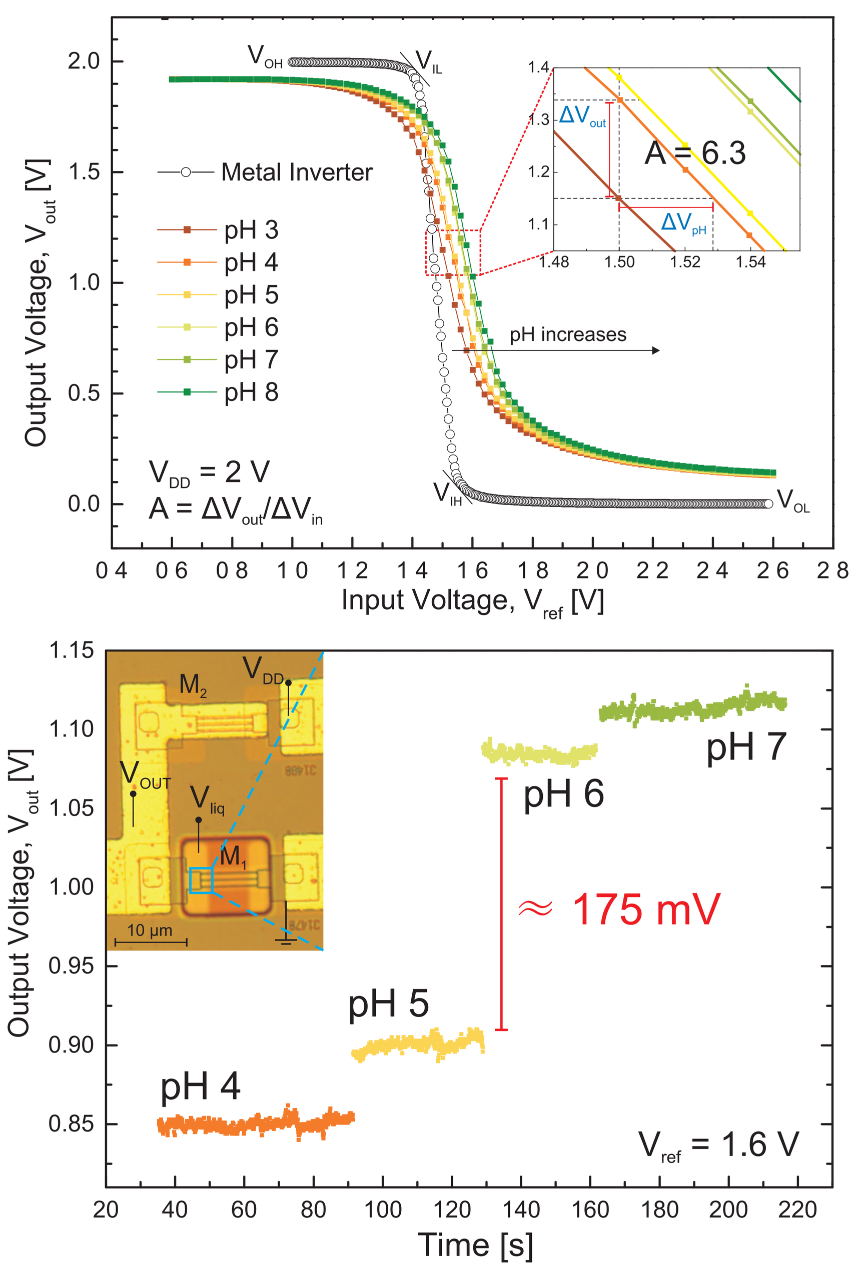


Figure 7: (top) V_{out}(V_{in}) characteristics of the metal gate (black curve) an sensing (coloured curves) FinFET amplifier for 3 ≤ pH ≤ 8, with gain = $\Delta V_{out}/\Delta V_{in}$ = 6.3; (bottom) amplifier output voltage versus time for different pH values, the inset shows the microfluidic platform connected to the measurement set-up.

3) Metal FinFETs- Electrical Characterization

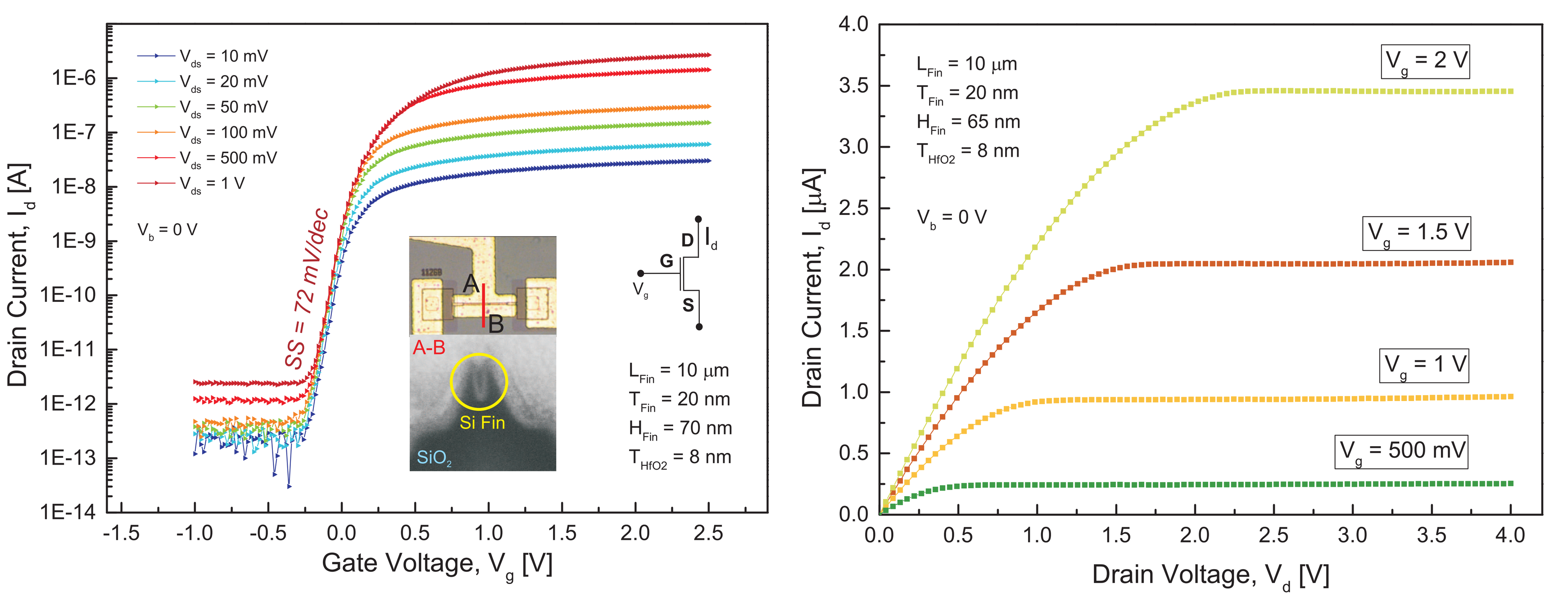


Figure 5: Measured I_d-V_g for a metal gate FinFET (left) for 10 mV < V_{ds} < 1 V; the inset shows an optical top view of the device with fin cross-section obtained by FIB. Measured I_d-V_d of the same device for 500 mV < V_g < 2 V; the inset shows an optical top view of the device with fin cross-section obtained by FIB. Both measurements have been performed on the smallest available fin having T_{Fin} = 20 nm and H_{Fin} = 70 nm.

Using a metal gate, the FinFETs can also be electrically characterized. Excellent subthreshold slope ≈ 72 mV/dec and I_{on}/I_{off} ratio ≈ 10^6 and stable current output have been achieved. This characterization is useful for (i) performance comparison of MOS (Metal-Oxyde-Semiconductor) and the EOS (Electrolyte-Oxide-Semiconductor) system, (ii) FinFET sensor and driver transistors integration.

Collaboration works!

- All measurements in liquid have been carried out at the University of Basel (collaboration with Mathias Wipf, Ralph L. Stoop, Alexey Tarasov)
- PDMS microfluidic channels and layout compatibility directions have been provided by Paul Scherrer Institut (collaboration with Kristine Bedner)
- Circuit simulations and modeling of sensing integrated circuits have been performed together with ETHZ (collaboration with Paolo Livi)
- A major contribution in the characterization of ALD high-k oxides has been provided by Paolo Scarbolo (University of Udine)
- All measurements in air have been performed and investigated at EPFL, with the support of NanoLab (Antonios Bazigos and Wladek Grabinski)