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High-k Dielectric FinFETs for Ionic and Biological Sensing Integrated Circuits[1]

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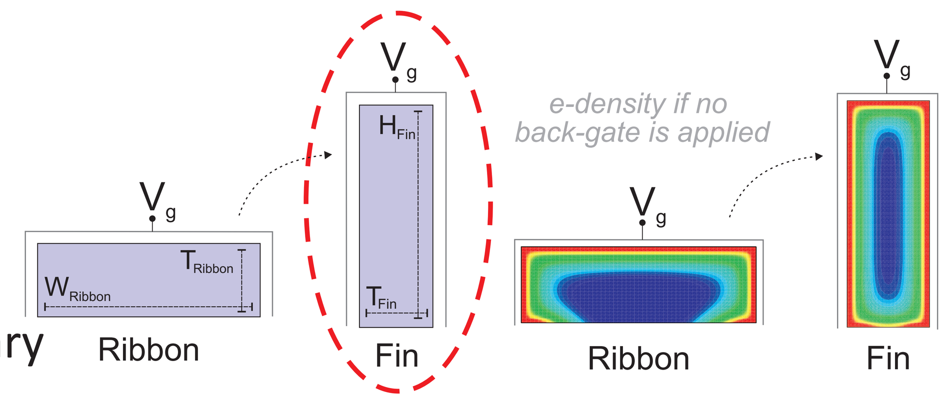
NanoLab

FinFET: State-of-the-art Nanoelectronics

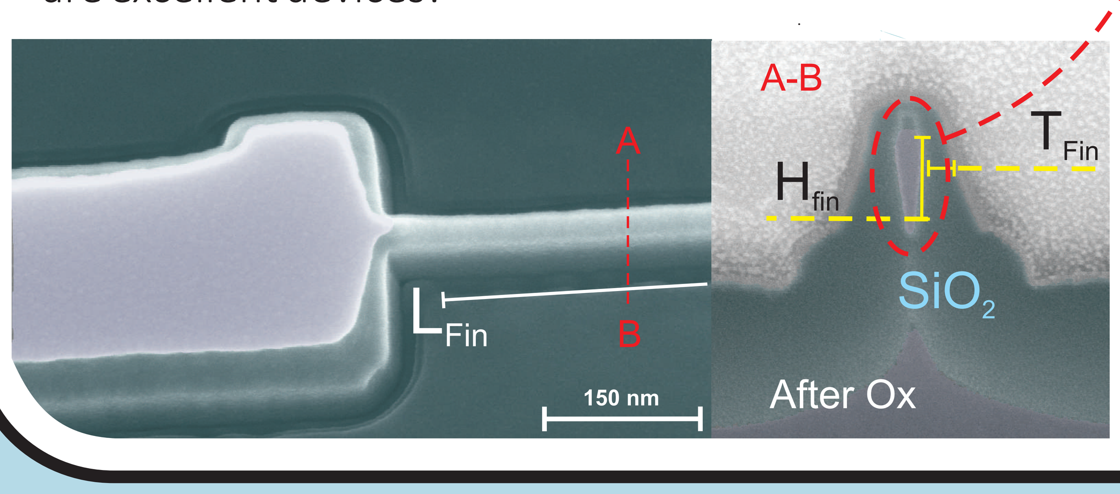
Despite the SiNW great potential has largely been proved, their integration with CMOS Integrated Circuits is still a challenge. Commonly, SiNWs are designed with rather large width and reduced thickness (Ribbon) and high supply voltages are applied, especially at the back-gate. In this work, we propose *n-channel fully-depleted FinFETs* (Fin Field Effect Transistor) featuring an HfO_2 gate oxide for optimized sensing measurements, toward Sensing ICs.

Especially upon scaling, FinFETs:

- Provide high channel control
- Less electrical degradation
- The use of back-gate is not necessary
- Steep Subthreshold Slope



FinFET are expected to be optimal sensors because they are excellent devices!



Si-Bulk FinFETs: Technology Development

The FinFETs have been fabricated on Si-Bulk by top-down approach. Using Si_3N_4 spacers and wet oxidation, it is possible to detach and insulate the FinFETs from the Si-Bulk. The main features are:

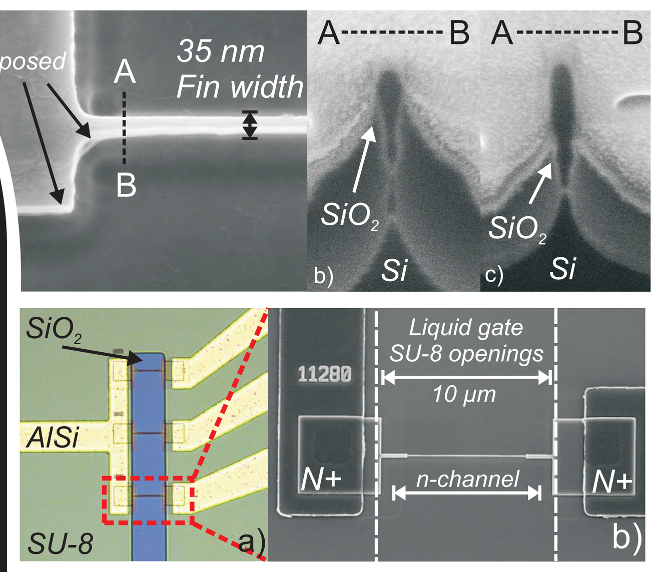
- Substrate: p-type Si-Bulk
- Total number of masks: 7, 3 virtual and 4 Chromium
- Si_3N_4 spacer technology for local bulk insulation

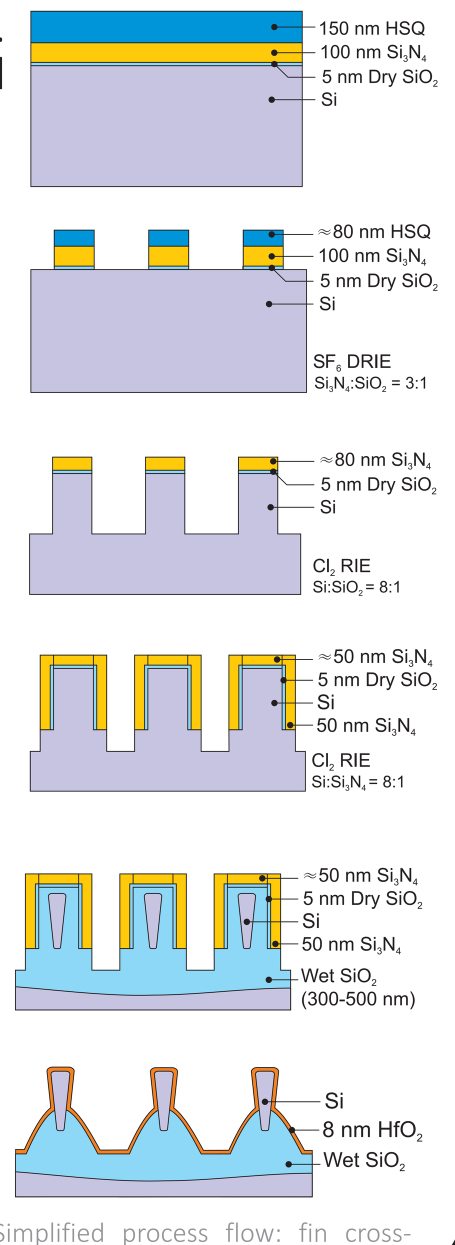
Critical steps:

- E-beam lithography for sub 20 nm features
- Wet oxidation of Si-Bulk
- Resistant SU-8 coverage for liquid environment

All devices have been fabricated at the Center of MicroNanoTechnology (CMi) at EPFL

CMi EPFL Center of MicroNanoTechnology

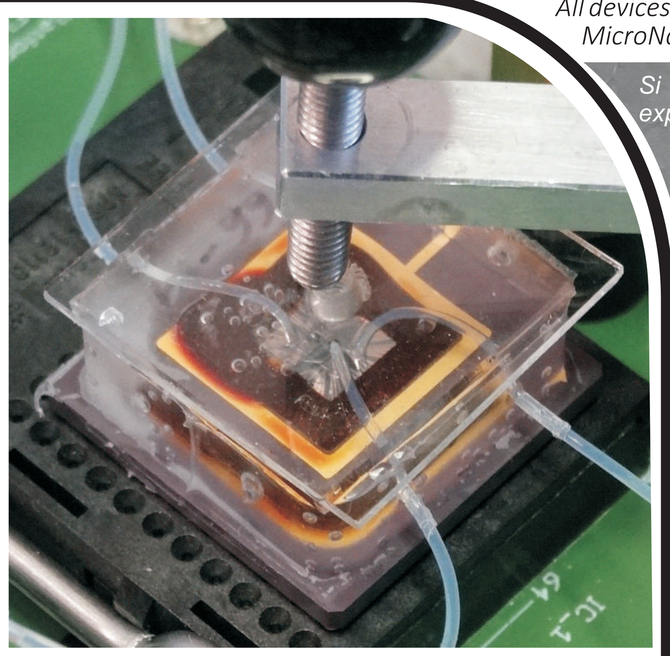


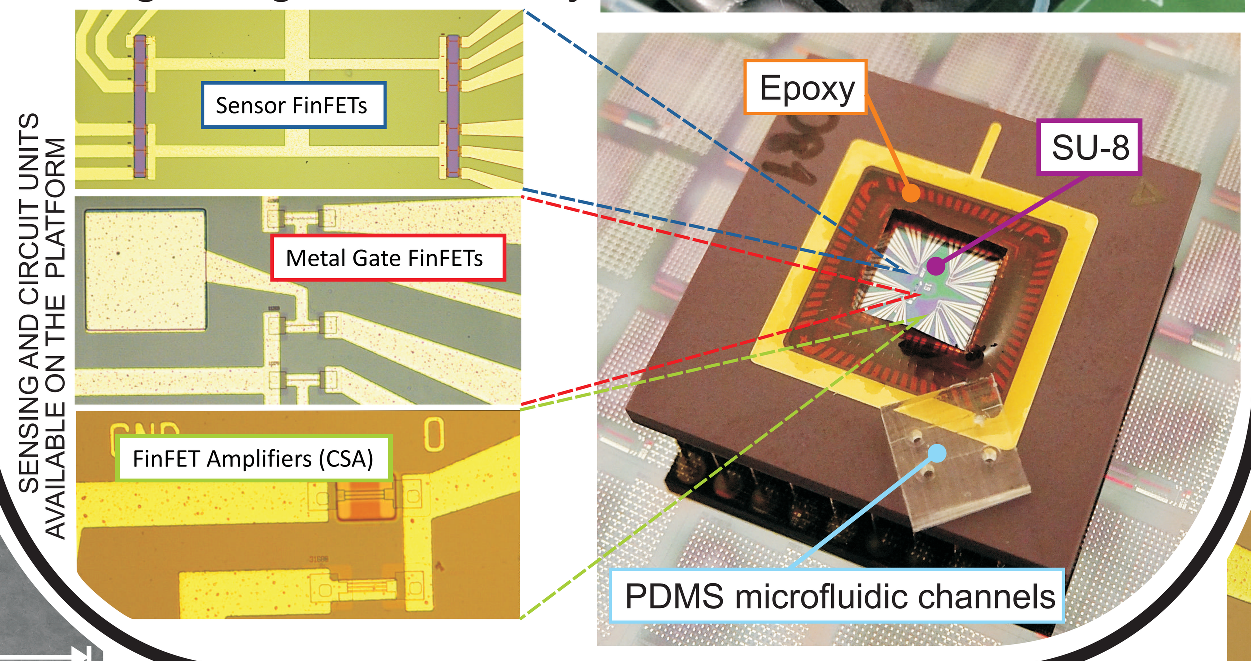


Simplified process flow: fin cross-sections

Keywords

Microfluidic platform
Label-Free FET
FinFET on Si-Bulk
High-k gate oxide
CMOS compatible
Low power
Full pH response
High long-term stability



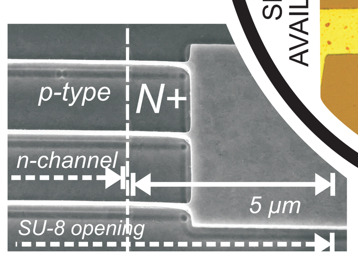


FinFETs as pH Sensors

The FinFET sensors with HfO_2 as sensing gate, have been characterized in a liquid environment. The liquid potential is controlled by a flow through Ag/AgCl reference electrode which can be swept or kept fixed.

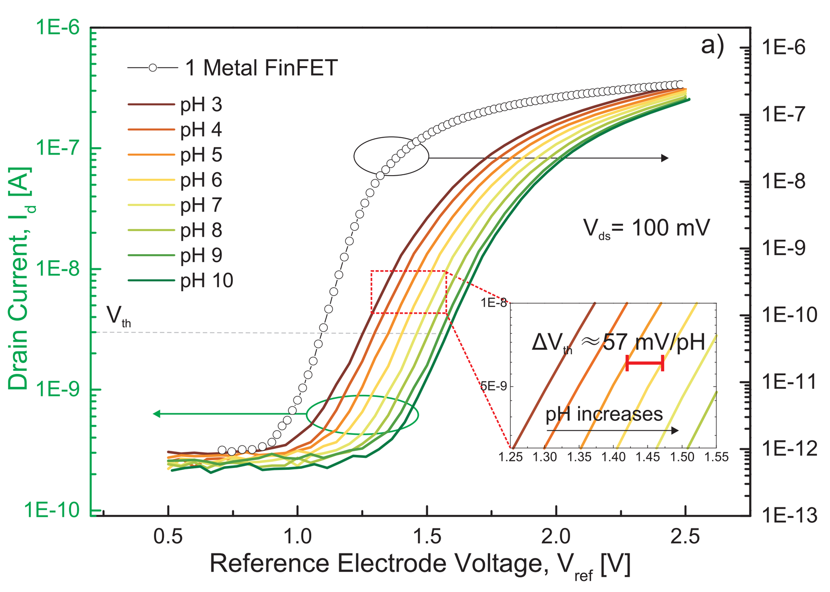
Main achievements:

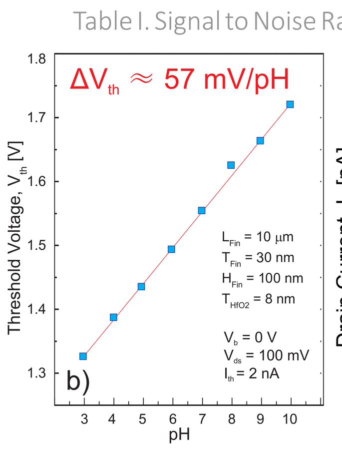
- Full pH response: $\Delta V_{th} = 57$ mV/pH
- Constant pH response, independent of salts
- High readout sensitivity: S_{out}=60%
- High Accuracy: 0.013 pH
- Low power consumption: P ≈ 10 nW

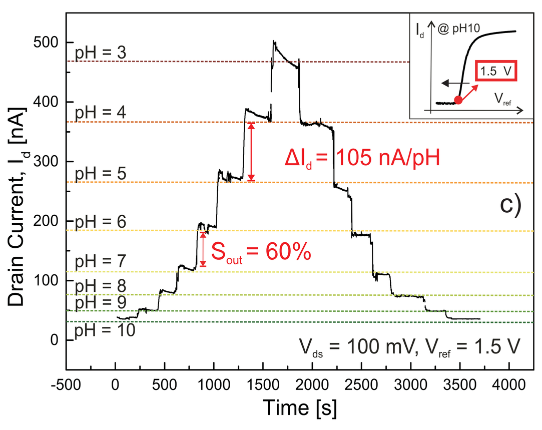


	FinFET, SNR = $\Delta I_d/\sigma_{Id}$					
pH	3→4	4→5	5→6	6→7	7→8	3-8
V_{ref1} = 1.5 $V_{@ph3}$	44	87.5	85	71	80	≈ **74**
V_{ref2} = 2 $V_{@ph3}$	32	42	117	123	210	≈ **80**
V_{ref3} = 1.5 $V_{@ph8}$	42	87	82	88	90	≈ **78**

Table I. Signal to Noise Ratio, for different biasing conditions of V_{ref}



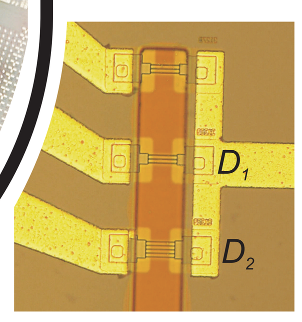


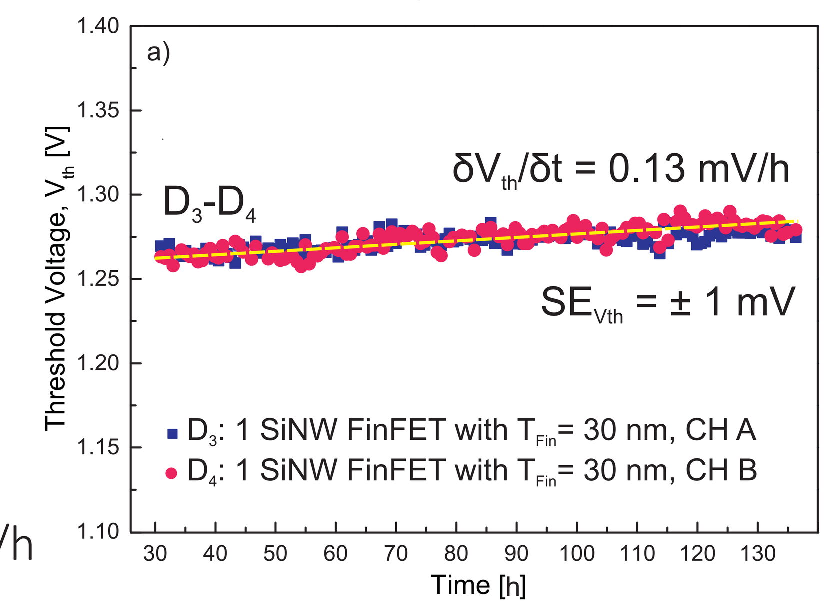


FinFETs as pH sensors: (a) I_d (V_{ref}) transfer characteristic for a metal (right Y-axis) and liquid gate (left Y-axis) FinFET, for 3 < pH < 10 with the inset showing the curve shift V_{th}; (b) V_{th}(pH), extracted at $I_d = I_{th}$ = 2nA; (c) I_d, for a FinFET sensor during a time period of 25minutes for 3 < pH < 8 at V_{ref} = 1.5 V.

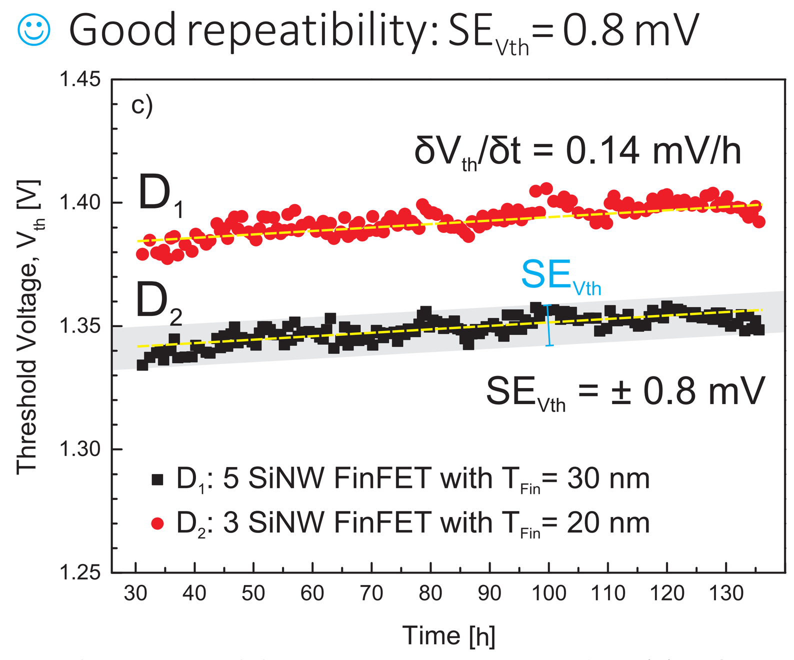
Long-Term Stability

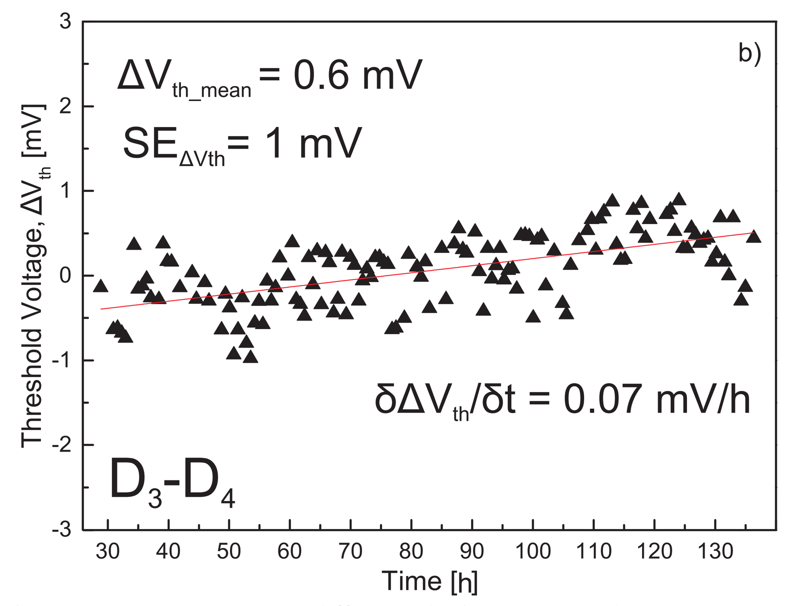
- 4.5 days
- pH = 6





- Excellent long-term stability: 0.13 mV/h
- Good repeatability: SE_{Vth} = 0.8 mV

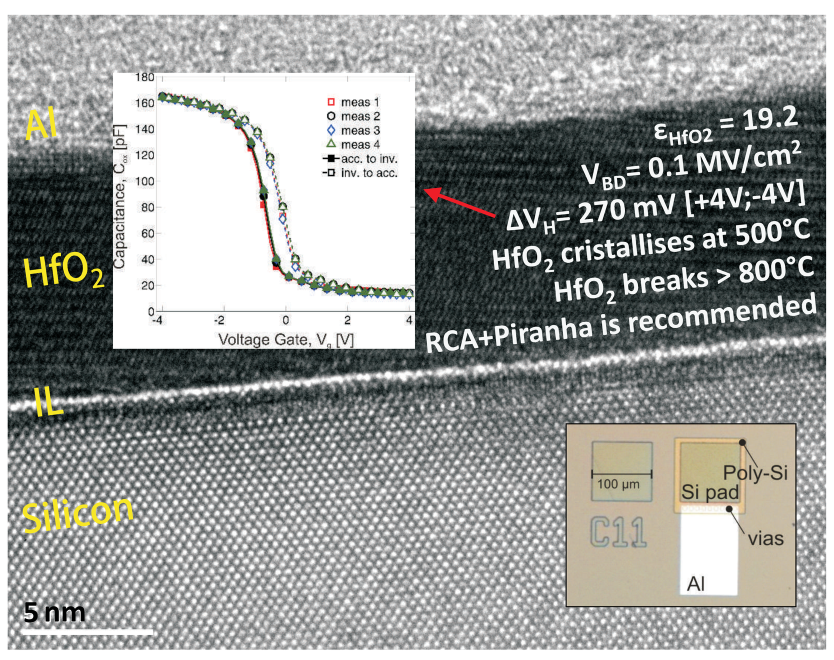




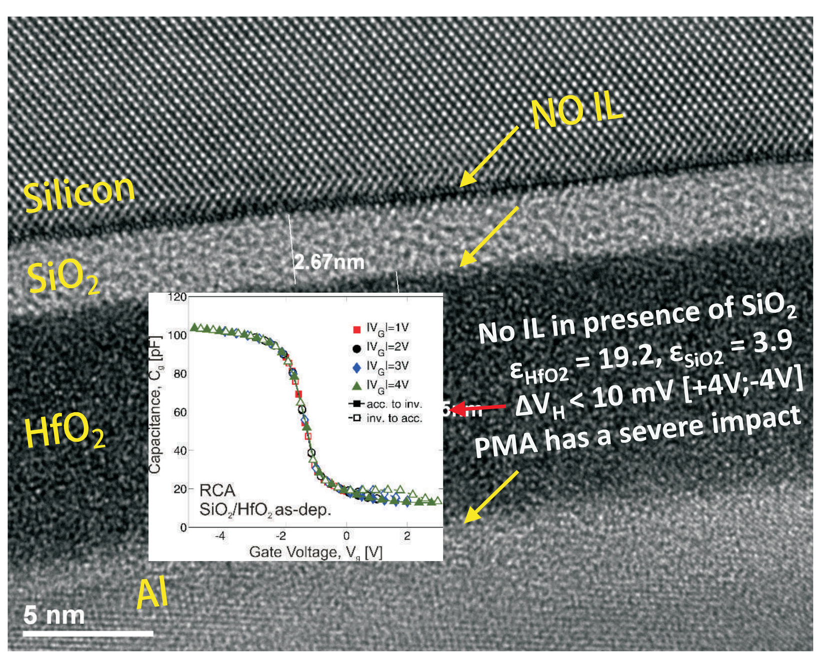
FinFET long-term stability measurement over 4.5 days: (a) V_{th} for equal single-wire FinFET sensors at different die locations and constant pH = 6; (b) result of the subtraction of the data set of V_{th} for the devices D3 - D4; (c) V_{th} for different multiwire FinFET sensors at constant pH = 6.

HfO_2 MOSCAP Characterization

- The intrinsic sensitivity is always given by the gate oxide properties in contact with liquid;
- HfO_2 as gate oxide can provide a pH response up to the Nernst limit;
- HfO_2 fully satisfies the CMOS scaling process constraints;



TEM image (Cime, EPFL) of a Si-HfO_2-Al stack with Interfacial layer; C-V measurements performed by MOSCAPs (bottom right inset).



TEM image (Cime, EPFL) of a Si-SiO_2-HfO_2-Al stack with Interfacial layer; C-V measurements performed by MOSCAP (no hysteresis).

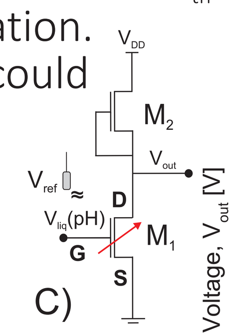
- Only growing thermal SiO_2 between Si and HfO_2 we can get rid of uncontrolled IL;
- Removing the IL achieves the complete suppression of hysteresis.

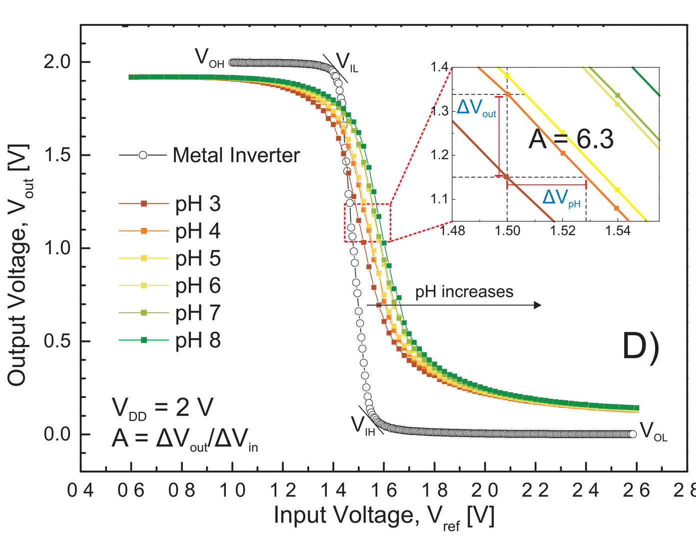
Sensing Common Source Amplifier

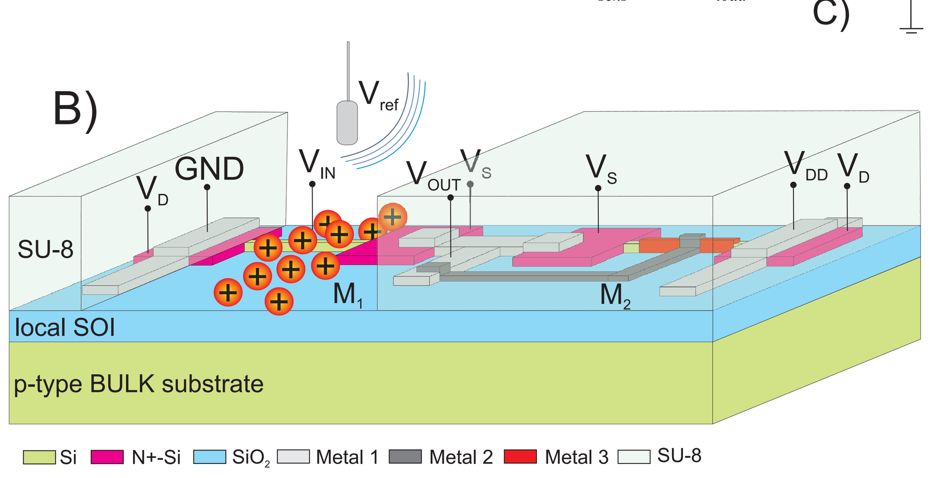
A simple architecture with one FinFET connected as load and another one as driving sensor can provide a readout gain of 6.3 with a ΔV_{th} readout of 175 mV/pH and a linear voltage-to-voltage input-output correlation. Multiple connections of these stages could lead to sensing frequency readout.

A)

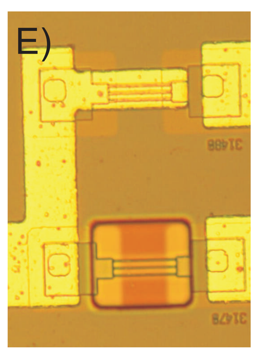
$$A = \left| \frac{\Delta V_{out}}{\Delta V_{in}(pH)} \right| = g_{m_{sens}} * R_{load} = \frac{g_{m_{sens}}}{g_{ds_{sens}} + g_{ds_{load}}}$$







(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.



(D) V_{out}(V_{ref}) 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;
(E) the fabricated common source amplifier with microfluidic opening for the liquid gate FinFET connected to the metal gate FinFET.

[1] EPFL THESIS N°6134, available online (http://dx.doi.org/10.5075/epfl-thesis-6134)