"Low Power FinFET pH-Sensor with High-Sensitivity Voltage Readout"

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[5] "POLITEHNICA" University Bucharest, Romania

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Introduction

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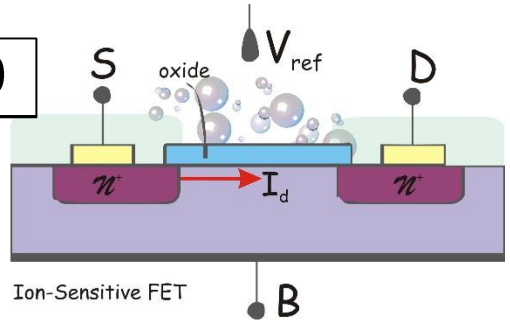
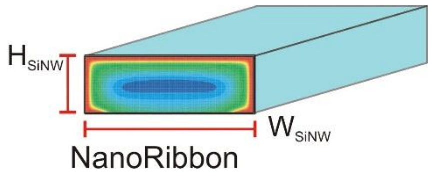
FET sensors

- Why label-free FET sensors?
  - Alternative promising techniques?
    - mass spectroscopy
    - microcantilevers
    - surface plasmon..
  - real-time, more reliable and durable
  - simpler technology → should compete with ELISA test
  - less expensive
  - easier to be integrated towards home point-of-care

1970





- FET sensors evolved from ISFETs into SiNWs:
  - Implementation of multi-gates: lateral, back-gate
  - high-k material for full pH response: **HfO_2 → Nernst limit: 59 mV/pH**
  - Highly scaled SiNWs → higher analyte-analyzer interaction
  - Mass production and integration are still challenging

FinFET sensors

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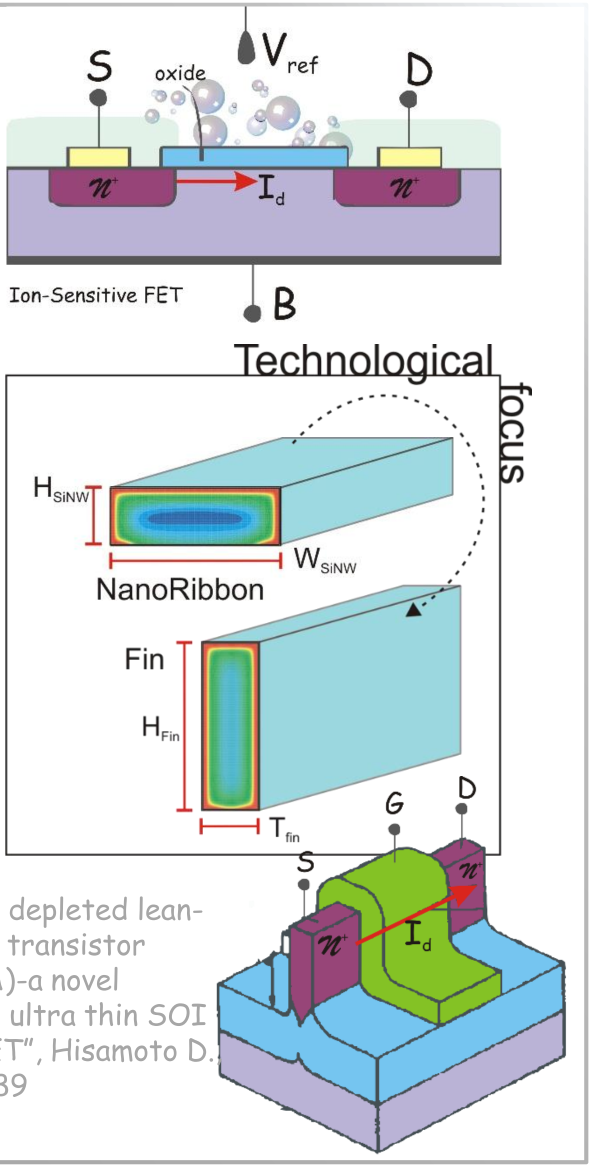
Why FinFET sensors?

- are they more pH-sensitive?
- They are not.

- **they do match today's technology requirements:**
  - advanced channel control → stability, reproducibility
  - realistic power supply scenarios
  - concrete integration with CMOS ICs
  - no degradation upon scaling
  - accurate micro- and nanoelectronic models

- **Enhanced read-out can compensate ultra-sensitivity**



"A fully depleted lean-channel transistor (DELTA)-a novel vertical ultra thin SOI MOSFET", Hisamoto D. IEDM '89

HfO_2 for full pH response

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1556 **Gerald Lucovsky: Transition from thermally grown gate dielectrics**

TABLE I. Classification of dielectrics, including amorphous morphology, average electronegativity difference, ΔX, average bond ionicity, I_b, and metal and oxygen atom coordinations.

Dielectric	ΔX	I_b	Coordination	Coordination
Continuous random networks			metal/silicon	oxygen
SiO_2	1.54	0.45	4	2.0
CRNs with network modifiers				
Al_2O_3	1.84	0.57	4 and 6 (3:1 ratio)	3.0
Ta_2O_5	1.94	0.61	6 and 8 (1:1 ratio)	2.8
TiO_2	1.90	0.59	6	3.0
$(ZrO_2)_{0.1}(SiO_2)_{0.9}$	1.61	0.48	8 and 4	2.2
$(ZrO_2)_{0.23}(SiO_2)_{0.77}$	1.70	0.51	8 and 4	2.46
$(ZrO_2)_{0.5}(SiO_2)_{0.5}$	1.88	0.59	8 and 4	3.0
$(TiO_2)_{0.5}(SiO_2)_{0.5}$	1.72	052	6 and 4	2.5
$(Y_2O_3)_1(SiO_2)_2$	1.88	0.59	6 and 4	2.86
$(Y_2O_3)_2(SiO_2)_3$	1.93	0.61	6 and 4	3.0
$(Y_2O_3)_1(SiO_2)_1$	1.99	0.63	6 and 4	3.11
$(Al_2O_3)_4(ZrO_2)_1$	2.02	0.64	4 and 8	3.0
$(Al_2O_3)_3(Y_2O_3)_1$	1.97	0.62	4 and 6	3.0
Random close packed ions				
HfO_2	2.14	0.68	8	4.0
ZrO_2	2.22	0.71	8	4.0
$(La_2O_3)_2(SiO_2)_1$	2.18	0.70	6 and 4	3.5
Y_2O_3	2.22	0.71	6	4.0
La_2O_3	2.34	0.75	6	4.0

FinFET Fabrication and Microfluidic Platform Assembly

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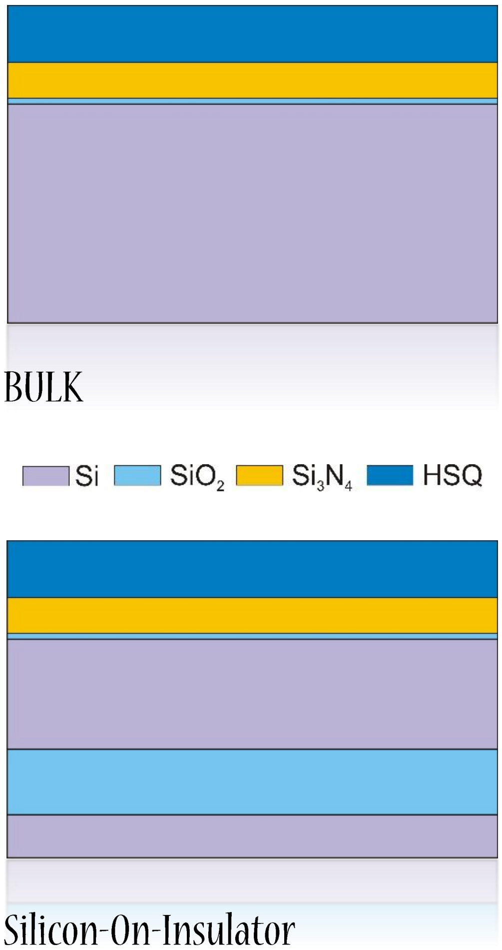
Process flow



- SiO_2/Si_3N_4/HSQ deposition
- PEC assisted e-beam lithography
- Si_3N_4 Deep Reactive Ion etching
- Vertical fins RIE
- Si_3N_4 spacers creation
- Si anisotropic etching
- FEA assisted wet oxidation
- Si_3N_4 hot phosphoric acid
- S/D N+ implantation (LTO + RTA)
- SiO_2 DIP Hydrofluoric Acid
- Atomic Layer Deposition (HfO_2)
- Argon Ion Milling for VIAS
- AlSi1% Lift Off Metallization

FinFET Fabrication

Process flow

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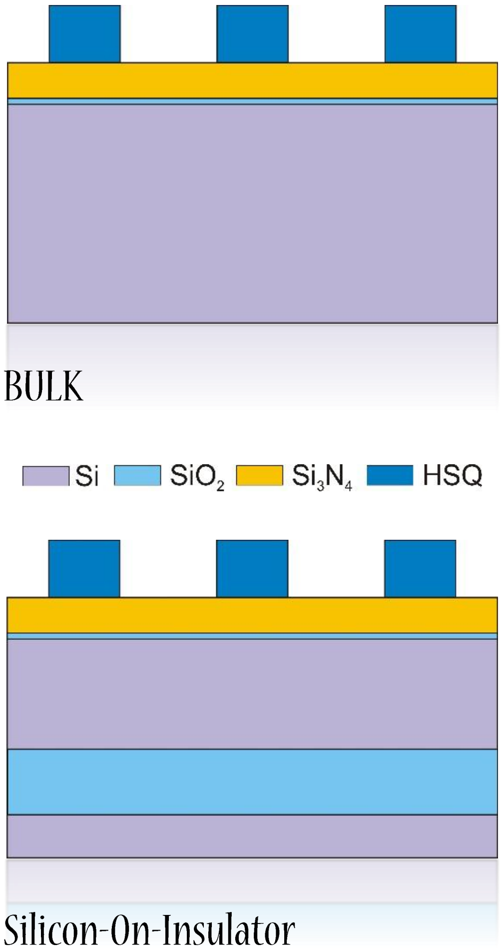

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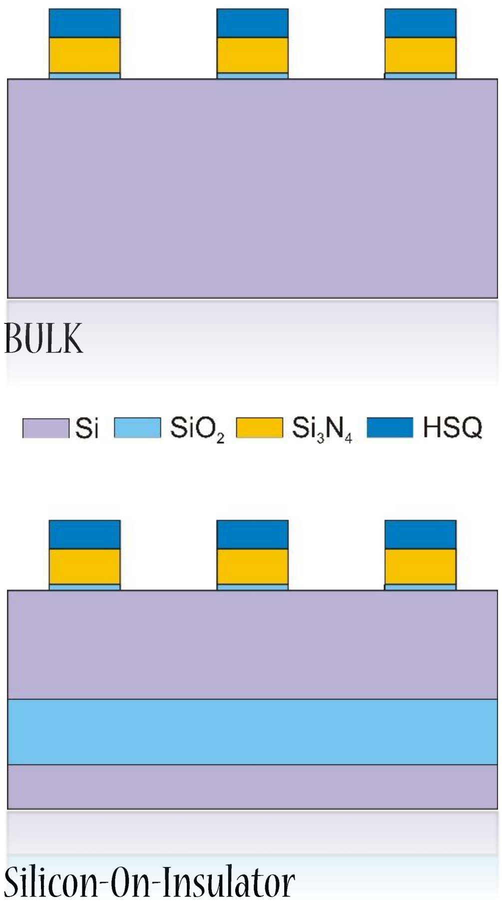

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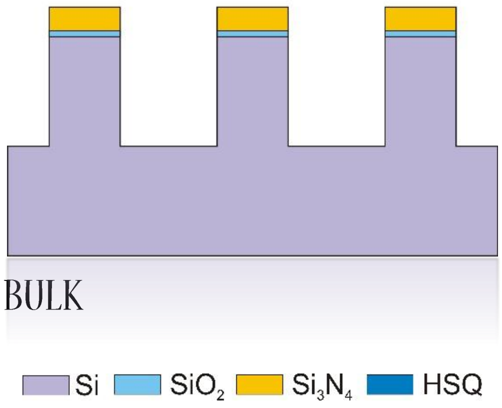

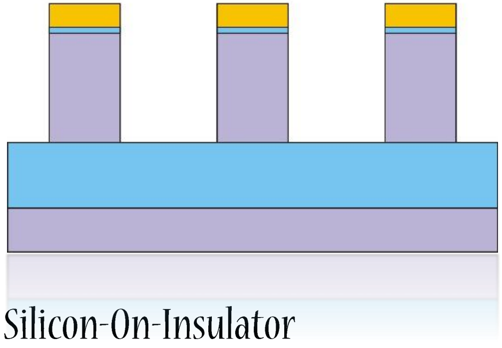

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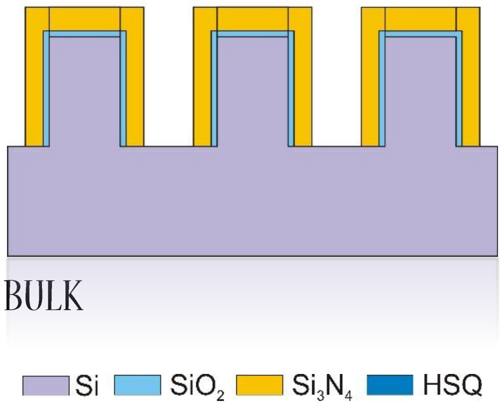

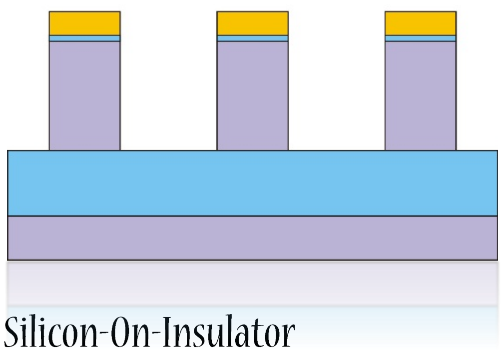

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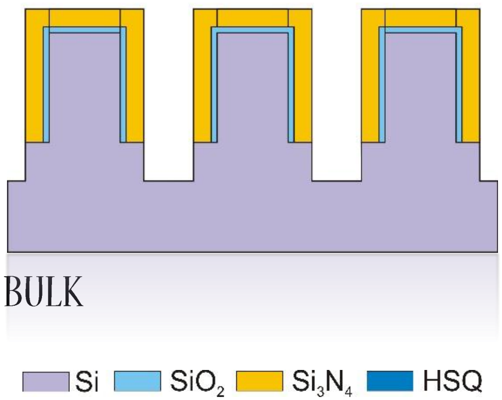
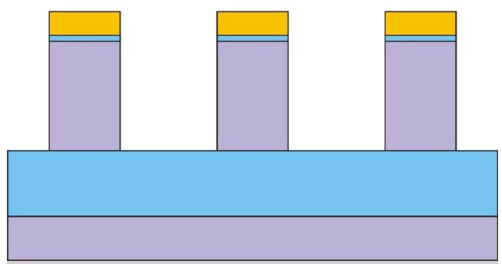


BULK



Silicon-On-Insulator

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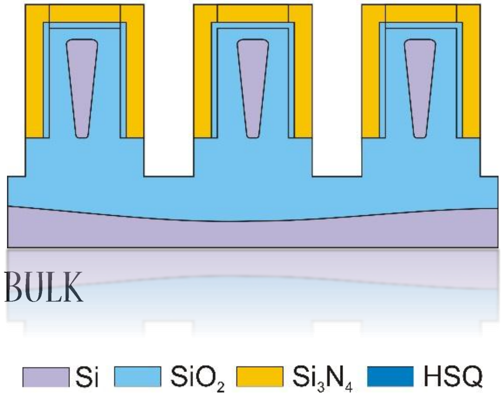

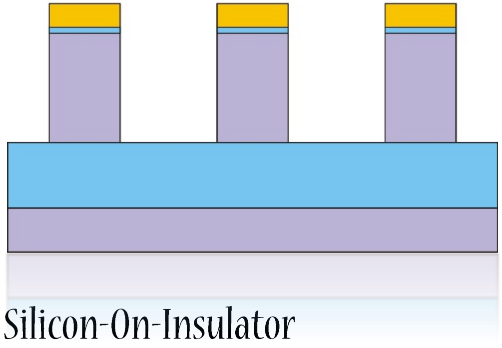

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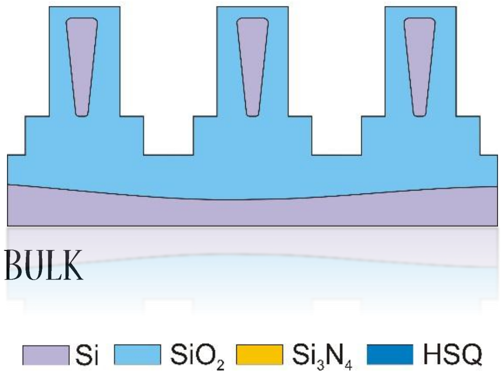

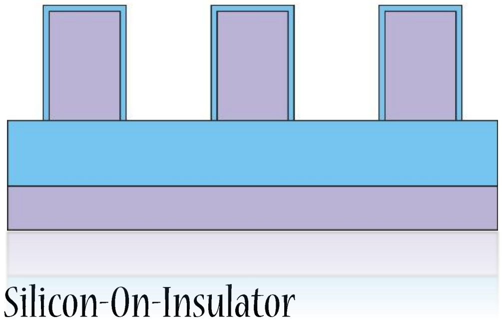

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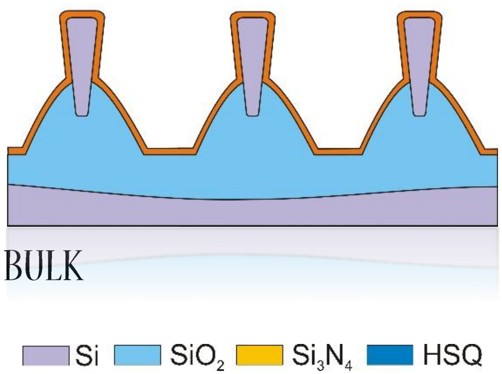

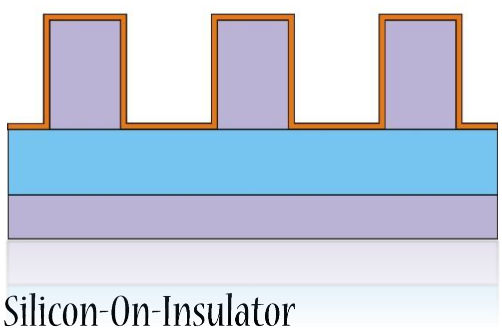

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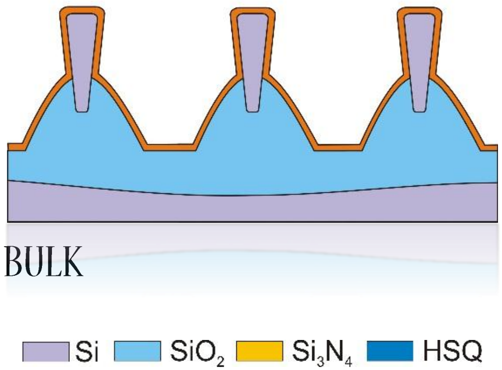

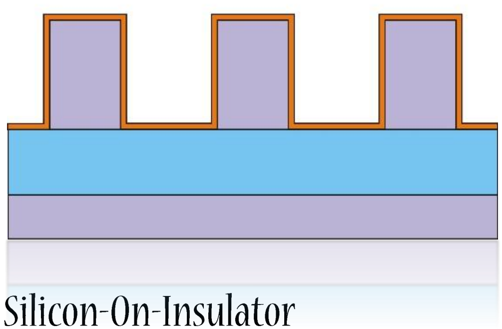

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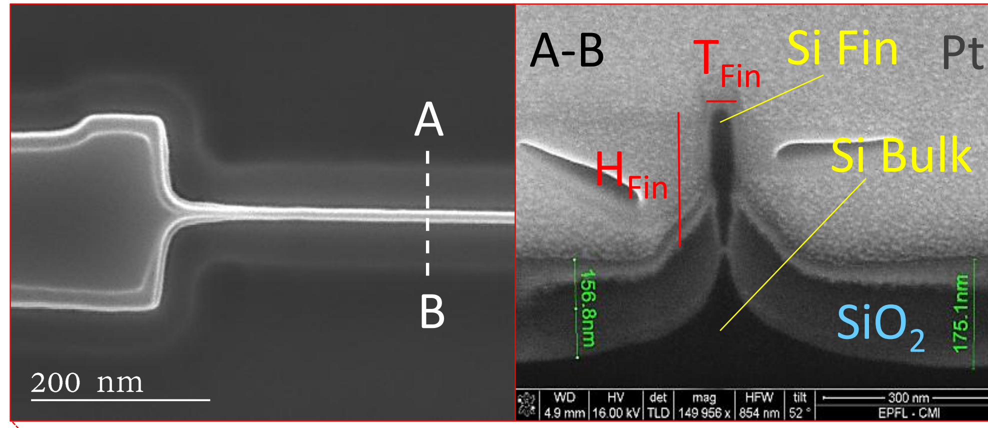
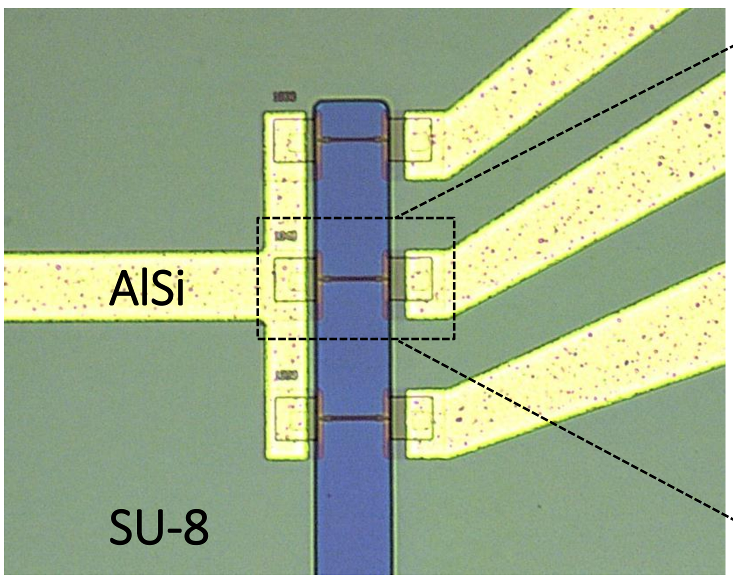
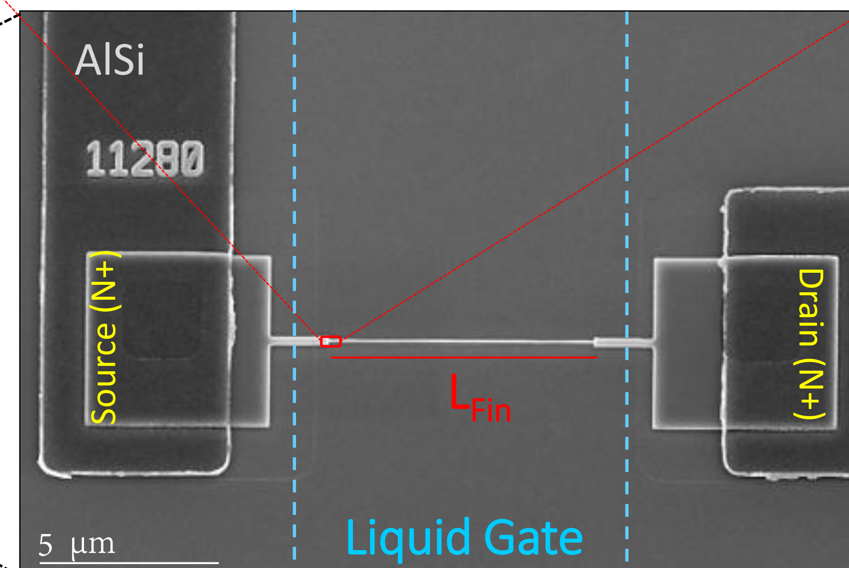
FinFET overview

- p-type BULK substrate
- n-channel fully depleted FinFET
- Local SOI by “Spacers Technology”
- 20 nm < T_{Fin} < 40 nm
- 65 < H_{Fin} < 150 nm
- 8 µm < L_{Fin} < 12 µm
- HfO_2 gate oxide

$$\frac{H}{T} > 3$$





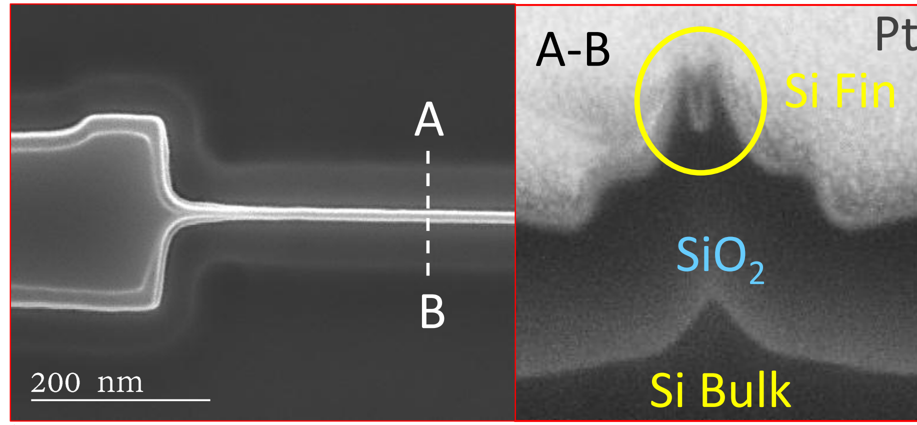


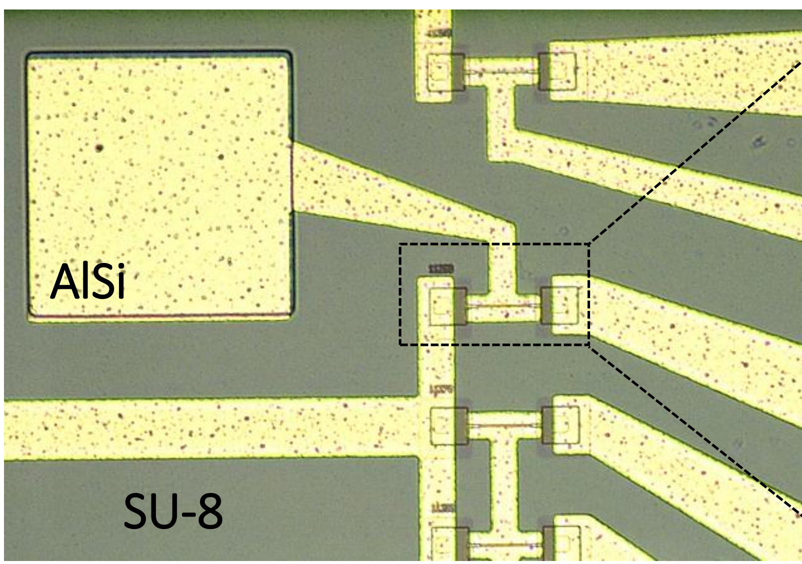
S. Rigante, P. Scarbolo, D. Bouvet, “High-k dielectric FinFETs towards Sensing Integrated Circuits”, Ultimate Integration on Silicon (ULIS), 2013 14th International Conference

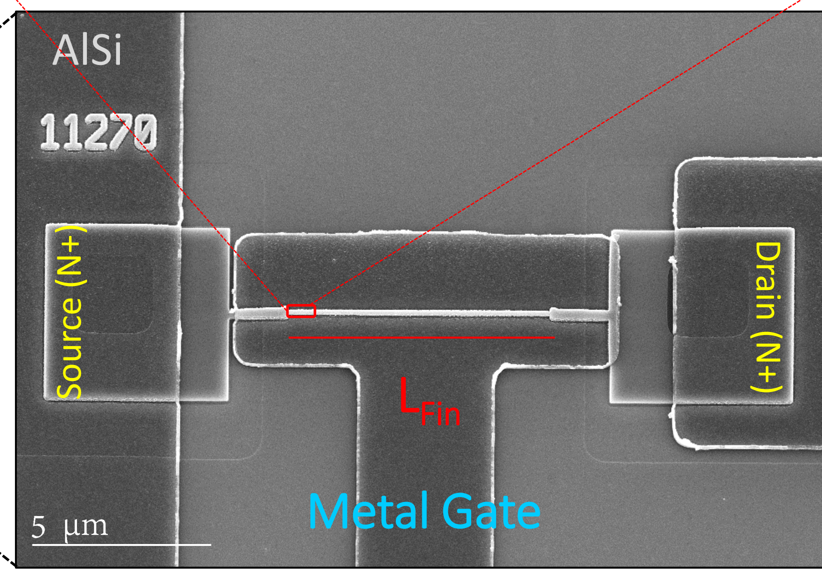
FinFET overview

- p-type BULK substrate
- n-channel fully depleted FinFET
- Local SOI by “Spacers Technology”
- 15 nm < T_{Fin} < 40 nm
- 65 < H_{Fin} < 150 nm
- 8 µm < L_{Fin} < 12 µm
- HfO_2 gate oxide

$$\frac{H}{T} > 3$$







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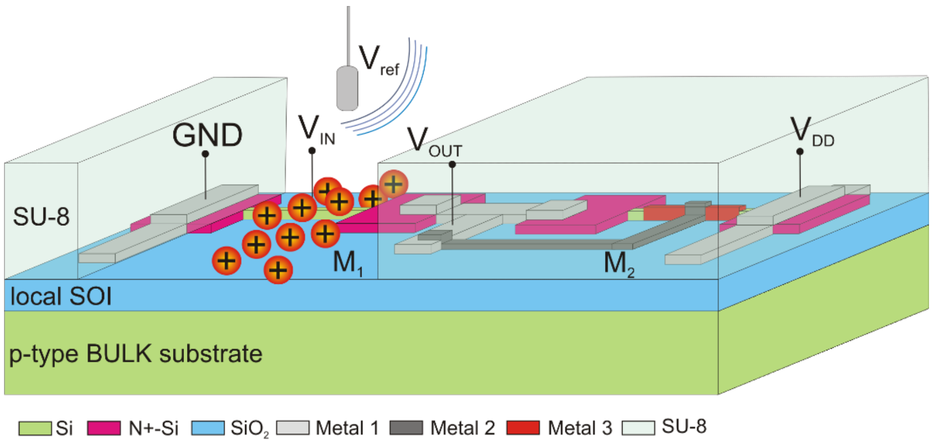
FinFET Fabrication

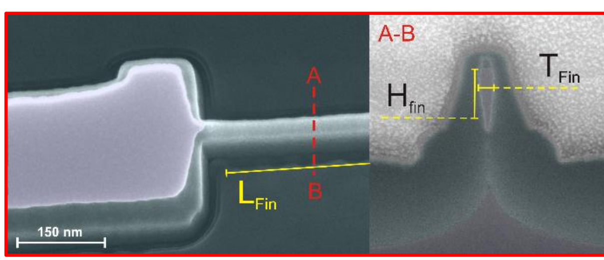
A sensing common source amplifier

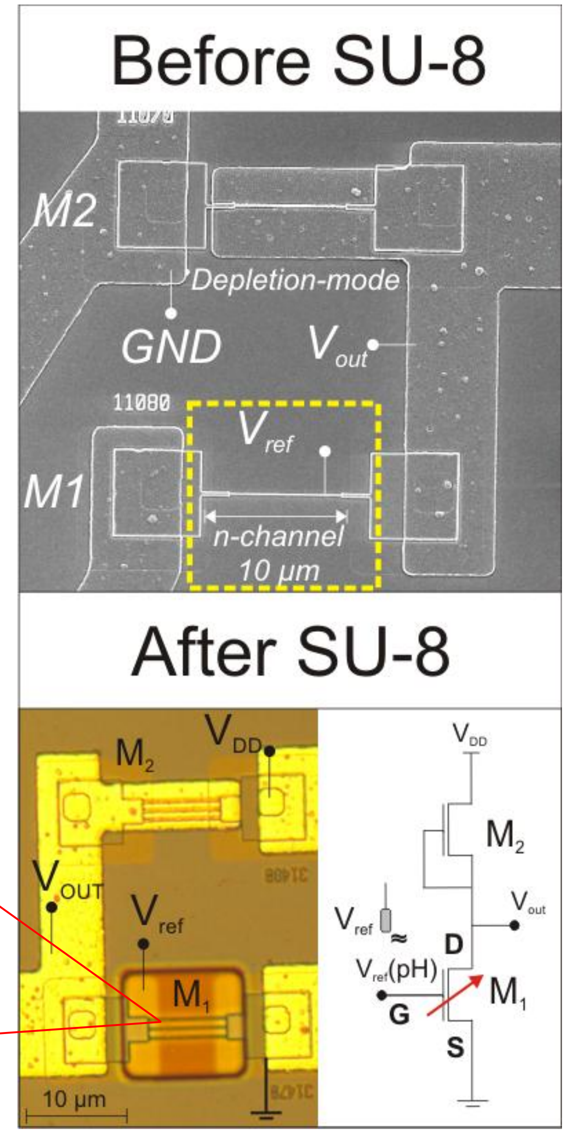


- $V_{in} \rightarrow V_{ref}$ (Ag/AgCl electrode)
- The gain can be approximated as:

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

$$A \propto \frac{T_{M2}}{T_{M1}}$$

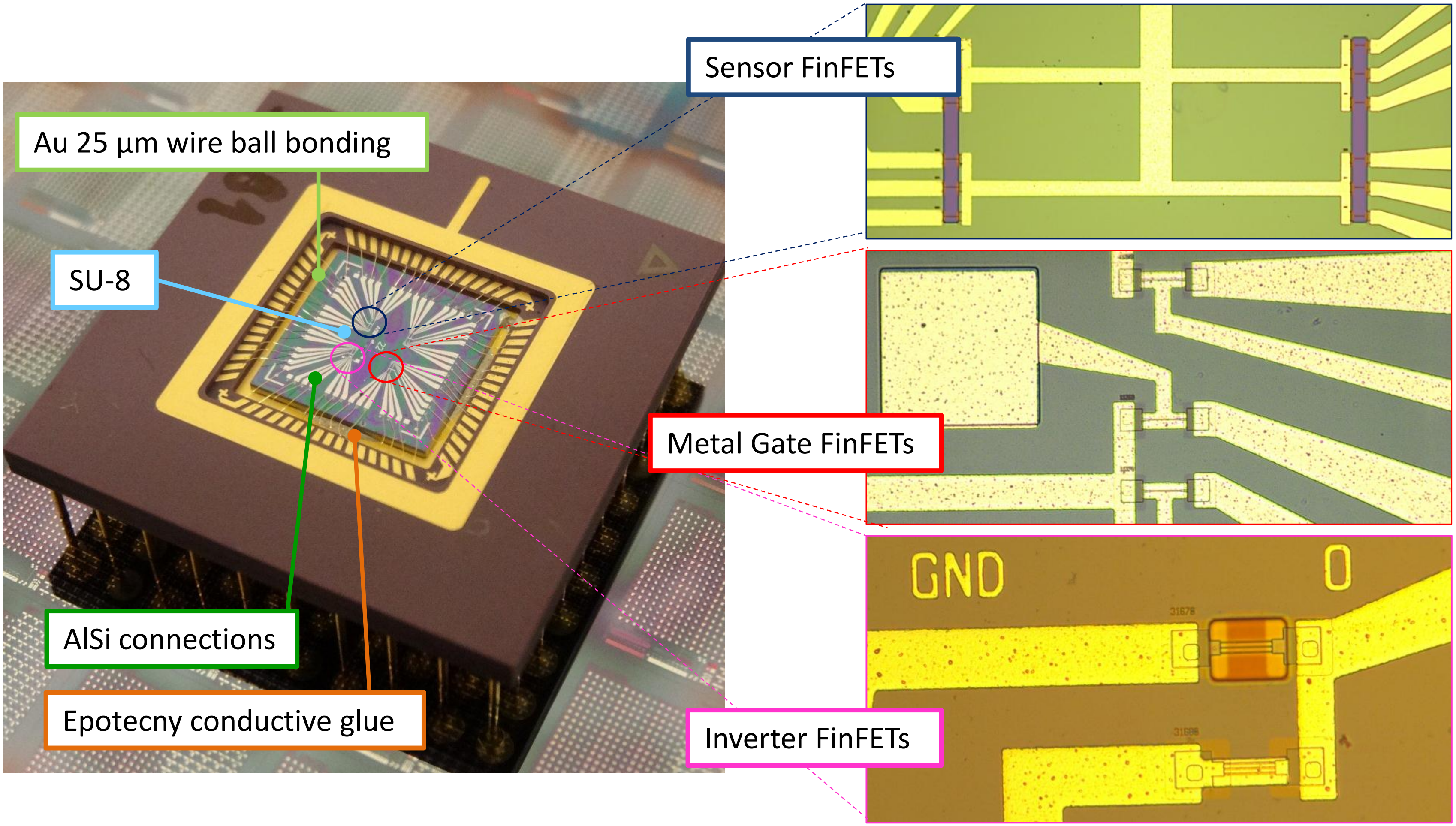




Die overview

One die incorporates:

- FinFET based **sensors** and **metal gate transistors** (**single** and **multi wires**)
- **Amplifying architectures** based on two FinFET components



Microfluidic set-up

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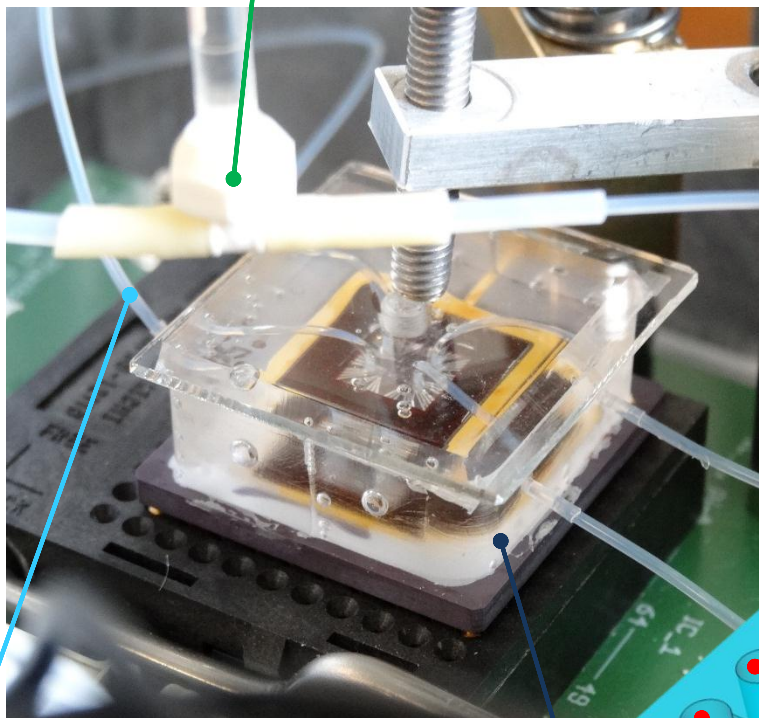
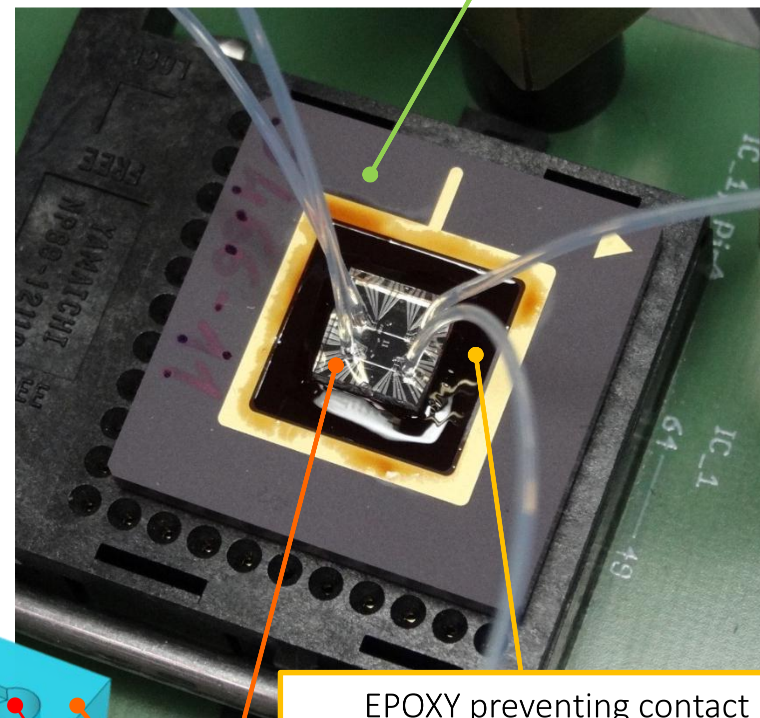
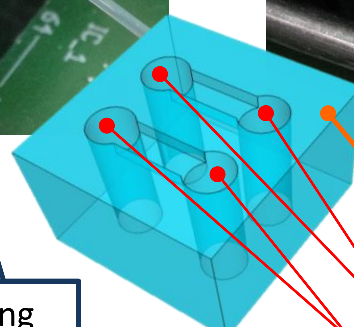
Flow through Ag/AgC reference electrode

Chip carrier for PCB connection with a total of 48 addressable devices







EPOXY preventing contact between Au wires and liquid

PTFE tubes connected to set-up andreference electrode

PDMS integrating μ-fluidic channels for electrolyte flow

Complete PDMS embedding

Devices location in μ-fluidic channels

Measurements

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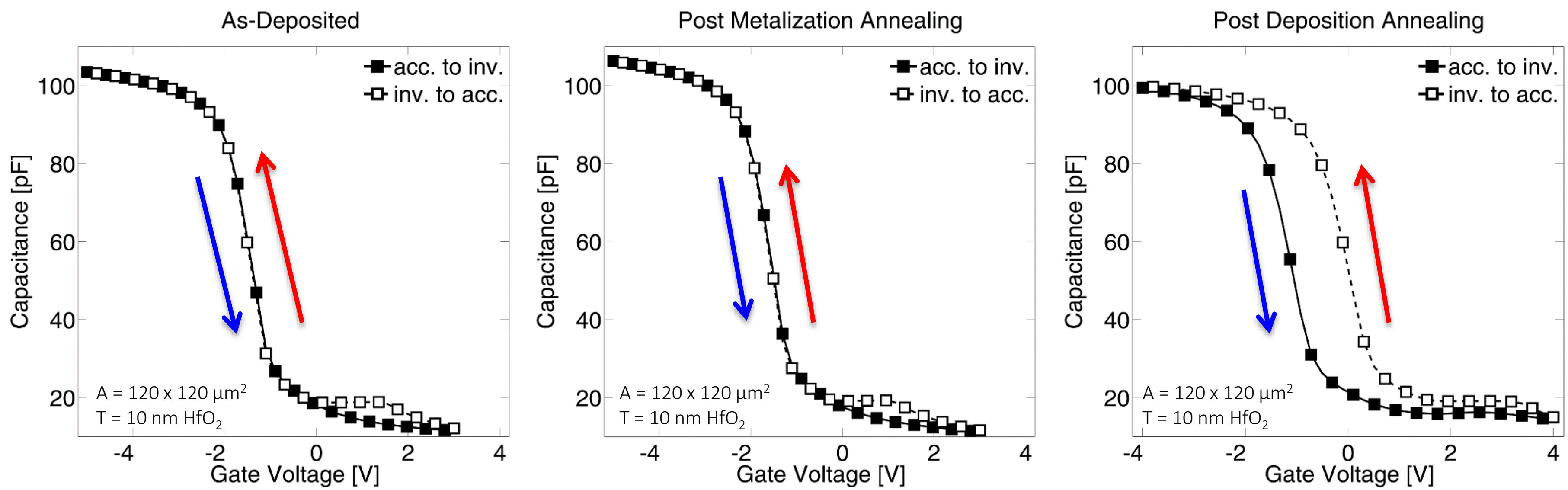
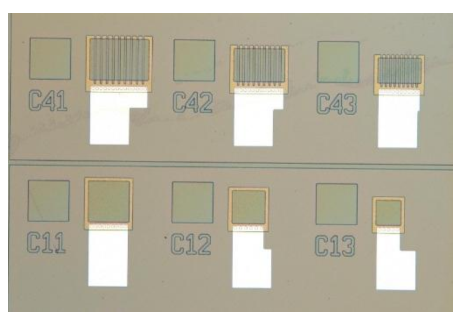
SiO_2/HfO_2 characterization*

- Interface thermal **SiO_2 (≈nm) + HfO_2** → **HYSTERESIS ≈ 15 mV**
- It is true only if SiO_2/HfO_2 is «**as deposited**» or the **annealing** is done **after metallization**
- The metal prevents Oxygen chemical reactions → no extra growth of silicate



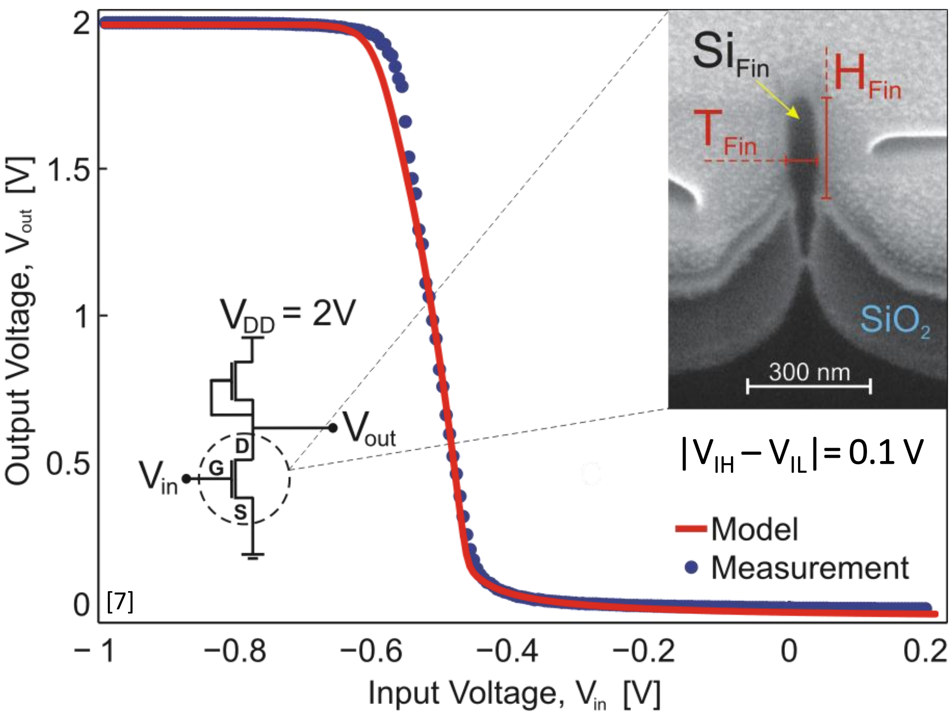
* Results based on the work performed by CMi (Center of MicroNanotechnoly, EPFL) and characterized by P. Scarbolo (NanoLab, EPFL)

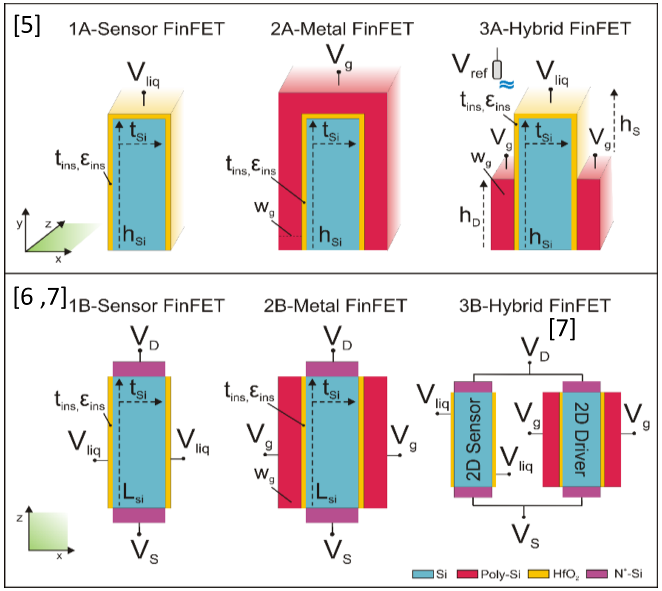


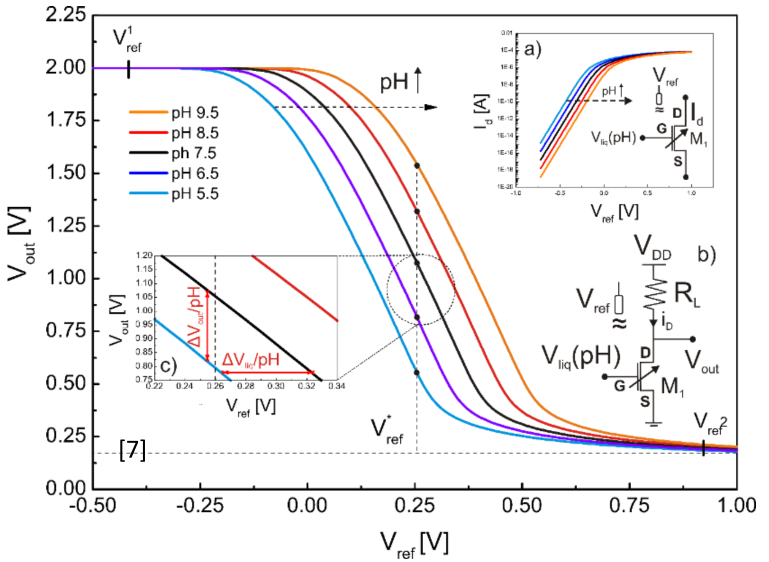
- C-V measurements: ε_{HfO2} ≈ **16.5**
- **$V_{breakdown}$ ≈ 6.7 V** with leakage current **I_{leak} < 1 pA** at V_g = 2 V

Measurements

T-CAD simulations for sensing circuits







[5] “FinFET for high sensitivity ion and biological sensing applications”, S.Rigante et al., Microelectron Eng, 88 (2011), 1864-1866.
[6] “Implementation of the symmetric doped double-gate MOSFET model in Verilog-A for circuit simulation”, J. Alvarado et al., Int. J. Numer. Model., 23 (2010), 88-106
[7] “ FinFET integrated low-power circuits for enhanced sensing applications”, S. Rigante, P. Livi et al., 186 (2013), 789-795.

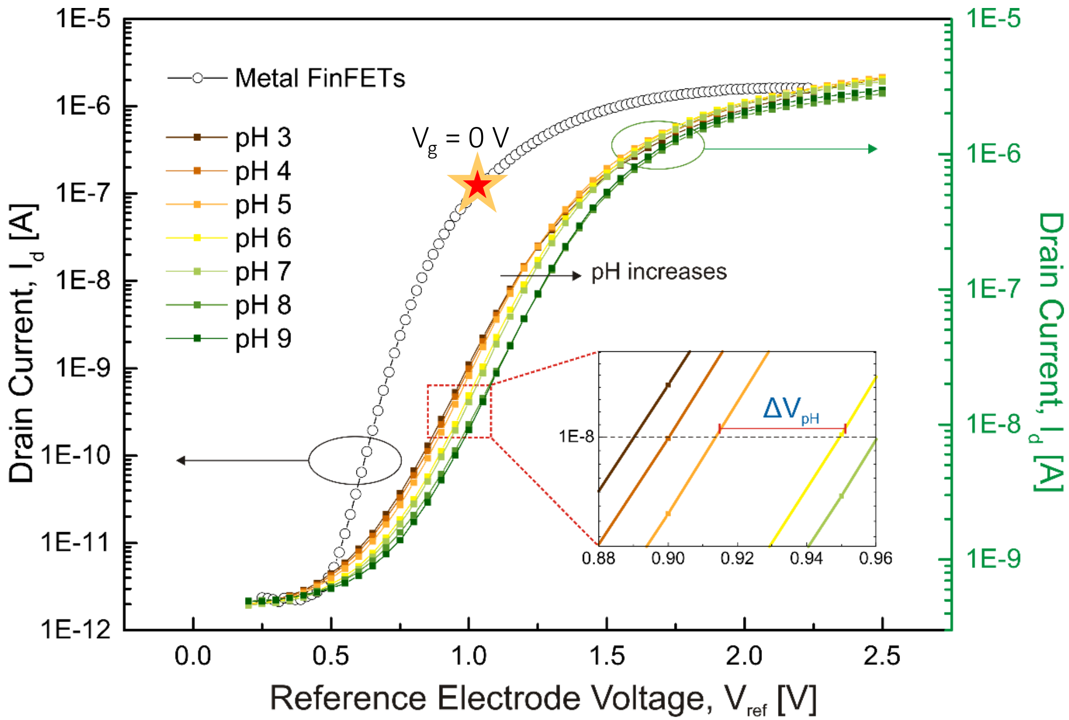
Measurements

$I_d(V_{ref})$ and $I_d(V_g)$ characteristics

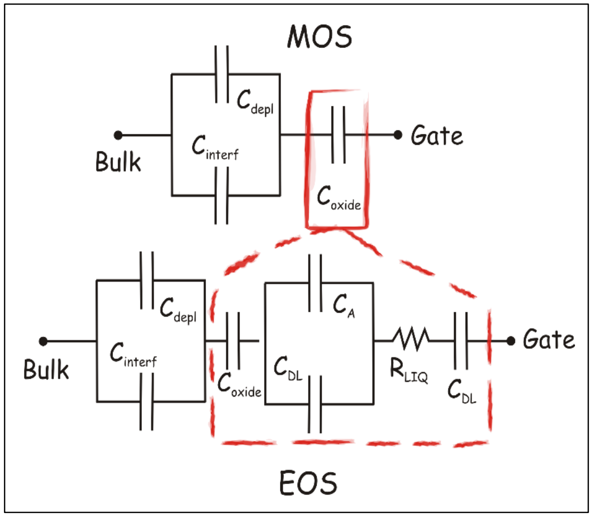
- ‼ Good electrical features → Depletion devices
- ‼ Very low bulk contribution if $V_b = 0$ V
- ‼ Good gating response: **ΔI_d = 33 nA/pH**
- ‼ **Monotonic** expected **ΔV_{th}**

- ‼ ΔV_{th} is not constant and "full"
- ‼ "Liquid" SS > "Metal" SS

Metal-Gate	Liquid-Gate
$I_{on}/I_{off}1 \approx 10^6$	$I_{on}/I_{off} \approx 10^4$
SS = 72 mV/dec	SS = 185 mV/dec



$$V_{ref} - V_g = \Delta V_{sol} = \Delta\Phi_{Al-Ag} + \Delta\chi_{sol}$$

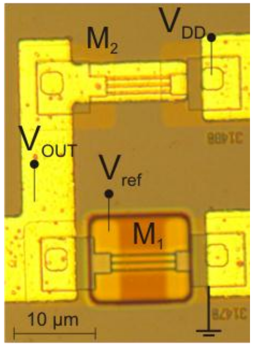


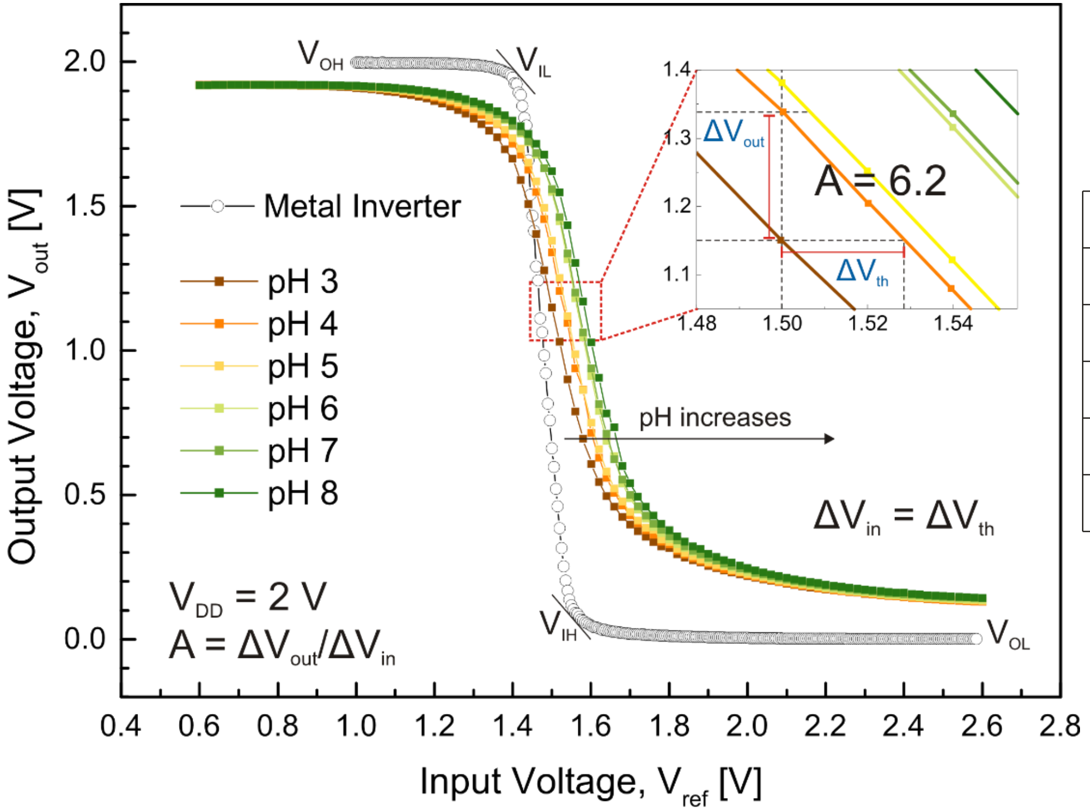
Bousse L., J Chem Phys (1982),76(10), 5128-33

Measurements

$V_{out}(V_{ref})$ characteristics

- Two n-MOS FinFETs → common source depletion-mode inverter
- The **driver transistor** is the **sensor**, the **load** is **not** in contact with **liquid**
- !! ΔV_{out} (ΔV_{th}) is LINEAR and AMPLIFIED
- !! The gain is independent from ΔV_{in} /pH
- !! **$A = \Delta V_{out} / \Delta V_{in} \approx 6.4$** ← obtained only through device connection



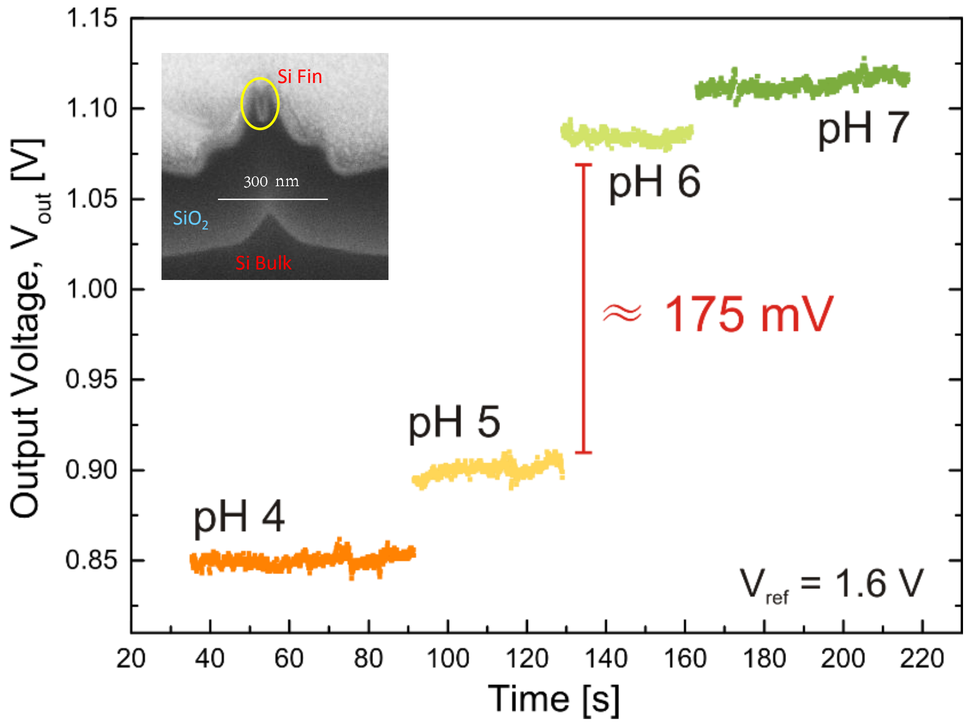


	FinFETs-based Amplifier		
pH	ΔV_{in}[mV]	ΔV_{out}[mV]	**$A = \Delta V_{in}/\Delta V_{out}$**
3-4	30	185	**6.2**
4-5	6	40	**6.6**
5-6	27	174	**6.5**
6-7	5	31	**6.2**
7-8	16	102	**6.4**
	≈ 17 mV/pH	**≈ 107 mV/pH**	**≈ 6.4**

Measurements

V_{out} vs. time

- ...in kinetic studies, fast reaction cannot be measured in steady-state
- ...V_{ref} sweep can have hysterical components → small ΔV_{th} ≠ drift
- For fast read-out and small ΔV_{th} → **fixed V_{ref} and $\Delta V_{out}/V_{out}$ adjustement**



- Depending on V_{ref} and S → **high ΔV_{out} ≈ 175 mV/pH**
- Negligible background noise:

$$\frac{DS}{N} = \frac{DV_{out}}{s} \approx 76$$

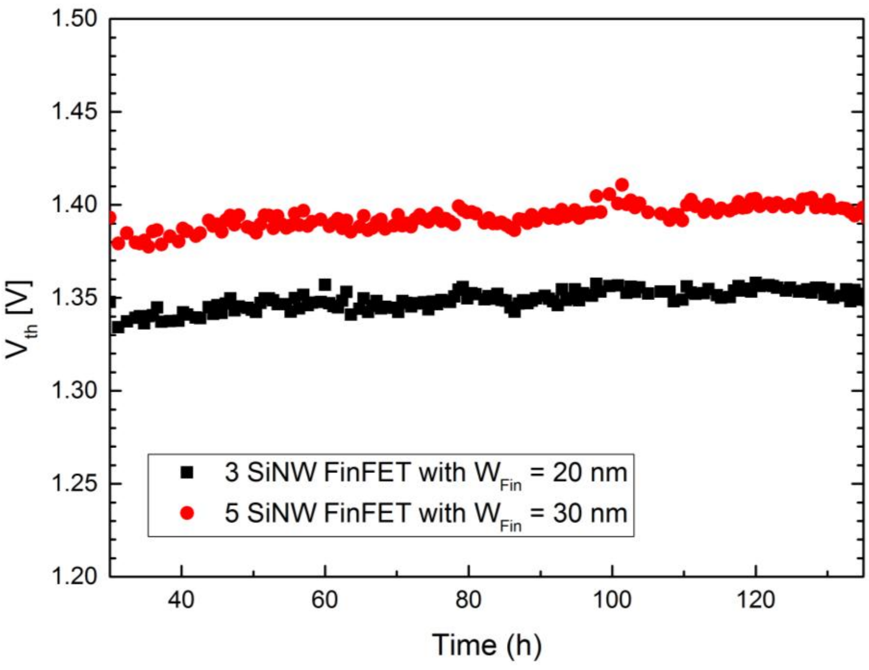
with σ = 2.6 mV

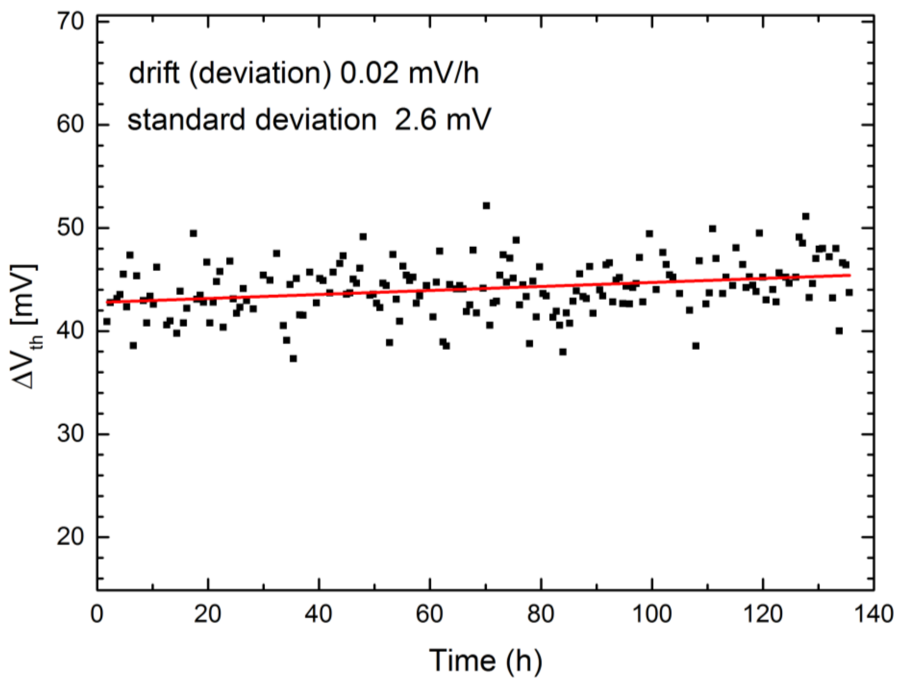
- Negligible drift in short-time periods

Measurements
Long-term stability

- Stability measurements over 4.5 days
- 8nm HfO_2 gate oxide
- buffer solution at pH = 6
- different nanowires

- Similar drift for different wires
- Drift ≈ 0.13 mV/h
- ΔV_{th} drift ≈ 0.02 mV/h





Conclusions

Conclusions

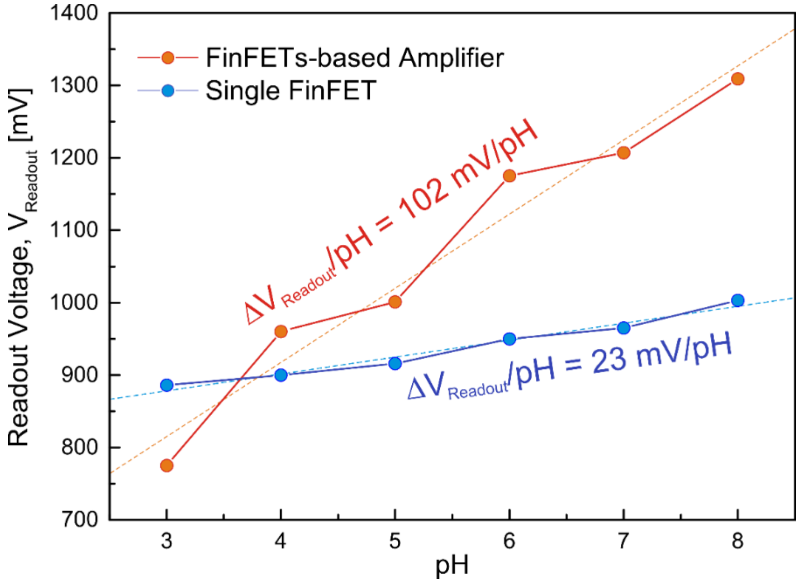
A well known architecture for (nano)electronics but not specifically used for sensing has been designed, fabricated and studied:

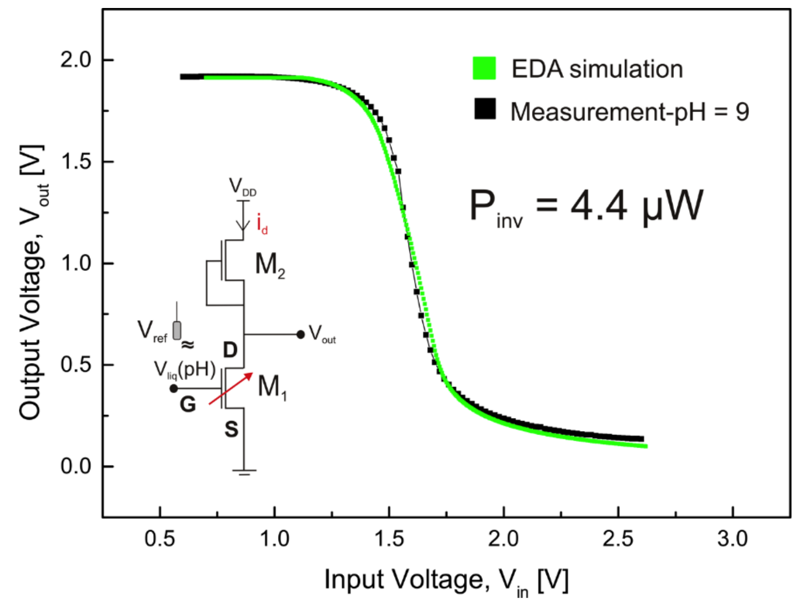
- ⇨ **FinFETs with H/W > 3** have shown **pH response and stability**;
- ⇨ Excellent **metal-gate FinFETs** have the **same sensor architecture**;
- ⇨ **Connection of two n-FinFETs** → **ΔV_{th} in-situ amplification** → frequency readout
- ⇨ The match between EDA simulations and experiments has been verified;
- ⇨ The consumed **DC power is very low**, < 5 μW;
- ⇨ HfO_2 has been implemented for both sensing and readout elements;

High-k dielectric FinFETs are a high profile candidates as both sensing and electronic unit for Integrated CMOS compatible Sensing Circuit, preserving performances under scaling and ensuring low power consumption.

Conclusions

A well known architecture for (nano)electronics but not specifically used for sensing has been designed, fabricated and studied:





High-k dielectric FinFETs are a high profile candidates as both sensing and electronic unit for Integrated CMOS compatible Sensing Circuit, preserving performances under scaling and ensuring low power consumption.

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ÉCOLE POLYTECHNIQUE FÉDÉRALE DE LAUSANNE

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