Innovative MOSFETs-based Pressure Sensors

in Thin Film SOI Technology

Dr. B. Olbrechts, Ir. B. Rue, Ir. M. Al Kadi Jazairli
Prof. D. Flandre, and Prof. J.P. Raskin

UCL Université catholique de Louvain

ICTEAM
Information and Communication Technologies,
Electronics and Applied Mathematics

icteam

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Outline

→ study on the feasibility of a concept

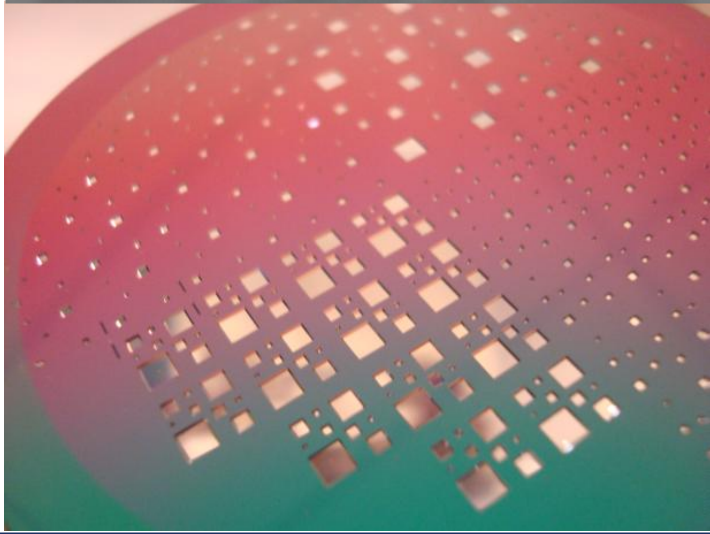
– Introduction

– Proof of concept

– Mechanical study

– Novel architectures

– Conclusions



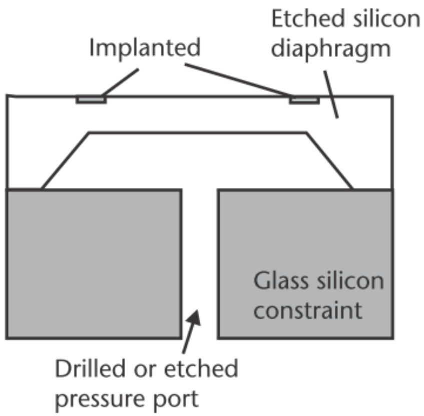
Pressure sensing systems

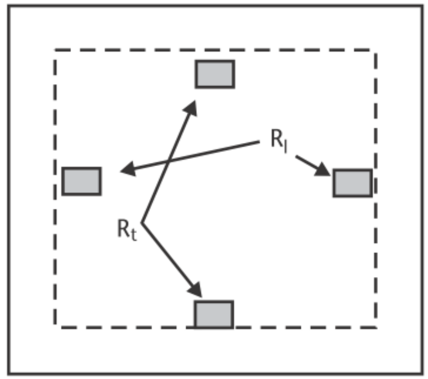
Tire pressure, industrial process control, hydraulic systems, microphones, intravenous blood pressure, …

Associated with Fluids – Flow in pipe, volume of liquid inside a tank, altitude, air speed, …

- Piezoresistive – bulk micromachined

[Beeby, Artech House 2004]

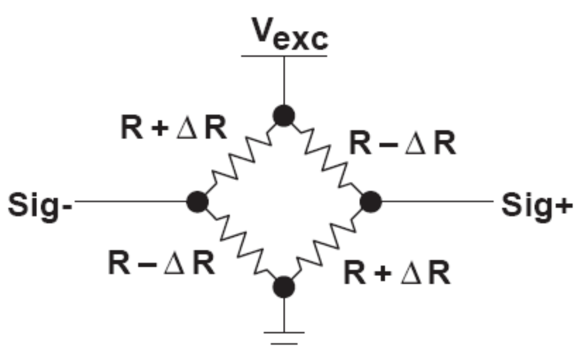




Diffused implanted resistors

KOH release
- Timing
- P-Doping
- Electrochemical stop

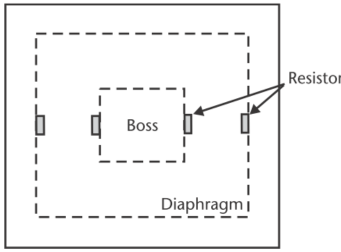
Wheatstone Bridge Sensor



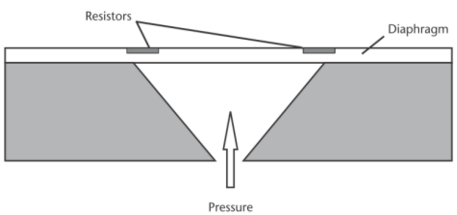
$$V_{SIG} = V_{EXC} \cdot \frac{\Delta R}{R}$$

Operating temperature limited by p-n leakage current → 120°C

Solution :
- Polysilicon
- SOI
- SiC up to 600°C



Higher sensitivity with bossed membranes

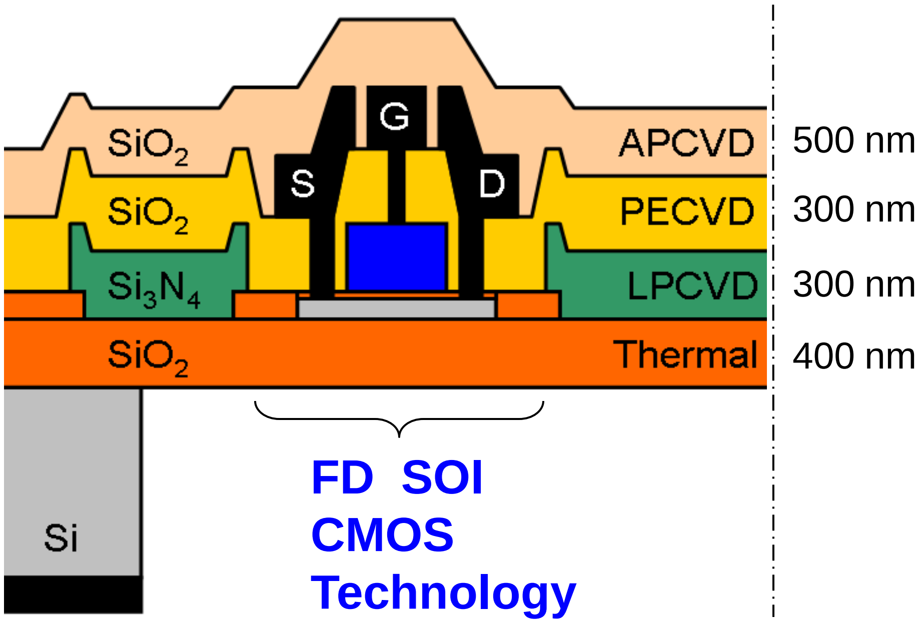


More compact solution:
Si fusion bonding in pre-process

CONCEPT: Novel Active Pressure Sensors in FD SOI Technology

= New paradigm

Based on the association of:



FD SOI CMOS Technology

Active

Novel

Thin Dielectric Membrane

Why?

- Ultra- Low Power Capability
- High Temperature Operation
- Radiation Hardening

Standard CMOS process + only 2 steps:

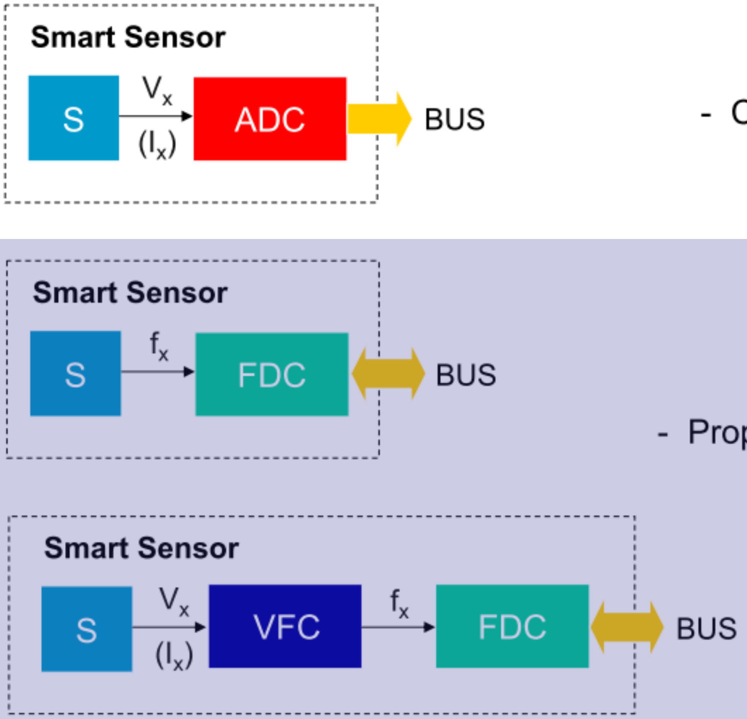
1- Nitride film deposition and patterning

2- Membranes release by Back etching

Intrinsically digital

P → Freq(P)

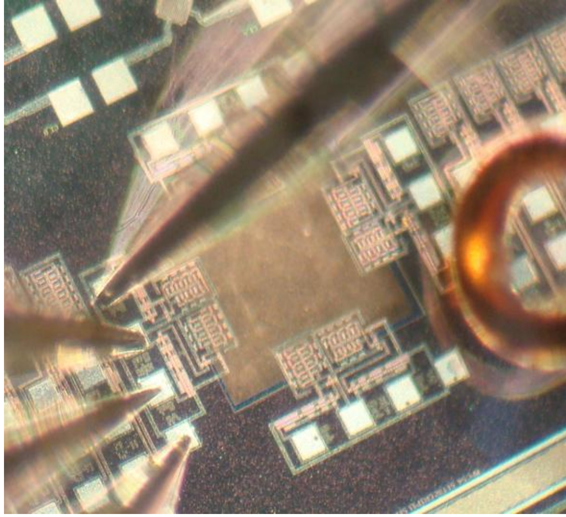
The intrinsic co-integration enables unique pressure transduction approaches:



- Classical approach

- Proposed approaches

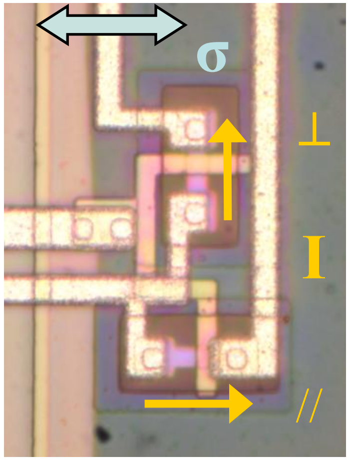
[Yurish, ICONS' 2011]

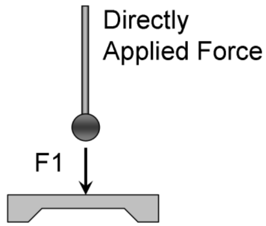


800 µm-side membrane with Ring Oscillators

- **High Noise Immunity**
  - thanks to frequency modulation
  - easy transmission on long distance
- **Wide Dynamic Range**
  - not limited by noise and supply voltage
  - 120 dB easily achievable
- **Simple Interfacing**
  - periods counter
  - signal sampling

Proof of concept - Ring Oscillators



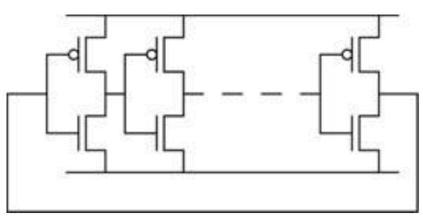


Single device

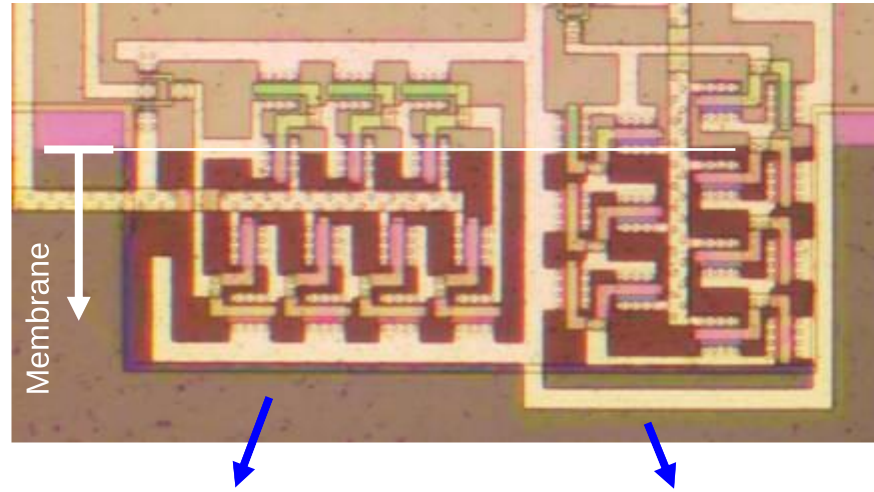
$$-\frac{\Delta I_D}{I_D} \cong \frac{\Delta \rho_{channel}}{\rho_{channel}} = \pi_{//}\sigma_{//} + \pi_{\perp}\sigma_{\perp}$$

Ring Oscillator

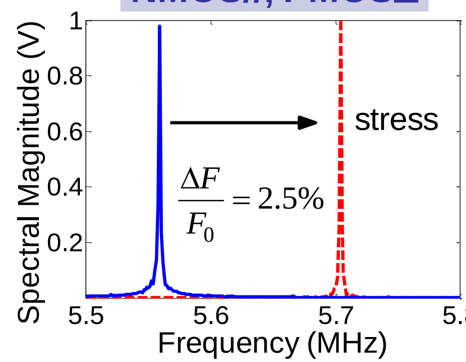
$$-\frac{\Delta F}{F_0} \approx \frac{\Delta \tau_{inverter}}{\tau_{inverter}} \approx \frac{1}{2}\left(\left(\frac{\Delta R}{R}\right)_{NMOS} + \left(\frac{\Delta R}{R}\right)_{PMOS}\right)$$



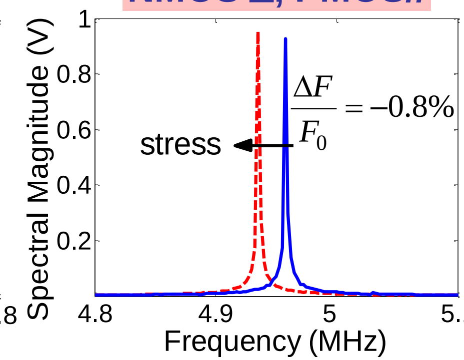
Odd number of inverters (7)



NMOS//, PMOS⊥



NMOS ⊥, PMOS//



Piezo-resistive coefficients (%/100MPa)

N-MOSFET		P-MOSFET	
$\pi_{//}$	$\pi_{\perp}$	$\pi_{//}$	$\pi_{\perp}$
-3.94	-2.46	+5.16	-4.86

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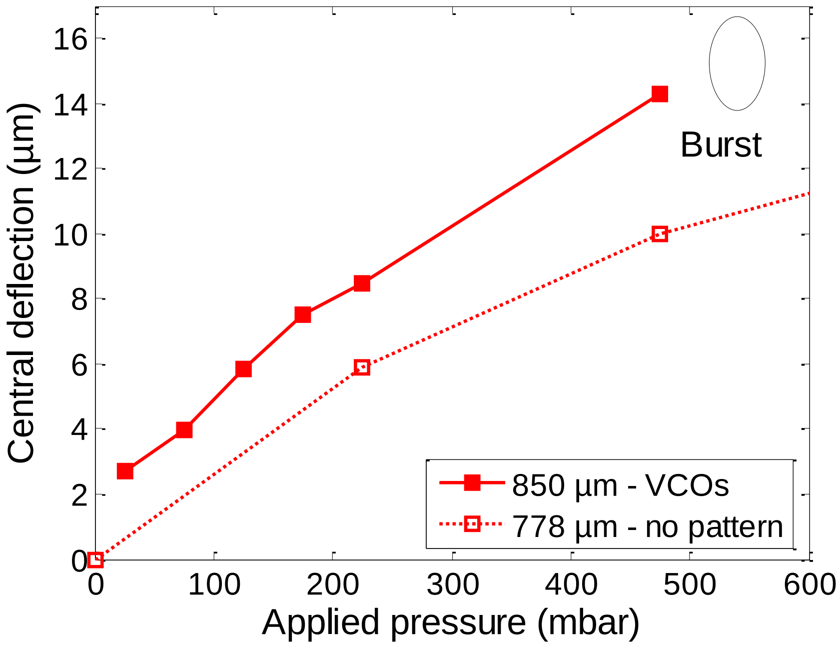
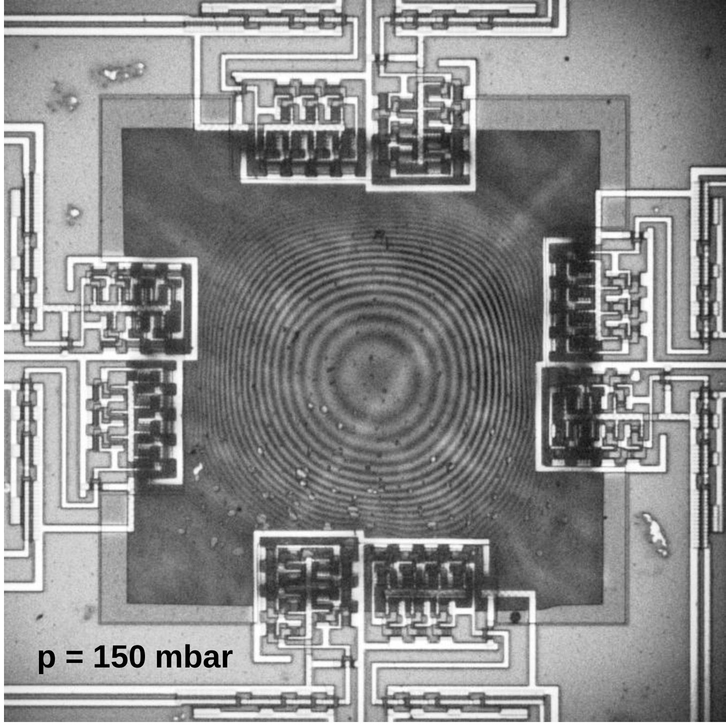
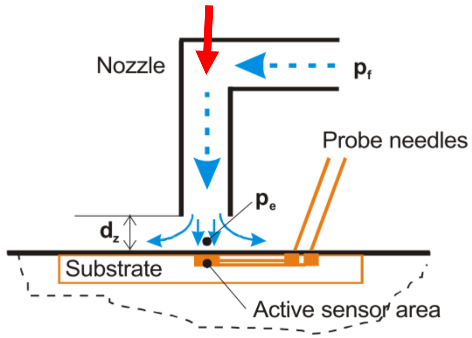
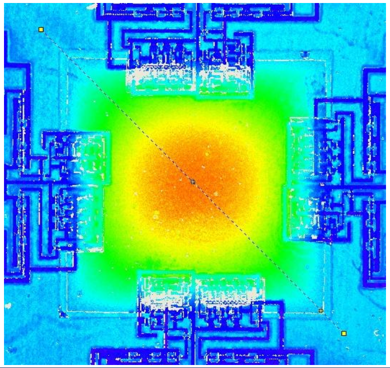
Mechanical Characterization

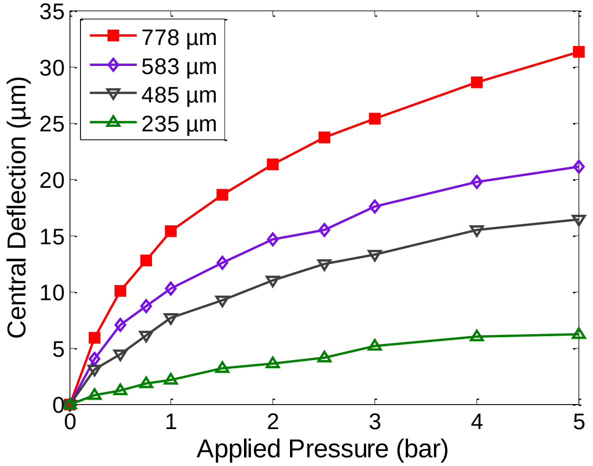
Membranes with oscillators do present early fracture (0.6 bar ⇔ > 5 bars)











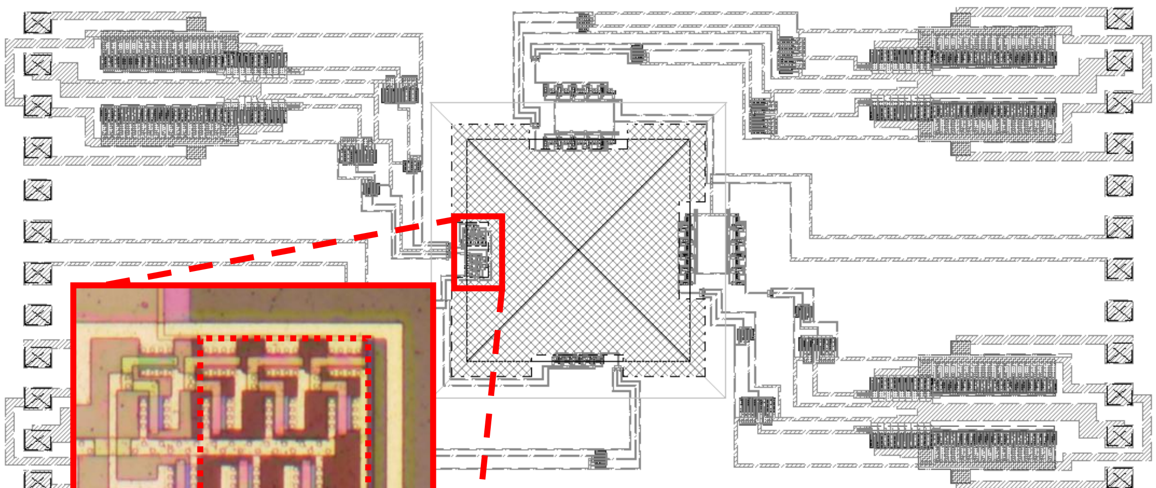
Hypothesis

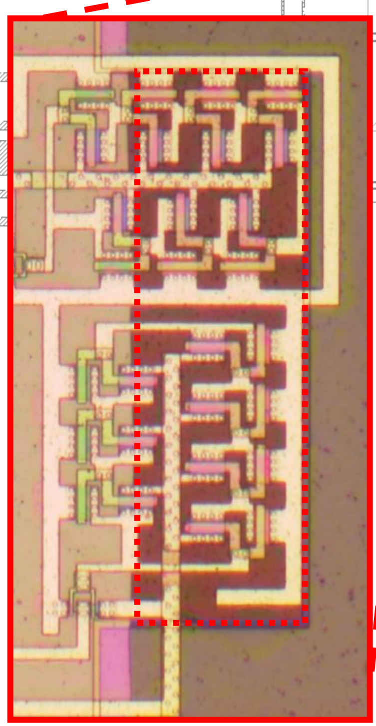
The patterning of the membrane is the cause of the burst pressure lowering

⇨

Finite Element Modeling

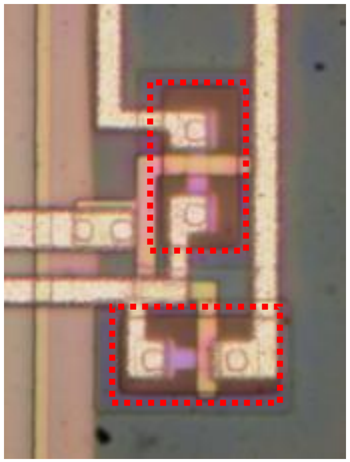
- **Understand strain distribution**
- **Try to verify this hypothesis**

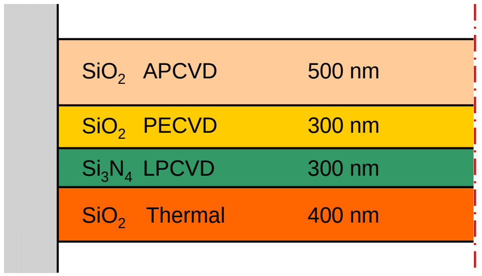


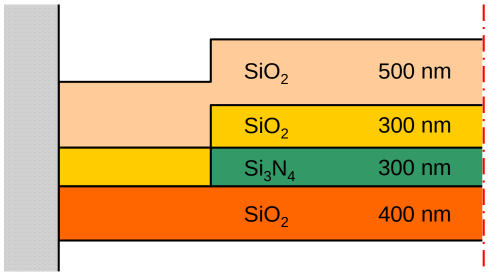


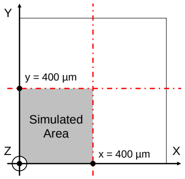
Ring oscillators
on membrane
Global patterning
of the nitride film

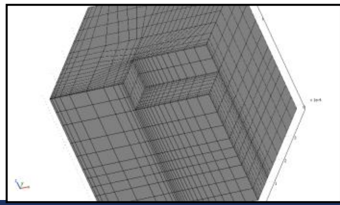
Local patterning,
around the devices,
of the nitride film



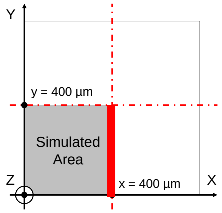




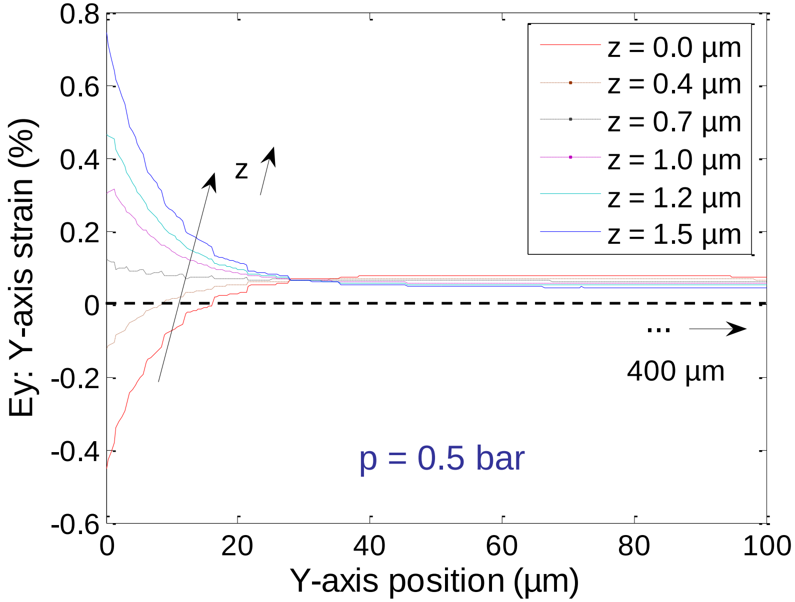


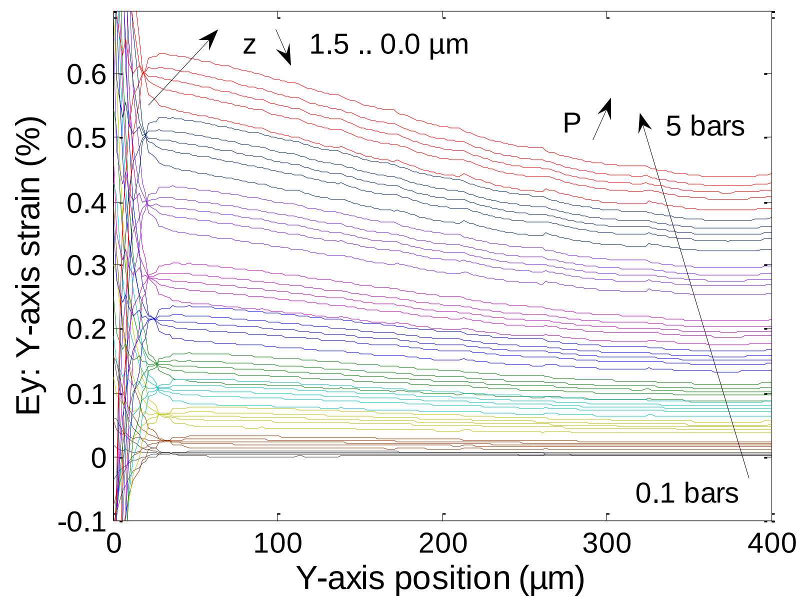


Simulations exploratory work



- Medial Axis Analysis – Plain Membrane





2 Regions:

19 .. 35 µm from border

"Clamped Beam" behaviour (flexion)

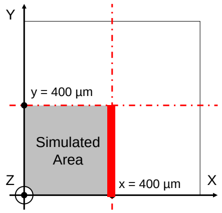
- **Strain gradient is the highest.**
- Strain may inverse his sign.
- The height of the fibre is determinant for the strain magnitude.

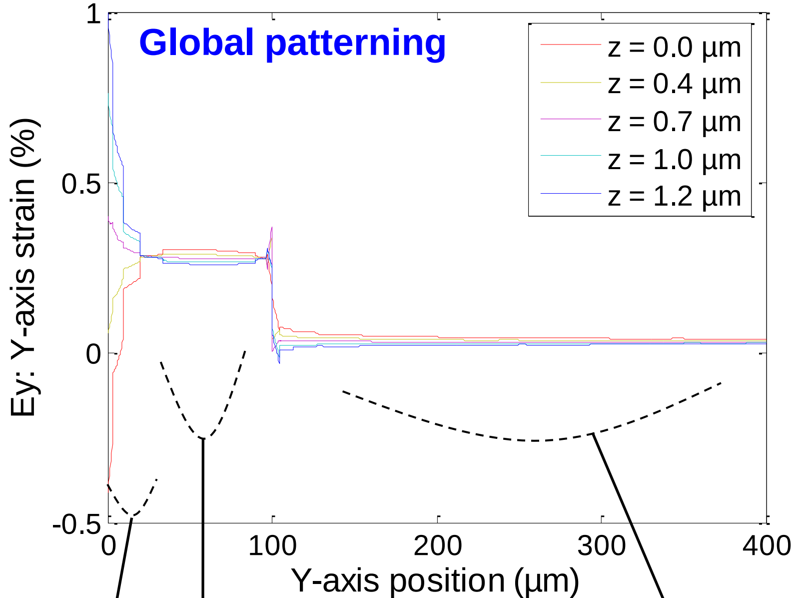
"Membrane" behaviour (tensile strain)

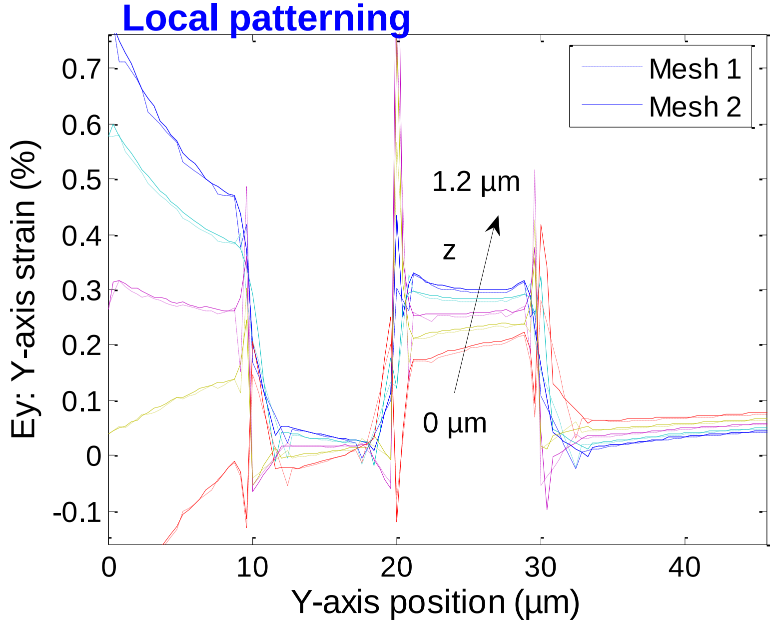
Strain is almost steady along the fibres.

Simulations exploratory work

- Medial Axis Analysis – Patterned Membranes







Simulation results show the existence of 'poles'

Low strain central zone

Near constant high strain plateau at the patterned area

High gradient zone near the clamping area

p = 0.5 bar

FEM Results & Outcomes

FEM simulations have shown:

- Strain peaks at film discontinuities
- High gradient and fiber dependence at edges

Proposed design rules:

- Reduced Membrane size
- Reduce active transducers footprint on membranes
- Locate transducers at center of membranes

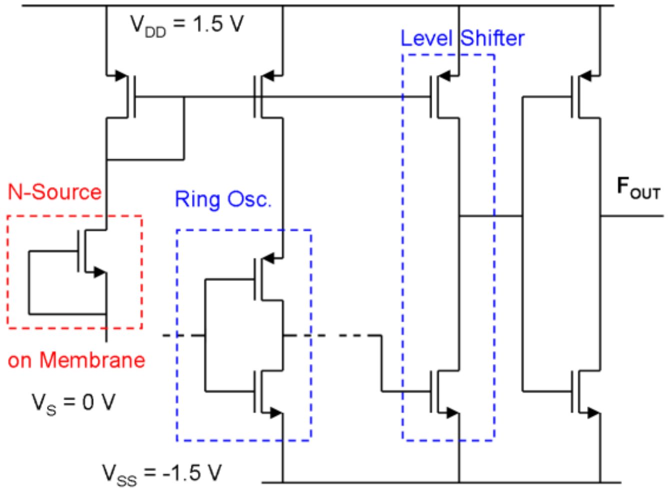
→ Novel Architectures with Out-of-Membranes oscillators

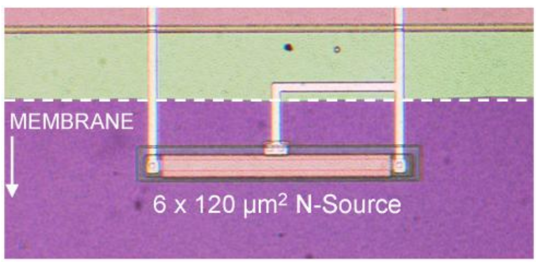
- **N-MOS based solution**
  - Single NMOSFET suspended on Membrane
- **P-MOS based solution**
  - Simple PMOSFET Mirror (2 devices on membrane)
  - Cascaded PMOSFET Mirror (4 devices on membrane)

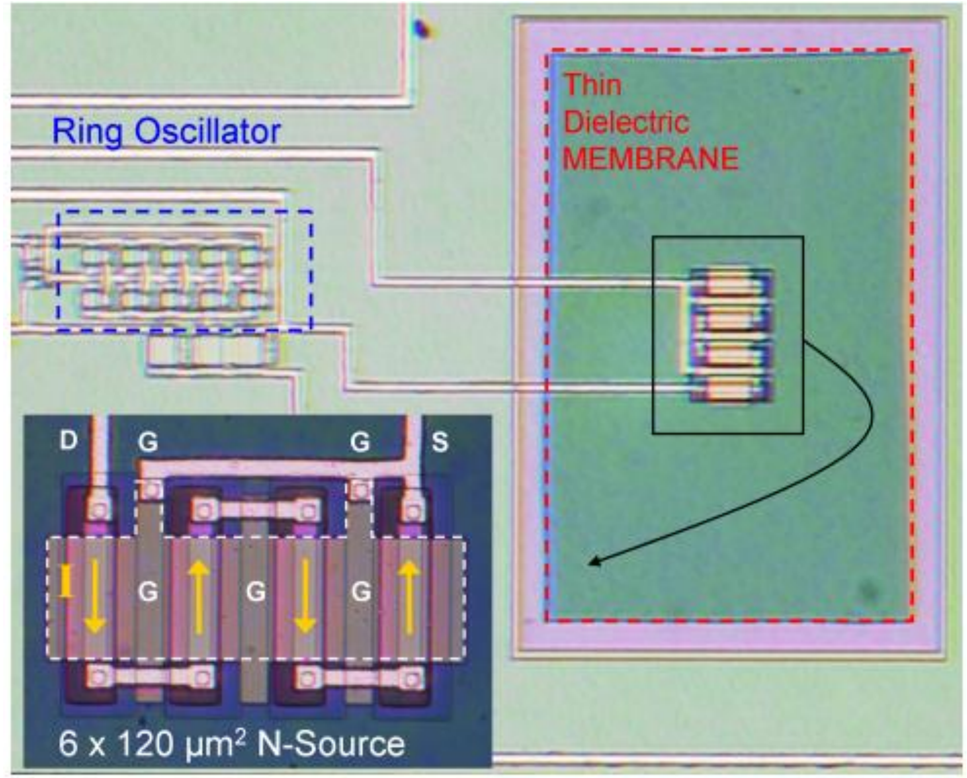
→ Experimental proof !

Single NMOSFET suspended

$$\frac{\Delta I_D}{I_{D_0}} \cong -\left(\pi_{NMOS//} \cdot \sigma_{//} + \pi_{NMOS\perp} \cdot \sigma_{\perp}\right)$$





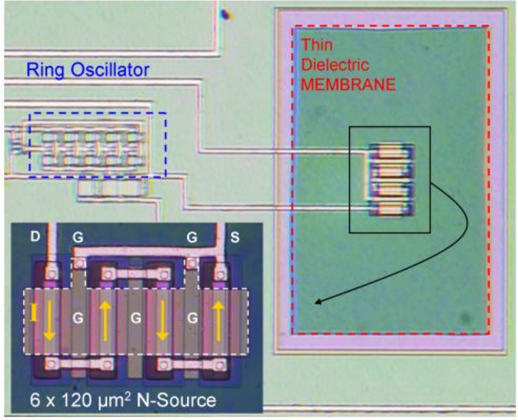


Source devices characteristics

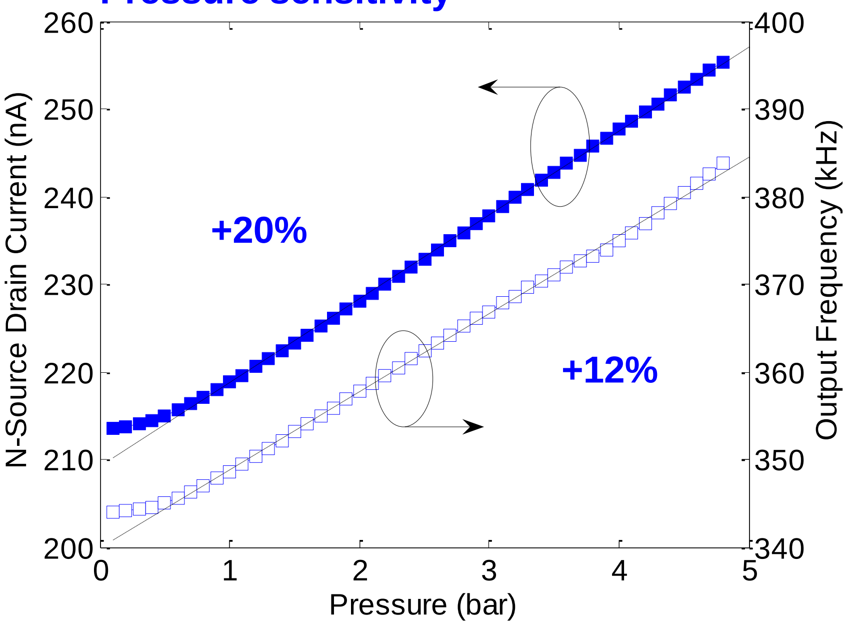
Configuration: Membrane dimensions and N-Source device location	Current Sensitivity (%/bar)	Full Scale Current Variation (%)	Measured range (bar)		Burst Pressure
			Min	Max	
Mb: 250x400 µm², device at the center	**4.59**	**19.58**	**0.1**	**4.8**	**> 4.8**
Mb: 340x340 µm², device at 60 µm from border	2.56	7.20	0.5	3.5	4
Mb: 340x340 µm², device at 27 µm from border	1.79	5.21	0.5	3.5	4
Mb: 600x600 µm², device at 35 µm from border	3.23	3.73	0.1	1.4	1.4
Mb: 800x800 µm², device at 52 µm from border	3.09	3.39	0.1	1.3	1.3

Single NMOSFET suspended

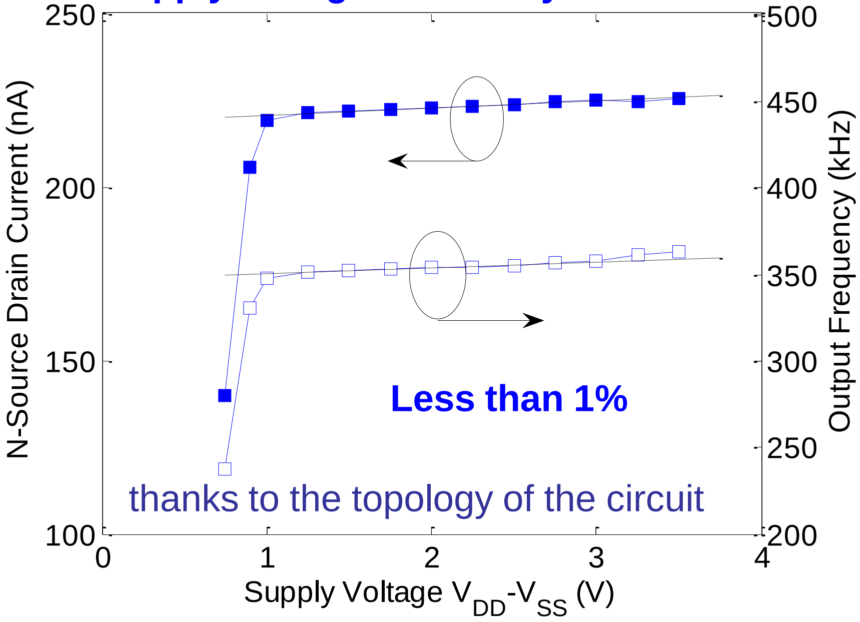
- Figures of Merit



Pressure sensitivity



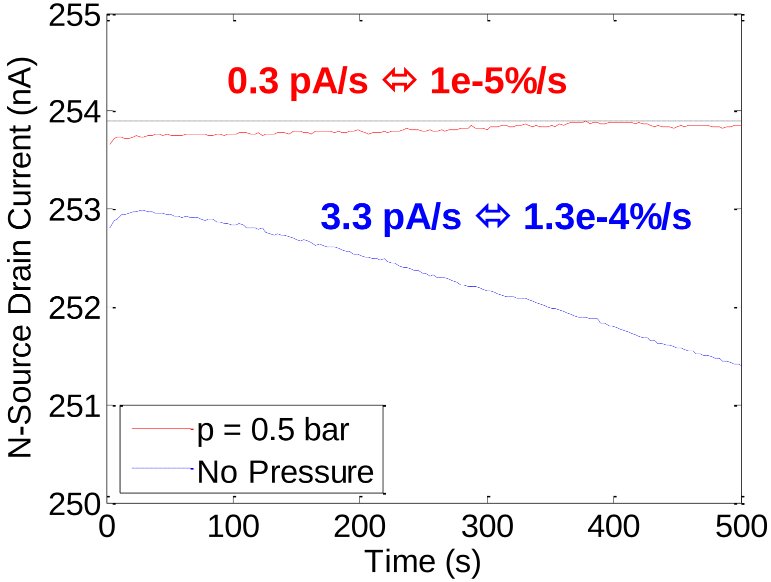
Supply voltage sensitivity

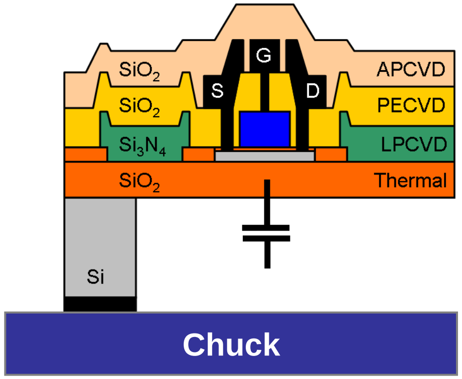


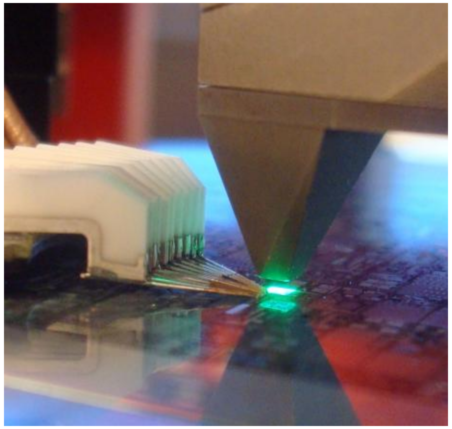
Pressure applied up to 4.8 bar → no burst

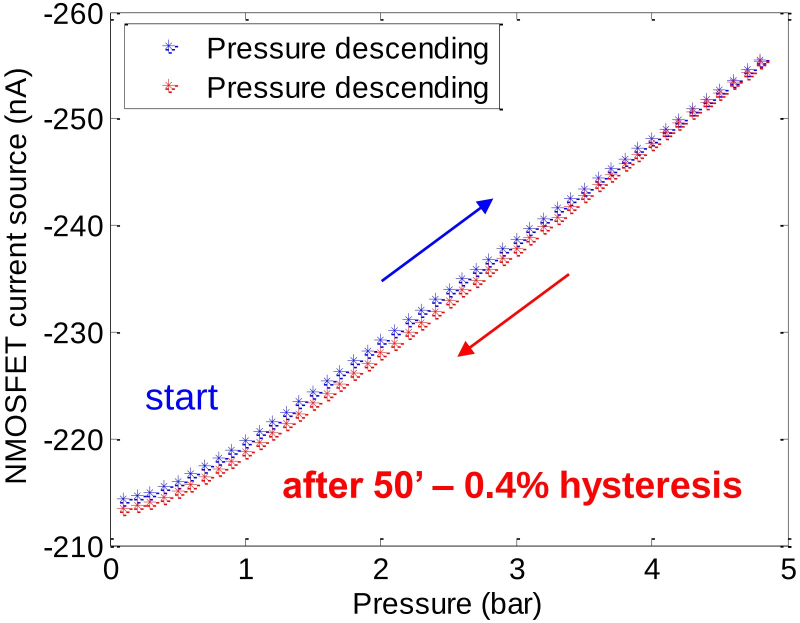
Power Consumption= 2.1 µW

Suspended Device Current Drift



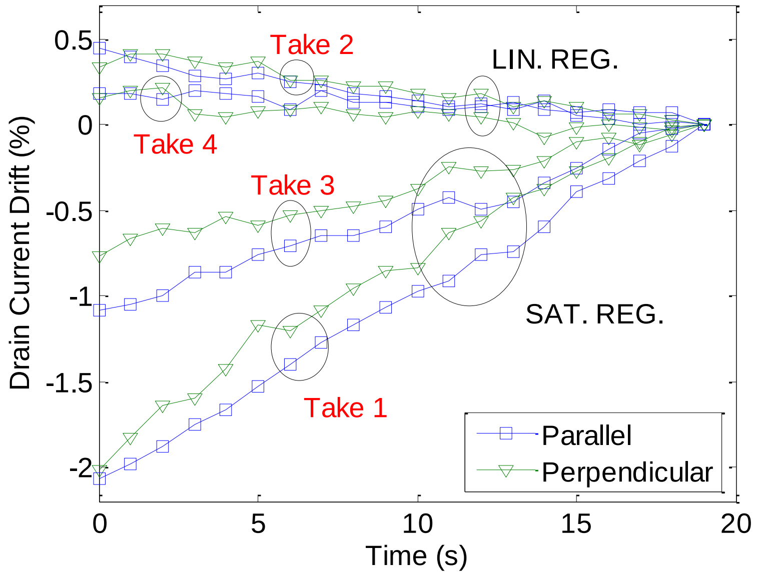




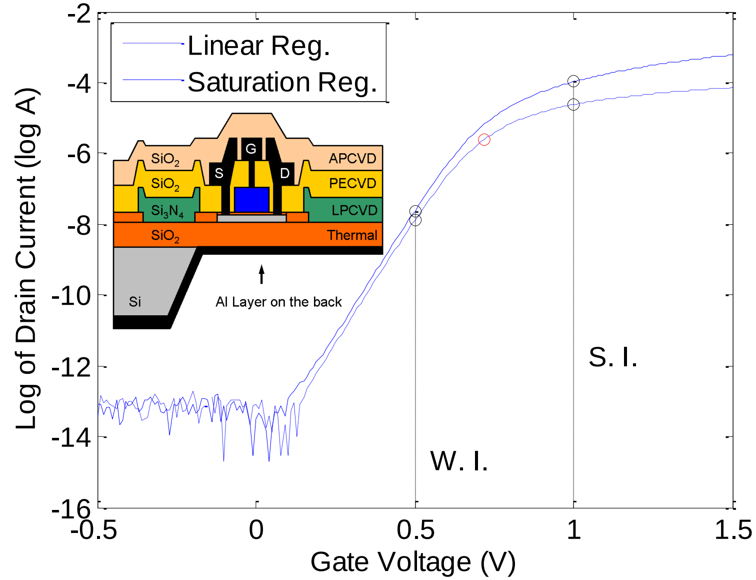


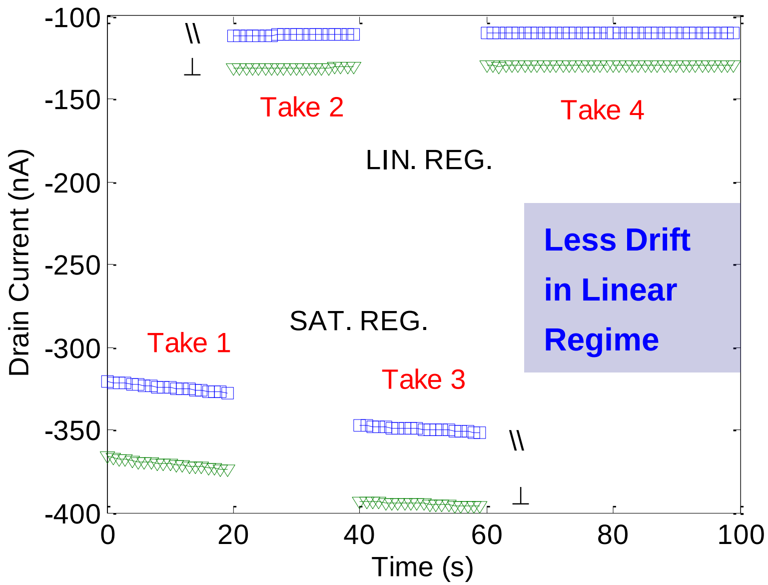
Drift

Bias Conditions

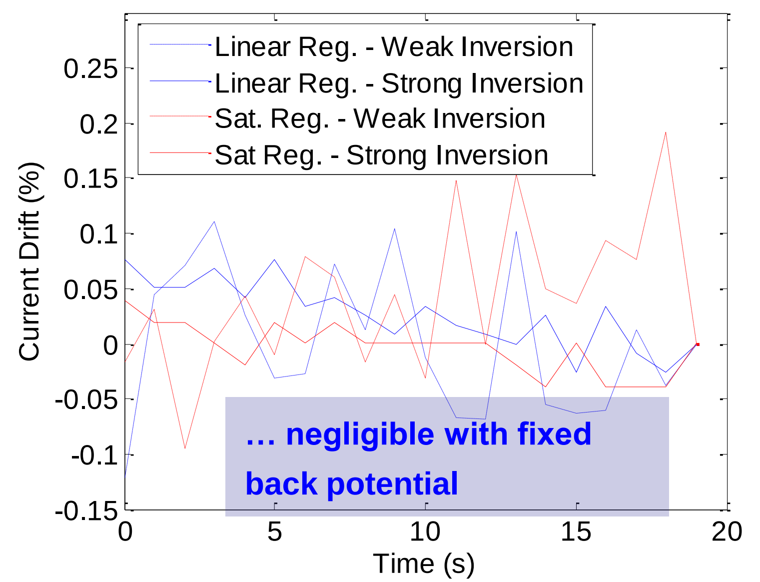


Metal on back side of the membrane





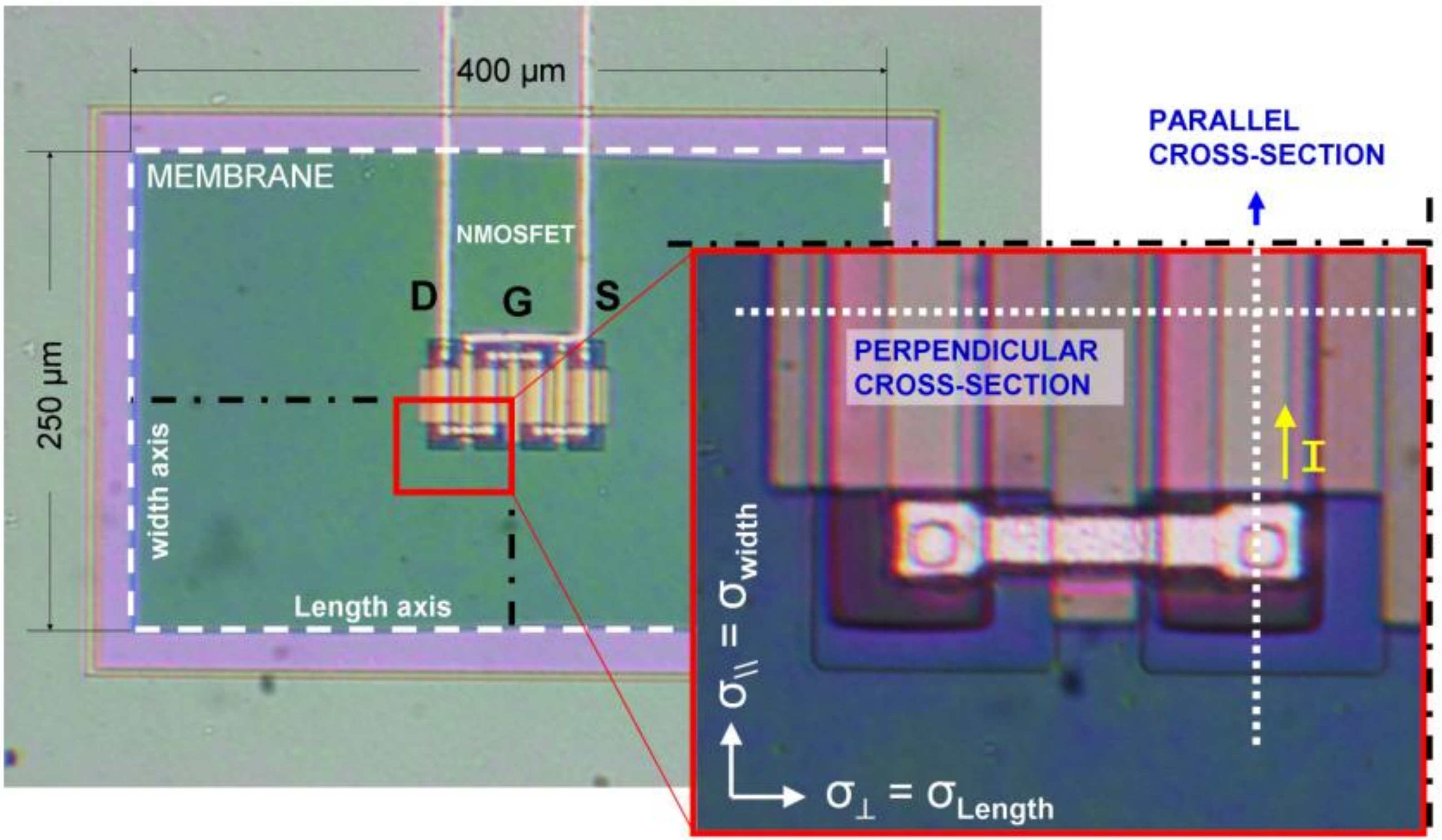
Less Drift in Linear Regime



… negligible with fixed back potential

Single suspended MOSFET – ELME Charac.

- **What is the stress value on the device?**



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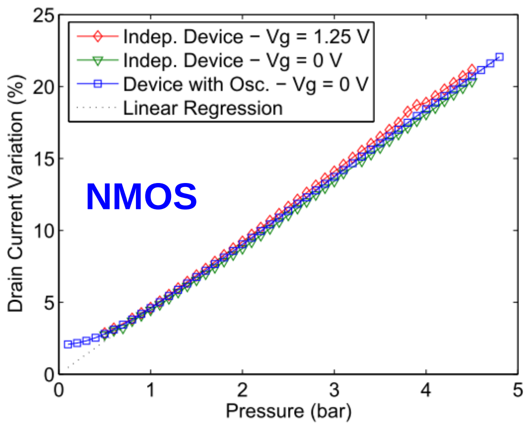
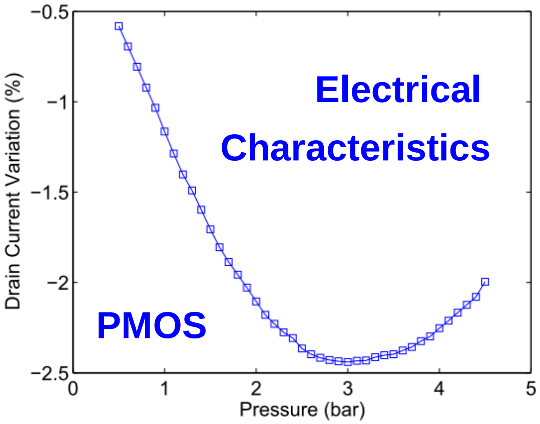
Methodology



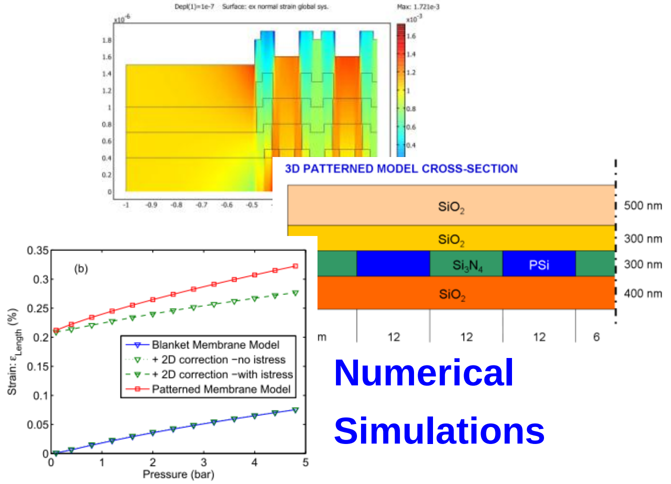


$$\frac{\Delta I_D}{I_{D_0}} = -\boldsymbol{\pi} \cdot \boxed{\boldsymbol{\sigma}}$$

Piezoresistive Coefficients

NMOS transistor		PMOS transistor	
$\pi_{//}$ (%/100MPa)	$\pi_{\perp}$ (%/100MPa)	$\pi_{//}$ (%/100MPa)	$\pi_{\perp}$ (%/100MPa)
-3.94	-2.46	+5.16	-4.86

Technology specific



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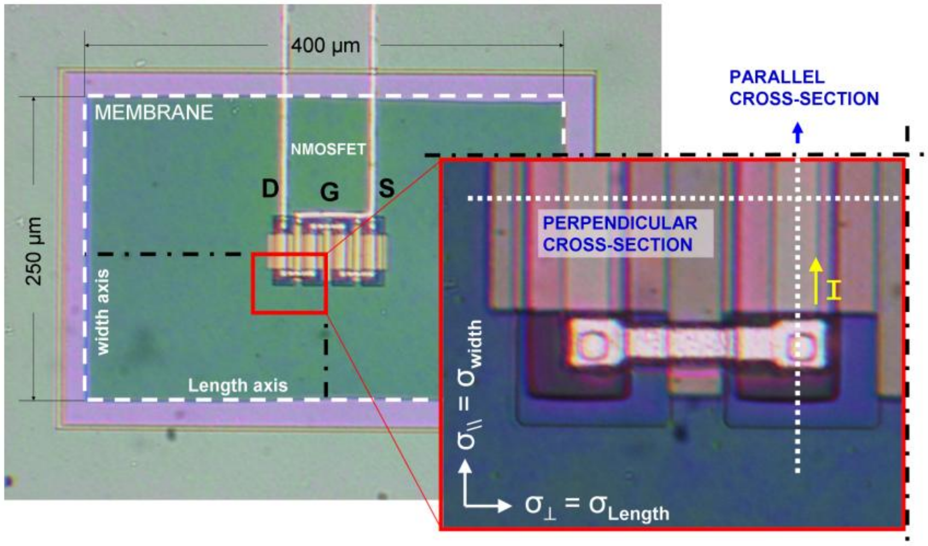
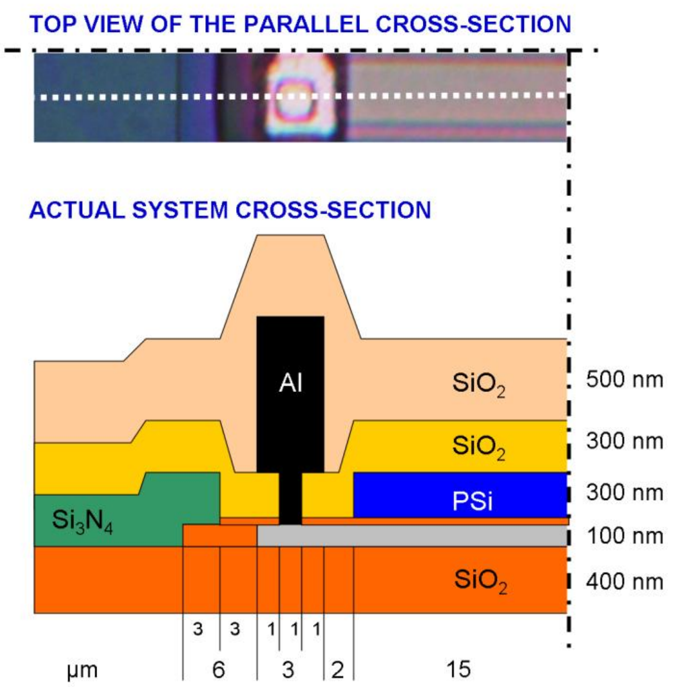
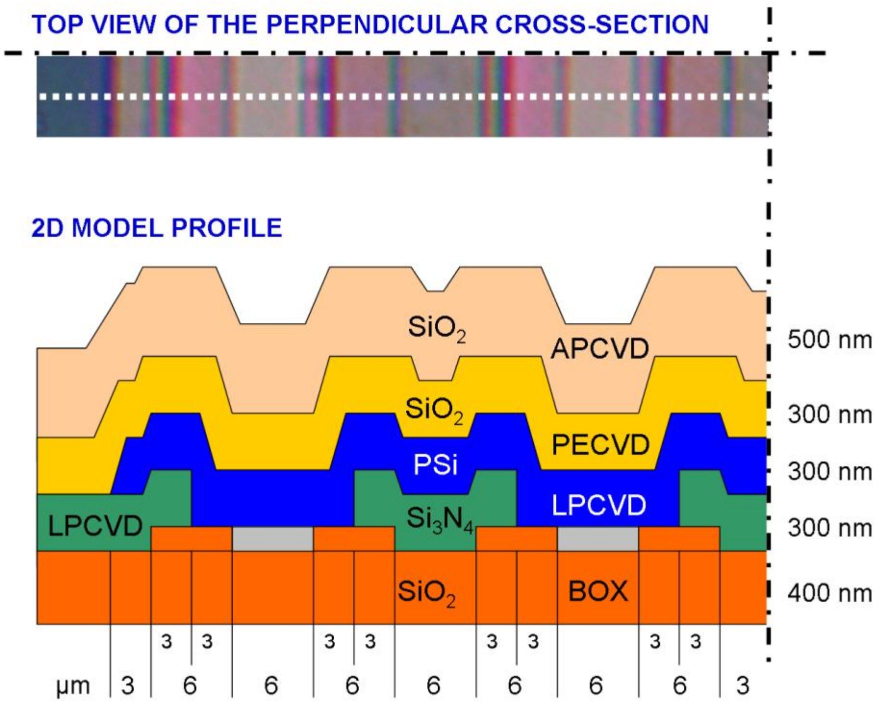
Numerical Modeling

Structure too complex to be modeled without simplifications

→ 3 Models are elaborated

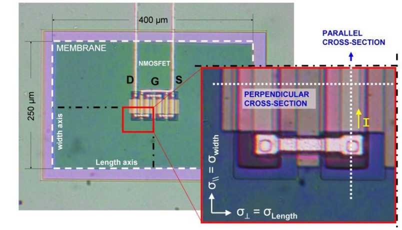


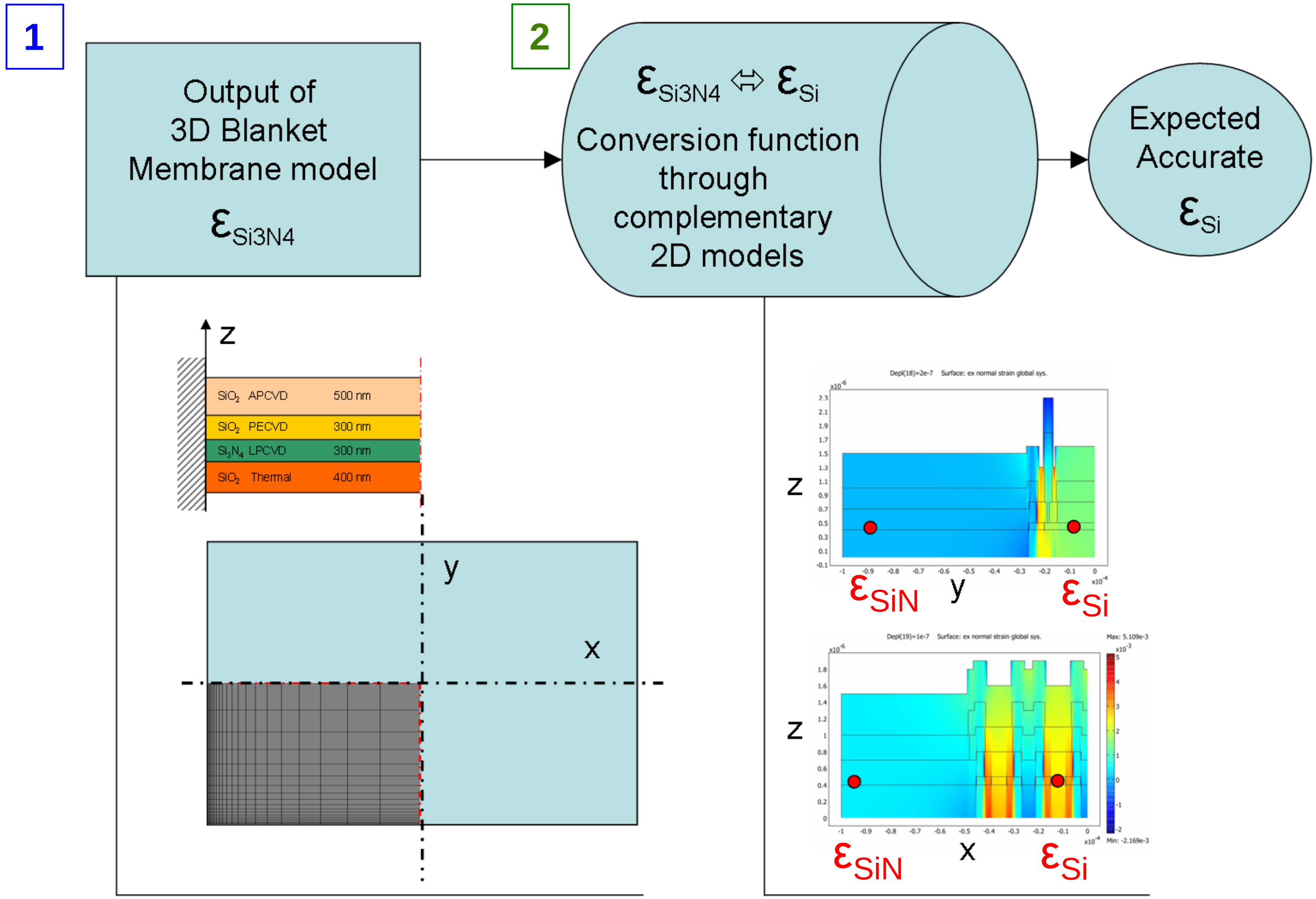




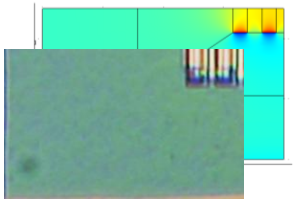
Modeling Routes

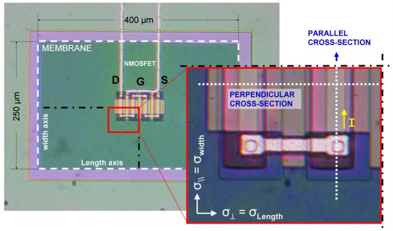
The device is very small
on a large planar membrane
→ stress follows the plane value ?





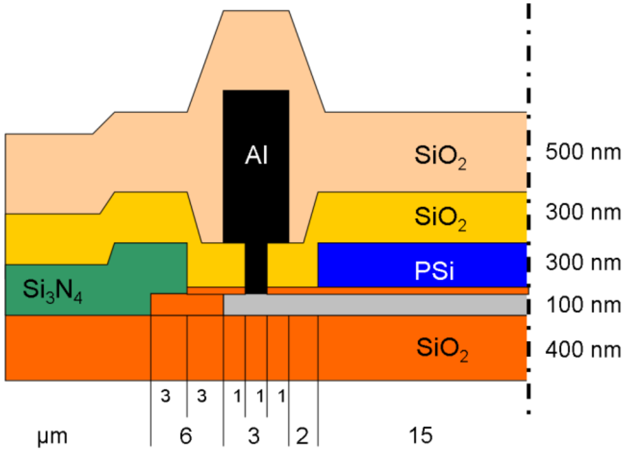
System's Cross-Sections





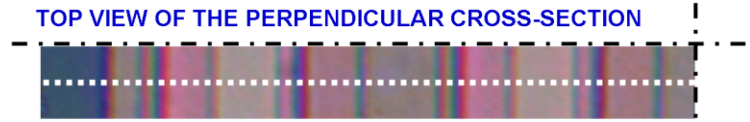
TOP VIEW OF THE PARALLEL CROSS-SECTION

ACTUAL SYSTEM CROSS-SECTION

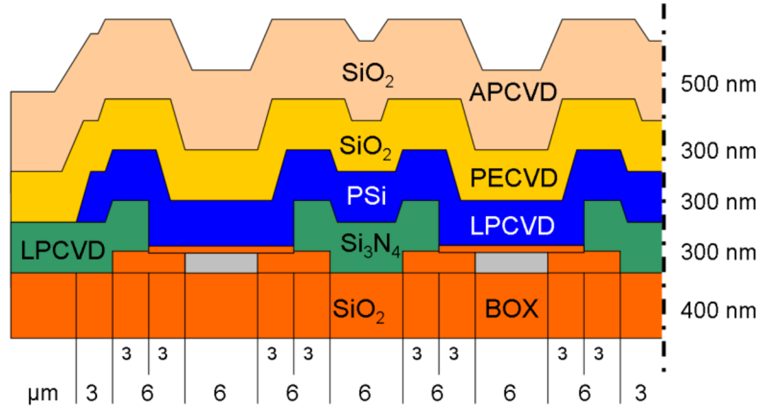


3

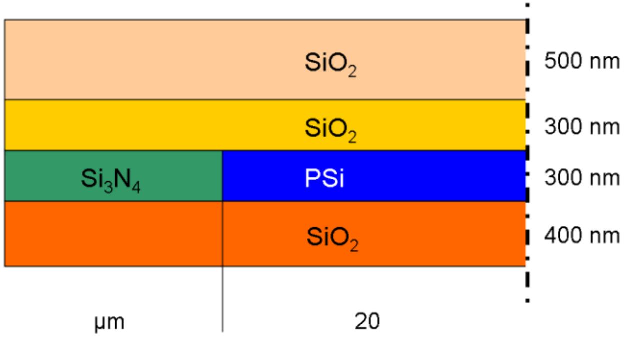
TOP VIEW OF THE PERPENDICULAR CROSS-SECTION



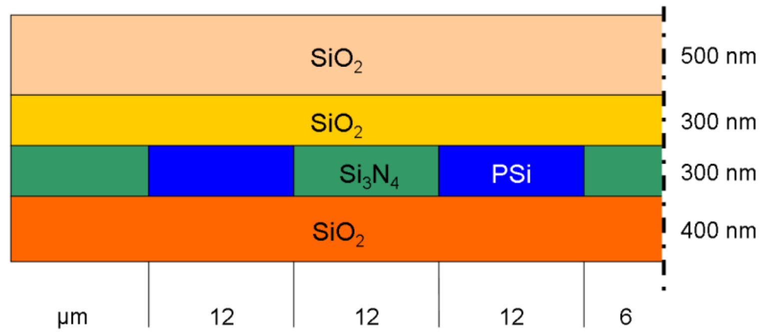
ACTUAL SYSTEM CROSS-SECTION



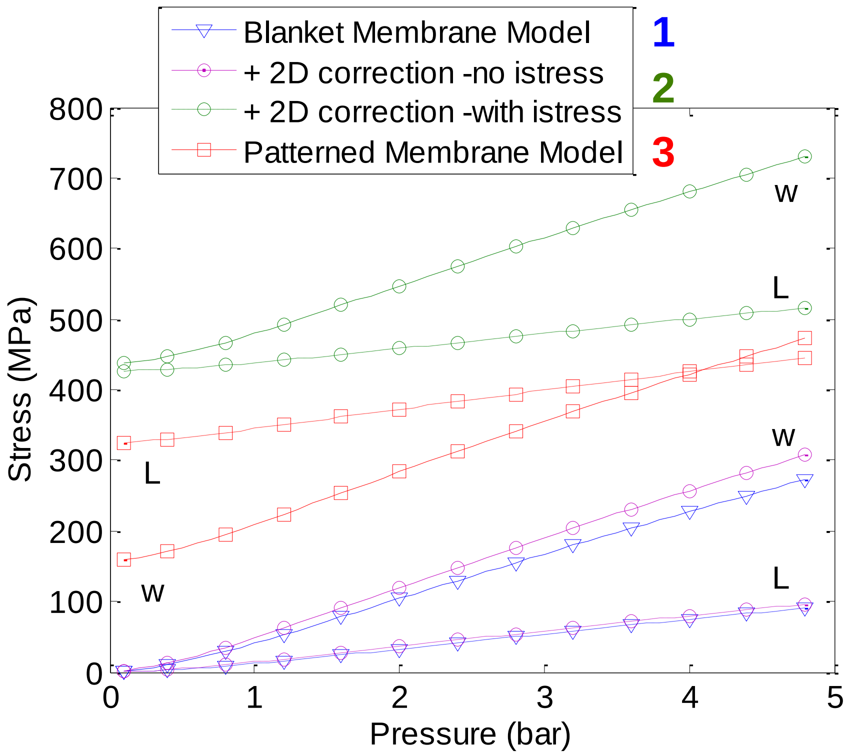
3D PATTERNED MODEL CROSS-SECTION

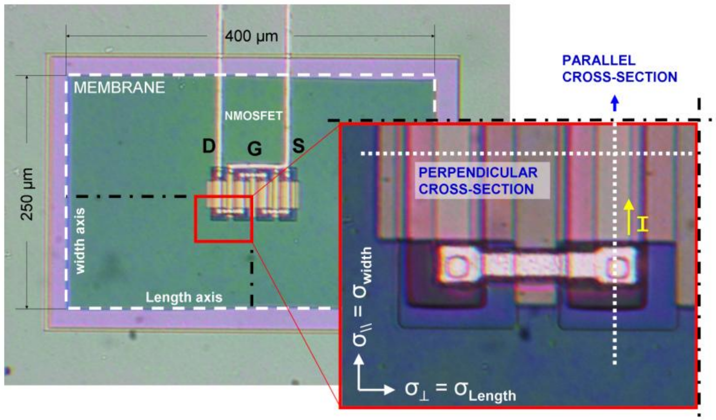


3D PATTERNED MODEL CROSS-SECTION



Modeling Results





Strong influence of the residual film stresses

All model routes exhibit Same slope values (MPa/bar)

	Width-axis	Length-axis
3D Blanket Membrane	**63.8**	**21.4**
+ 2D correction -no istress	**71.5**	**22.3**
+ 2D correction -with istress	**68.9**	**21.1**
3D Patterned Membrane	**71.8**	**27.0**

Stress resolution

Direct Stress Calculation

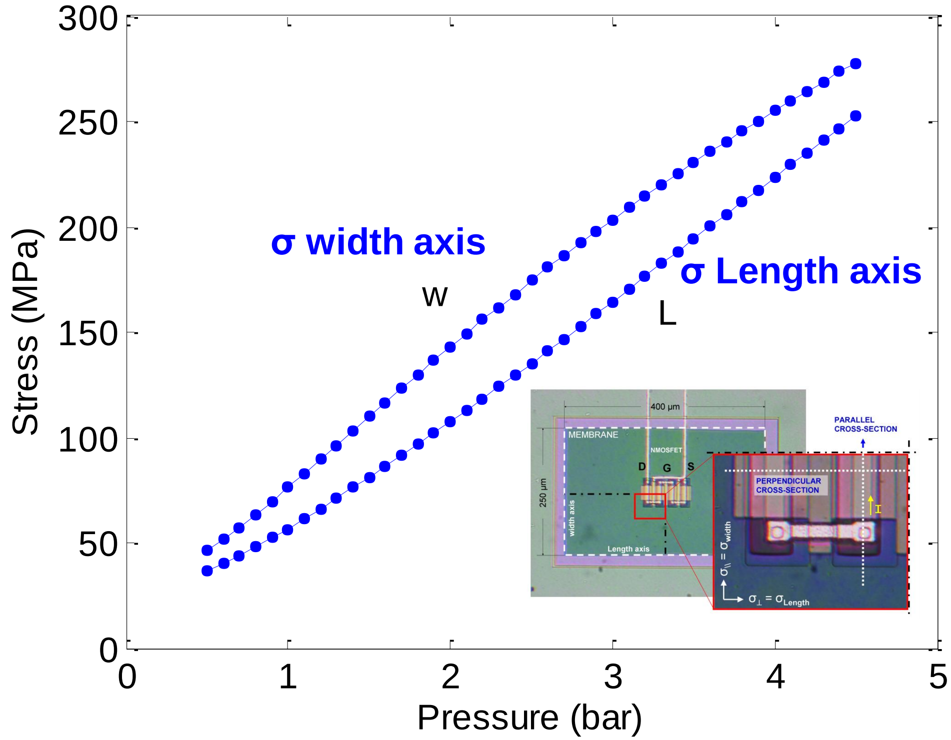
$$\frac{\Delta\rho}{\rho_0} = \boldsymbol{\pi} \cdot \boldsymbol{\sigma}$$

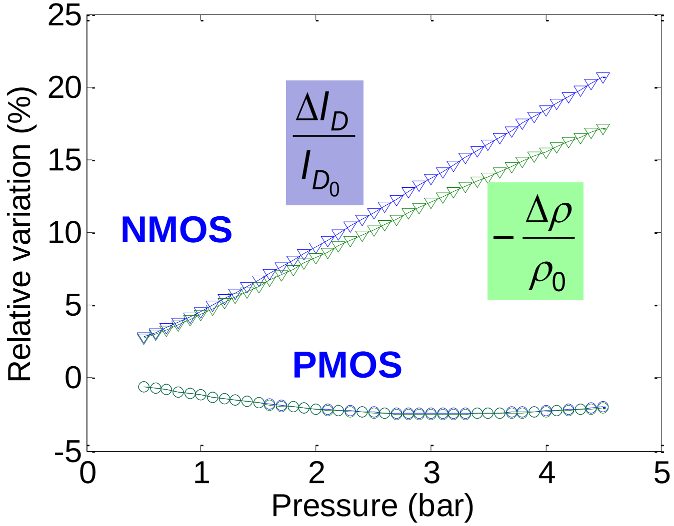
$$\frac{\Delta I_D}{I_{D_0}} = \frac{\Delta\mu}{\mu_0} \approx -\frac{\Delta\rho}{\rho_0}$$

At higher stress values

[Tsang, EDL 2008]

$$\frac{\Delta\rho}{\rho_0} = \frac{1}{\frac{\Delta\mu}{\mu_0}+1} - 1 = \frac{1}{\frac{\Delta I_D}{I_{D_0}}+1} - 1$$

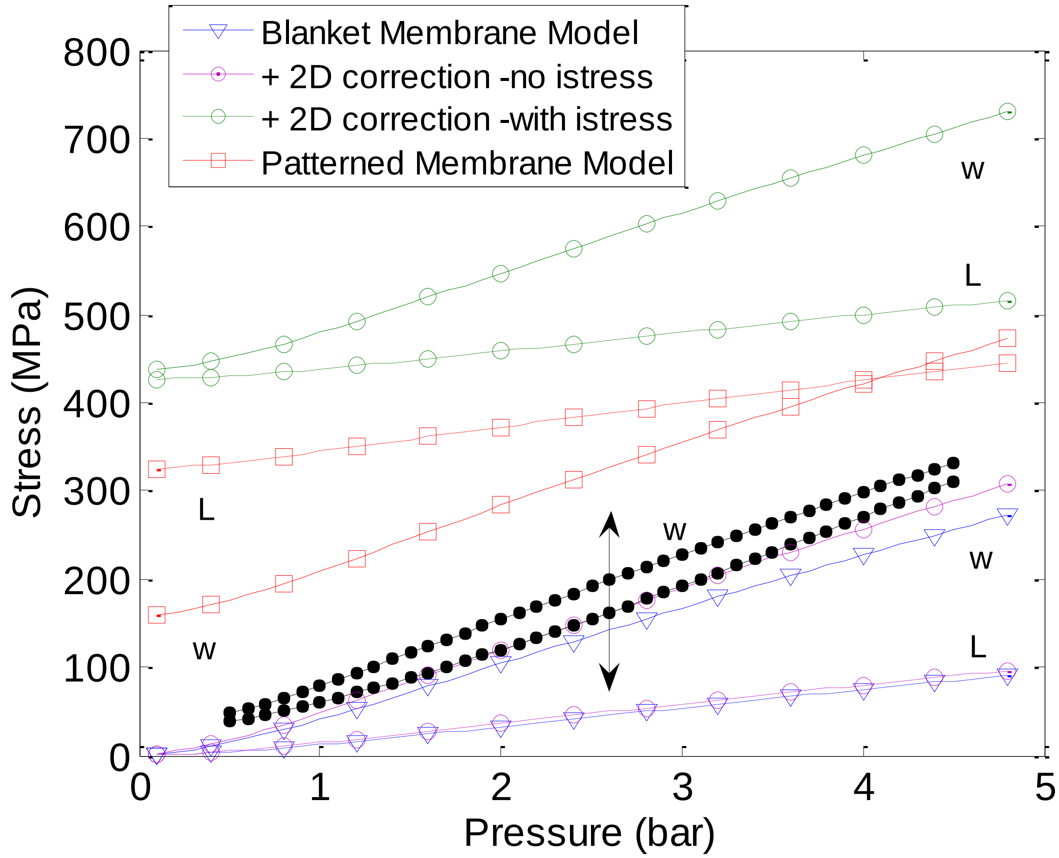


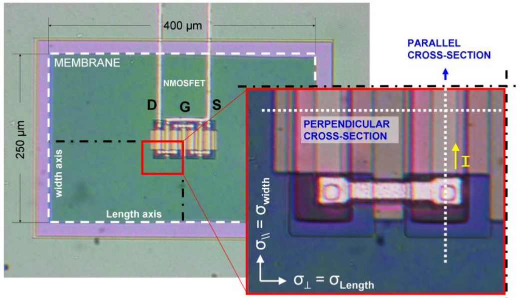


NMOS – PMOS System

$$\begin{cases} \left(\frac{\Delta\rho}{\rho_0}\right)_{NMOS} = -\pi_{NMOS,\backslash\backslash} \cdot \sigma_{width}^{Mb} - \pi_{NMOS,\perp} \cdot \sigma_{Length}^{Mb} \\ \left(\frac{\Delta\rho}{\rho_0}\right)_{PMOS} = -\pi_{PMOS,\backslash\backslash} \cdot \sigma_{width}^{Mb} - \pi_{PMOS,\perp} \cdot \sigma_{Length}^{Mb} \end{cases}$$

Stress resolution





$$-\frac{\Delta I_D}{I_D} \cong \frac{\Delta \rho_{channel}}{\rho_{channel}} = \pi_{//}\sigma_{//} + \pi_{\perp}\sigma_{\perp}$$

The measurement is a **relative variation of drain current**

which corresponds to a **delta of stress**

Stress resolution

- Absolute value of stress knowledge

  = 1. Tool for electron transport characterization

  = 2. Platform for sensor optimization

  = 3. Robustness analysis for critical applications!

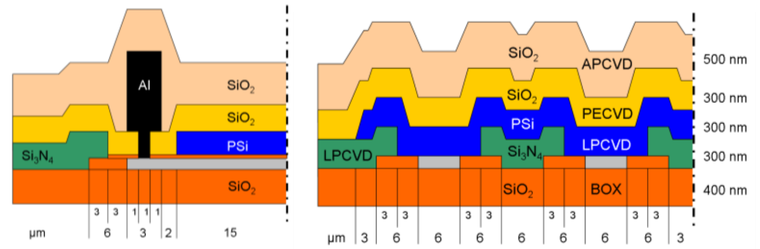
➔ Further work in collaboration with Open Engineering

Romisy Project (WR)

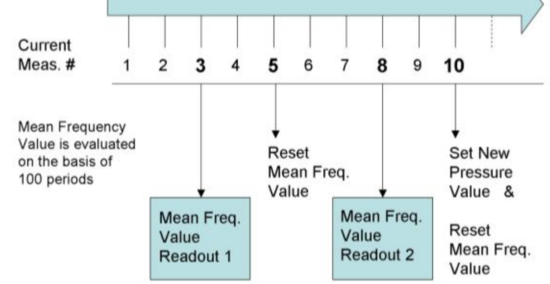
Material Characterization

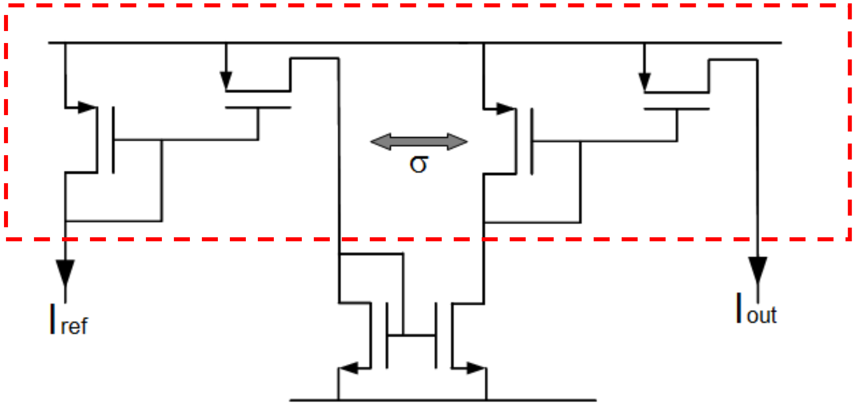
Advanced Modeling Concepts in OOFELIE::Multiphysics

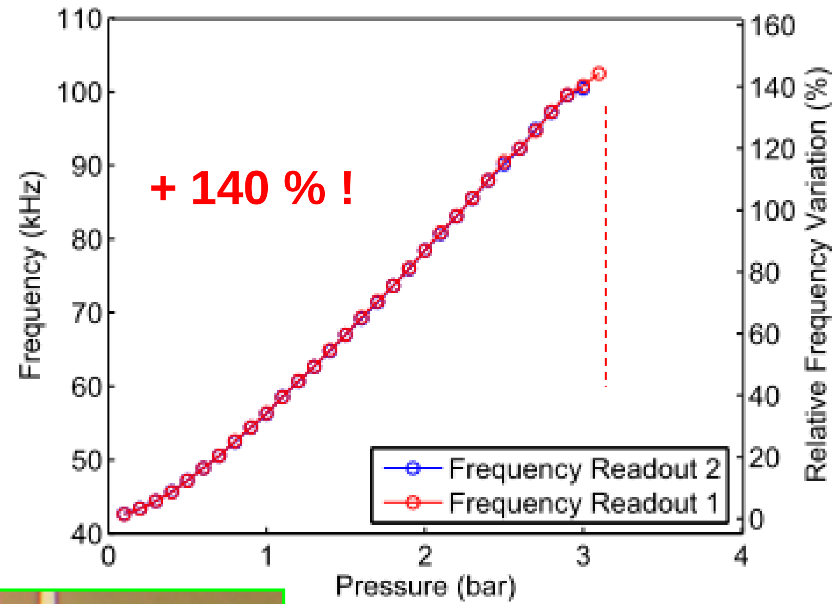
- Numerical gluing // Sub-modeling
- Oriented solids



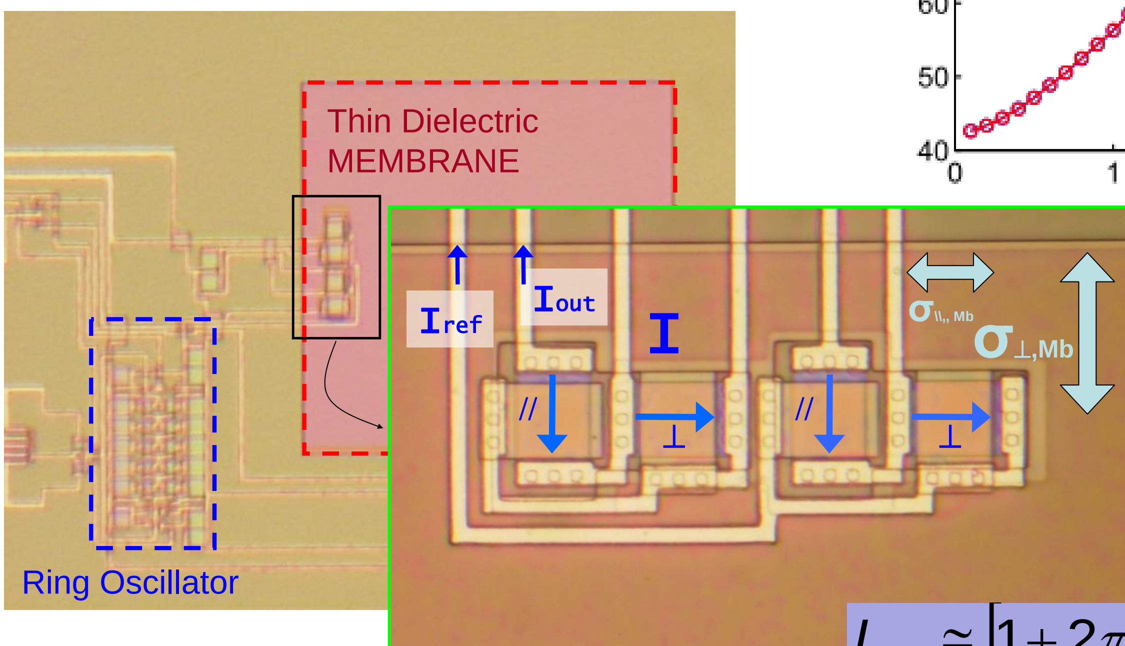
PMOS-based Architectures







4 Devices on membrane



Burst at 3.1 bar

500 µm-side Membrane
Devices at 50 µm from border

$$I_{out} \cong \left[1 + 2\pi_{44,PMOS} \cdot \left(\sigma_{\perp,Mb} - \sigma_{//,Mb}\right)\right] \cdot I_{ref}$$

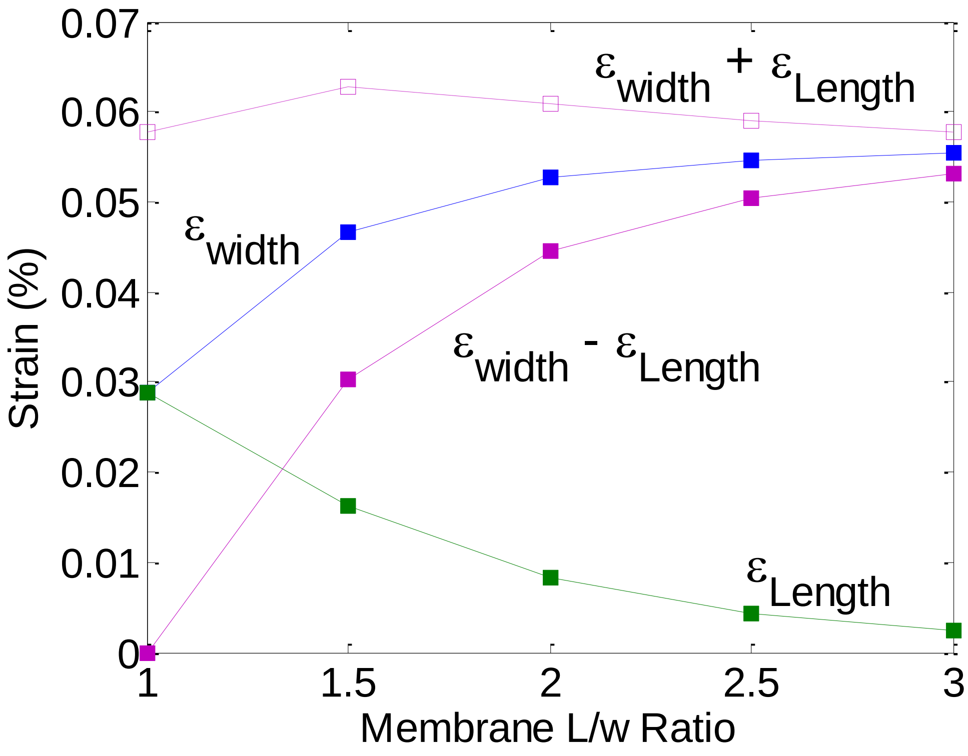
Rectangular Shaped Membranes

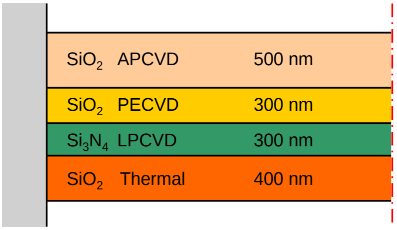
PMOS are sensitive to $\sigma_{\perp,Mb} - \sigma_{//,Mb}$

At the center of square membranes, we have $\sigma_{\perp,Mb} = \sigma_{//,Mb}$

Figuring more compact designs,

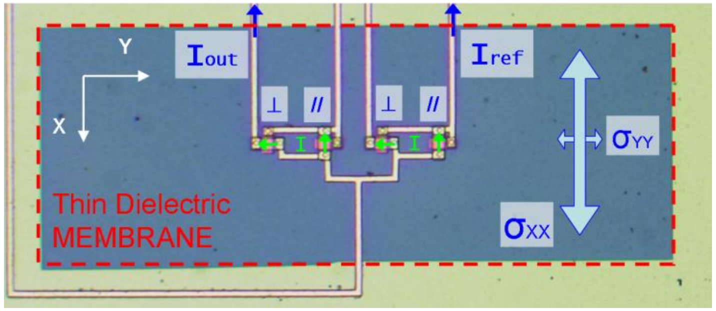
rectangular shaped membranes are a solution





p = 1 bar, z = 0.41 µm, width = 200 µm.

PMOS Mirror-based architectures

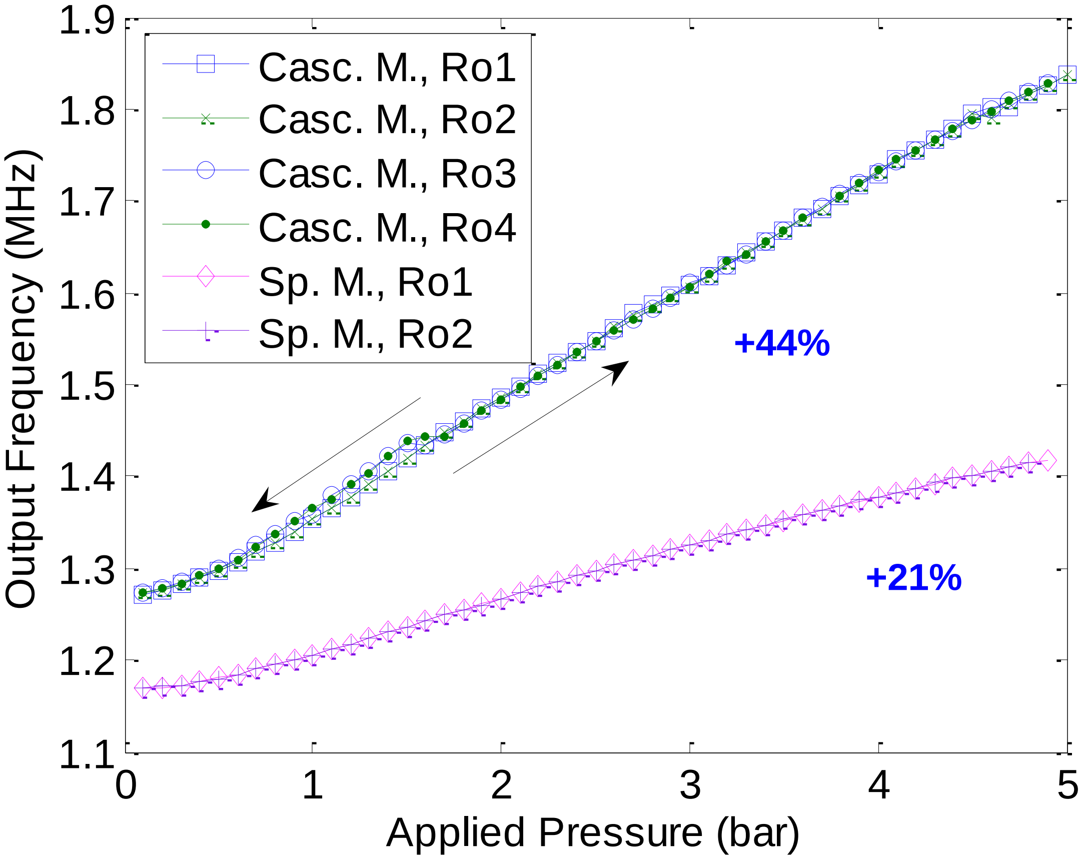


150 x 450 µm² Membrane
Devices at the center

Cascaded mirror sensitivity: ~20% / 100 MPa Δσ

$$I_{out} \cong \left[1 + 2\pi_{44,PMOS} \cdot \left(\sigma_{\perp,Mb} - \sigma_{//,Mb}\right)\right] \cdot I_{ref}$$

No additional FEOL
SiN Layer on this design



- No burst observed
- Very large process window

MOSFETs-based architectures conclusions

- Is there a technological opportunity?

  - Pressure Sensitivity – 12% → 140 % FS
  - Mechanical Robustness – > 5 bar
  - Power Consumption – in µW scale

- Open Way for Technology Transfer

- Forward key developments are:
  - Drift assessment
    - **Vacuum cavity sealing**
    - **Partially Depleted Technology** with a body contact
  - Numerical models for predictive simulations
  - Sensitivity further improvements

Thank you for your attention ;-

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