Innovative MOSFETs-based Pressure Sensors in Thin Film SOI Technology

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Information and Communication Technologies, Electronics and Applied Mathematics

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Outline

→ study on the feasibility of a concept

– Introduction

– Proof of concept

– Mechanical study

– Novel architectures

– Conclusions
Pressure sensing systems

- Piezoresistive – bulk micromachined

Diffused implanted resistors

KOH release
- Timing
- P-Doping
- Electrochemical stop

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

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

More compact solution:
Si fusion bonding in pre-process

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, …

[Beeby, Artech House 2004]
CONCEPT: Novel Active Pressure Sensors in FD SOI Technology

Based on the association of:

FD SOI CMOS Technology

Active

Why?

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

= New paradigm

Novel

Thin Dielectric Membrane

Standard CMOS process + only 2 steps:

1- Nitride film deposition and patterning
2- Membranes release by Back etching
Intrinsically digital

The intrinsic co-integration enables unique pressure transduction approaches:

- Classical approach

<table>
<thead>
<tr>
<th>Smart Sensor</th>
<th>ADC</th>
<th>BUS</th>
</tr>
</thead>
<tbody>
<tr>
<td>S</td>
<td>(V_x)</td>
<td>(I_x)</td>
</tr>
</tbody>
</table>

- Proposed approaches

<table>
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<tr>
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<th>FDC</th>
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- 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

[Yurish, ICONS’ 2011]
Proof of concept - Ring Oscillators

\[
\frac{\Delta I_D}{I_D} \approx \frac{\Delta \rho_{\text{channel}}}{\rho_{\text{channel}}} = \pi_{/\parallel} \sigma_{/\parallel} + \pi_{\perp} \sigma_{\perp}
\]

**Ring Oscillator**

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

Odd number of inverters (7)

**Piezo-resistive coefficients** (%/100MPa)

<table>
<thead>
<tr>
<th></th>
<th>N-MOSFET</th>
<th>P-MOSFET</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\pi_{/\parallel})</td>
<td>-3.94</td>
<td>-2.46</td>
</tr>
<tr>
<td>(\pi_{\perp})</td>
<td>+5.16</td>
<td>-4.86</td>
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</table>
Mechanical Characterization

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

- Applied pressure (mbar)
- Central deflection (µm)

850 µm - VCOs
778 µm - no pattern
Burst

\[ p = 150 \text{ mbar} \]
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

SiO$_2$ 500 nm
SiO$_2$ 300 nm
Si$_3$N$_4$ 300 nm
SiO$_2$ Thermal 400 nm
Simulations exploratory work

- Medial Axis Analysis – Plain Membrane

2 Regions:

“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

**Global patterning**

- Low strain central zone
- Near constant high strain plateau at the patterned area
- High gradient zone near the clamping area

**Local patterning**

Simulation results show the existence of ‘poles’

\[ p = 0.5 \text{ bar} \]
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

\[ \frac{\Delta I_D}{I_{D_0}} \approx -\left( \tau_{NMOS} \cdot \sigma + \tau_{NMOS} \cdot \sigma \right) \]

Source devices characteristics

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

- Figures of Merit

**Pressure sensitivity**

N-Source Drain Current (nA) vs Pressure (bar)

- +20%
- +12%

Pressure applied up to 4.8 bar

→ no burst

**Supply voltage sensitivity**

N-Source Drain Current (nA) vs Supply Voltage $V_{DD}-V_{SS}$ (V)

Less than 1%

thanks to the topology of the circuit

Power Consumption = 2.1 µW
Suspended Device Current Drift

![Graph showing current versus pressure](image)

- **0.3 pA/s ⇔ 1e-5%/s**
- **3.3 pA/s ⇔ 1.3e-4%/s**

**N-Source Drain Current (nA) vs Time (s)**
- p = 0.5 bar
- No Pressure

**Pressure vs NMOSFET current source (nA)**
- Pressure descending
- Pressure descending after 50’ – 0.4% hysteresis

**Chuck**
Drift

Bias Conditions

Drain Current Drift (%)

Time (s)

Parallel
Perpendicular

Take 1
Take 2
Take 3
Take 4

LIN. REG.
SAT. REG.

Log of Drain Current (log A)

Gate Voltage (V)

Linear Reg.
Saturation Reg.

S. I.
W. I.

Metal on back side of the membrane

Log of Drain Current (log A)

Gate Voltage (V)

Linear Reg.
Saturation Reg.

S. I.
W. I.

... negligible with fixed back potential

Less Drift in Linear Regime

Drain Current (nA)

Time (s)

LIN. REG.
SAT. REG.

Less Drift in Linear Regime
Single suspended MOSFET – ELME Charac.

- What is the stress value on the device?
Methodology

\[ \frac{\Delta I_D}{I_{D0}} = -\pi \sigma \]

Piezoresistive Coefficients

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<th>NMOS transistor</th>
<th>PMOS transistor</th>
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<td>$\pi_{//}$ (%)/100MPa</td>
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Technology specific

Electrical Characteristics

PMOS

Drain Current Variation (%)

Pressure (bar)

Indep. Device - $V_g = 1.25 \text{ V}$

Indep. Device - $V_g = 0 \text{ V}$

Device with Osc. - $V_g = 0 \text{ V}$

Linear Regression

Piezoresistive Coefficients

Numerical Simulations
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?

1. Output of 3D Blanket Membrane model $\varepsilon_{Si3N4}$

2. $\varepsilon_{Si3N4} \leftrightarrow \varepsilon_{Si}$
   Conversion function through complementary 2D models

Expected Accurate $\varepsilon_{Si}$

$\varepsilon_{SiN}$

$\varepsilon_{Si}$

$\varepsilon_{SiN}$
System’s Cross-Sections

TOP VIEW OF THE PARALLEL CROSS-SECTION

TOP VIEW OF THE PERPENDICULAR CROSS-SECTION

ACTUAL SYSTEM 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)

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<tr>
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<th>Length-axis</th>
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<tr>
<td>3D Blanket Membrane</td>
<td>63.8</td>
<td>21.4</td>
</tr>
<tr>
<td>+ 2D correction -no istress</td>
<td>71.5</td>
<td>22.3</td>
</tr>
<tr>
<td>+ 2D correction -with istress</td>
<td>68.9</td>
<td>21.1</td>
</tr>
<tr>
<td>3D Patterned Membrane</td>
<td>71.8</td>
<td>27.0</td>
</tr>
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</table>
Stress resolution

Direct Stress Calculation

\[ \frac{\Delta \rho}{\rho_0} = \pi \cdot \sigma \]

\[ \frac{\Delta I_D}{I_{D_0}} = \Delta \mu \cdot \frac{\mu_0}{\mu} - 1 \approx \frac{\Delta \rho}{\rho_0} \]

At higher stress values

[Tsang, EDL 2008]

\[ \frac{\Delta \rho}{\rho_0} = \frac{1}{\Delta \mu + 1} - 1 = \frac{1}{\frac{\Delta I_D}{I_{D_0}} + 1} - 1 \]

NMOS – PMOS System

\[
\begin{align*}
\left( \frac{\Delta \rho}{\rho_0} \right)_{NMOS} &= -\pi_{NMOS,\parallel} \cdot \sigma_{\text{width}} + \pi_{NMOS,\perp} \cdot \sigma_{Mb} \\
\left( \frac{\Delta \rho}{\rho_0} \right)_{PMOS} &= -\pi_{PMOS,\parallel} \cdot \sigma_{\text{width}} + \pi_{PMOS,\perp} \cdot \sigma_{Mb}
\end{align*}
\]

\[ \sigma \text{ width axis} \]

\[ \sigma \text{ Length axis} \]
Stress resolution

The measurement is a relative variation of drain current which corresponds to a delta of stress

\[
\frac{\Delta I_D}{I_D} \approx \frac{\Delta \rho_{\text{channel}}}{\rho_{\text{channel}}} = \pi_{\parallel} \sigma_{\parallel} + \pi_{\perp} \sigma_{\perp}
\]
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

![Ring Oscillator Diagram](image)

- **4 Devices on membrane**

![Thin Dielectric MEMBRANE](image)

**Burst at 3.1 bar**

500 µm-side Membrane Devices at 50 µm from border

\[
I_{\text{out}} \approx \left[ 1 + 2\pi 44_{\text{PMOS}} \cdot \left( \sigma_{\perp, \text{Mb}} - \sigma_{\parallel, \text{Mb}} \right) \right] I_{\text{ref}}
\]
Rectangular Shaped Membranes

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

At the center of square membranes, we have $\sigma_{\perp,\text{Mb}} \equiv \sigma_{\parallel,\text{Mb}}$

Figuring more compact designs, rectangular shaped membranes are a solution

$p = 1\ \text{bar}, \ z = 0.41\ \mu\text{m}, \ \text{width} = 200\ \mu\text{m}.$
PMOS Mirror-based architectures

150 x 450 µm² Membrane
Devices at the center

Cascaded mirror sensitivity: ~20% / 100 MPa \( \Delta \sigma \)

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

No additional FEOL SiN Layer on this design

- No burst observed
- Very large process window

1.1
1.2
1.3
1.4
1.5
1.6
1.7
1.8
1.9

Applied Pressure (bar)
Output Frequency (MHz)
Casc. M., Ro1
Casc. M., Ro2
Casc. M., Ro3
Casc. M., Ro4
Sp. M., Ro1
Sp. M., Ro2

\( \Delta \sigma \)
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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