How to Make Your Integrated Sensor Smarter

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1. What is Missing?
2. Too Tiny to Be Touched
3. Process & Matching Nightmares
4. Biasing Specials
5. Flexibility as a Must
6. Massive Parallel Processing
7. Power-Aware Design
8. When Package Matters
9. My Nice Smart Sensor
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More than Moore

- Technology **diversification** versus pure scaling

- Not only information processing applications but also **sensing**, communications, power control...

- **Ubiquitous** computing

- Interaction with the real **multi-domain** world! (physics, chemistry, biology, medicine...)

- New market demands for **custom smart sensors** as core of heterogeneous systems
What is Missing

Why some sensors are not smart enough to reach application stage?

device ➔ circuit ➔ system

Missing read-out integrated circuit (ROIC)!

Micro world
- signal integrity
- sensor biasing
- PVT compensation

Macro world
- power management
- signal processing
- multi-sensor muxing
- communications
What is Missing

Why some sensors are not smart enough to reach application stage?

Device → Circuit → System

Micro world
- Technology compatibility
- Device modeling
- Yield optimization

Macro world
- Apps specs
- Controllability & observability
- Packaging strategy

Multi-disciplinary design work can be a hard task
Filling the Gap

► Each smart sensor usually requires its own custom ROIC!

► General ROIC figures of merit (FOMs):

  ■ **Small size** for light packaging, aggressive system scaling and ubiquity

  ■ **Low power** for extended operative life, minimum overheating and local energy harvesting

  ■ **Low cost** for mass production, disposable products and multi-sensory applications

► **Real smart sensor examples** developed by ICAS group at IMB-CNMCNM(CSIC):
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8. The Shrinking Packaging

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Too Tiny to Be Touched

- **ROIC** first challenge is to link the **micro** and **macro** worlds by supplying the needed scaling.
  - Sensor **signal** power
  - Sensor **geometry**
  - Sensor **impedance**
  - Signal **integrity**
  - **Connectivity**
  - Protection against **parasitics**

- Minimum **area** and **power** overheads wanted

- Not all **integrated** sensors operate in the same signal domain, e.g.:

  - Current
  - Voltage
  - Charge
  - Impedance
NEMS Resonator Characterization

- Applications in quartz crystal monolithic replacement, accurate mass sensor and more...

- **Mechanical** resonator at frequencies exceeding MHz

- CMOS post-processed using nanostencil lithography (nSL) at wafer level

- Very high Q factors

- Accurate **modeling** needed in terms of size, materials and package air pressure

\[
f_{res} = \frac{1.015}{2\pi} \sqrt{\frac{E}{\rho}} \frac{W}{L^2}
\]

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>W</td>
<td>265</td>
<td>nm</td>
</tr>
<tr>
<td>L</td>
<td>14.5</td>
<td>(\mu)m</td>
</tr>
<tr>
<td>H</td>
<td>580</td>
<td>nm</td>
</tr>
<tr>
<td>D</td>
<td>650</td>
<td>nm</td>
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</tbody>
</table>
NEMS Resonator Characterization

- ROIC designed for the sole purpose of sensor characterization

- **Interface** challenge:
  - Current-mode read-out
  - Weak signal (nA)
  - Parasitic capacitance

\[ f_i = \frac{1}{2\pi} \sqrt{\frac{k_i}{m_{eff}}} \]

\[ I_{res} = \frac{dQ_{res}}{dt} \approx C_{stat} \frac{dV_{osc}}{dt} + (V_{bias} - V_{ref}) \frac{dC_{mot}}{dt} \]
NEMS Resonator Characterization

- **ROIC designed for the solely purpose of sensor characterization**

- **Interface** challenge:
  - Current-mode read-out
  - Weak signal (nA)
  - Parasitic capacitance

- **Current conveyor (CII) based ROIC:**
  - Low input impedance
  - Output current scaler
  - Built-in bias generator

\[
\begin{bmatrix}
I_Y \\
V_X \\
I_Z \\
\end{bmatrix}
= 
\begin{bmatrix}
0 & 0 & 0 \\
1 & 0 & 0 \\
0 & -MN & 0 \\
\end{bmatrix}
\begin{bmatrix}
V_Y \\
I_X \\
V_Z \\
\end{bmatrix}
\]
NEMS Resonator Characterization

Monolithic integration at IMB-CNMC(SIC) and experimental results:

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<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
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</thead>
<tbody>
<tr>
<td>$R_{res}$</td>
<td>40</td>
<td>MΩ</td>
</tr>
<tr>
<td>$L_{res}$</td>
<td>33</td>
<td>kH</td>
</tr>
<tr>
<td>$C_{res}$</td>
<td>0.34</td>
<td>aF</td>
</tr>
<tr>
<td>$C_{stat} + C_{coup}$</td>
<td>275</td>
<td>aF</td>
</tr>
<tr>
<td>$C_{cant}$</td>
<td>&lt;50</td>
<td>fF</td>
</tr>
</tbody>
</table>

$f_{res} = 1.5$MHz
$Q \approx 8000$
2V, 0.9Pa
NEMS Resonator Characterization

- Monolithic integration at IMB-CNMC(SIC) and experimental **results**:

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Process & Matching Nightmares

Sensor technologies tend to suffer from large **process** and **mismatching** deviations

Countermeasures at ROIC level?

- **Blind sensor** for process and interference cancellation in differential read-out, but its effectiveness can be limited by mismatching itself

- Large **area**, minimum **distance** and **symmetrical** layout design

- **Calibration** mechanism (automatic or with external control)

- Digital **post-processing** may be too late to recover dynamic range!

\[
\sigma^2 (\Delta P) = \frac{A_P^2}{WL} + B_P^2 D
\]

- **Local** e.g. dopant non-uniformity
- **Global** e.g. thickness gradient

\(D\)
A Microdroplet Dispensing System

- Applications in photonics, molecular electronics, biosensors...

- Fluidic NEMS operated as a bioplume

- Accurate positioning for microdoplet high uniformity

- Multi-channel digital ROIC for integrated piezo-resistive stress sensors:
  - Low power to prevent drying
  - Low voltage for single cell battery supply

- Blind sensor against interferences
Integrated Piezo-Resistors

► **Differential** read-out of weak stress signal ±0.1% / ±0.0004% = 9bit

► **Process** corners ±20%

► Large **disturbing** signals in the order of ±1%

► Technology **mismatching** deviations ±2%

► **Residual** disturbing signals ±0.02% = ±50LSB!

► **Gain tuning** mechanism to be included inside ROIC ±2% / 0.01% = (8+1)bit
Multichannel ROIC Architecture

- Overall programmable sensitivity \( I_{\text{com}} \)
- Differential gain balancing through sensor bias \( \Delta I_{\text{com}} \)
- Differential OTA pre-amplification
- Integrate & fire current-mode A/D conversion
- Digital-only read-out and program-in interface
- Channel-based modular ROIC design
Low-Voltage and Low-Power CMOS Circuits

- Gain calibration through built-in SC DAC:
  - Recalibrated at start-up
  - Compensation of piezo-resistor mismatch and OTA unbalance

- Differential V to single ended I conversion:
  - Biased in weak inversion for best $G_m/I_D$ and lowest technology sensitivity
  - Low equivalent input noise and high CMRR
Low-Voltage and Low-Power CMOS Circuits

**Spike-counting ADC:**

- **Class-AB** window comparator
- Built-in modular and **floating** threshold generator

**Compact** CTIA with correlated double sampling (CDS) for low-frequency noise reduction
Quad ROIC CMOS Integration

- 0.35μm 2P4M CMOS technology
- Direct wire-bonded to integrated piezo-resistors substrate

2.4mm x 1.3mm (3.1mm²)
Experimental Results

\[
\left| \frac{S_{11-0}}{\Delta R_{sens}/R_{sens}} \right| = \frac{G_m T_{int}}{C_{int} V_{th}} I_{com} R_{sens} \approx 6\text{LSB/}%
\]

- 130\mu W/ch at +1.25V (+3.3V technology)
- Thermal compensation
- Good linearity
- CMRR > 100dB

R. Durà et al., A 0.3mW/Ch 1.25V Piezo-Resistance Digital ROIC for Liquid Dispensing MEMS, IEEE Transactions on Circuits and Systems-I, 56:5(957-65), May 2009
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Biasing Specials

- Some sensors require ROIC to incorporate **control loops** for their proper DC biasing.

- **Multiple ports** may be needed by ROIC to compensate for unavoidable parasitics.

- When possible, **lock-in** operation is advised to strongly reduce equivalent noise bandwidth.

- Indirect measurement through **time-domain** processing is a promising alternative.
Integrated Electrochemical Sensors

- Applications in biosensors, quality control...
- Compatible with **CMOS** monolithic integration
- **Selectivity** by functionalization of their microelectrodes surface
- Reduced **speed** (~0.1s) and **life** time
- Expensive **package**
- **Potentiostatic** operation and **amperometric** reading
Mixed Electrochemical ROIC Architecture

- **Low-pass first-order single-bit CT $\Delta \Sigma$ A/D modulator** with sensor in the loop:
  - Minimalistic **analog** circuits
  - **Low power** ROIC overhead respect to sensor itself
  - Accurate sensor dynamic **modeling** needed

High oversampling against dead zones

Thermal noise dithering against tonal behavior
Low-Power All-MOS Circuits

- **Two analog blocks** only

- **Latched comparator** for 1bit quantization + **current reference** for 1bit feedback DAC
Monolithic CMOS Integration

- IMB-CNMC(SIC) inexpensive 2.5μm 1M CMOS technology (CNM25)
- In-house sensor Au post-processing at wafer level
- 2.3mm x 2.8mm (6.4mm²)

- Low area overhead of ΔΣ ADC
- Digital only interface for low-pass filtering and programming of potentiostatic voltage and current full-scale
- Overall 25μW at +5V
Experimental Results

▲ **Electrical** tests show good enough dynamic range to not limit measurements

![Electrical Test Diagram](image)

- **Power on/off**
- **Current steering**

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**2Hz noise bandwidth (OSR=256)**

![Noise Bandwidth Graph](image)

- **$f_{in}$ [dBFS/0.25mHz]**
- **$d_{SNDR}$ [ENOB]**

- **Frequency [Hz]**
- **$I_{in}$ [dBFS]**

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**Electrical tests**

- **$V_{in}$**
- **$R_{ctw}$**
- **$C_{dtw}$**

- **Sensor emulator**

**Digital interface**
Experimental Results

▲ **Electrical** tests show good enough dynamic range to not limit measurements

▲ **Electrochemical** tests return comparable performance to lab desktop equipment

\[ [\text{Fe(CN)}_6]^{4-} \rightarrow [\text{Fe(CN)}_6]^{3-} + \text{e}^- \]

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Flexibility as a Must

- **ROIC controllability/observability** to increase overall sensor yield?

- Single ROIC can fit several sensor designs

- **Built-in test** mechanism to screen smart sensors before post-processing or packaging

- Compensate for **sensor aging**

- Independent optimization of **dynamic range** for each stage

- If available, **non-volatile** memory (Flash, OTP...) to store configuration

- Specially useful when sensor or application **specifications** are incomplete!

- **Extra design** work for making each stage configurable
IR Spectroscopic Gas Recognition System

- Applications in toxic gas warning, environmental monitoring...
- Thermal \textbf{\textmu}bolometer LWIR sensors
- Multipath optical cell to amplify gas IR \textbf{absorption} effect
  - Blind reference and lock-in demodulation for \textbf{high accuracy} read-out
  - Sensor deviations and mixed IR technologies need \textbf{high flexibility} for each channel
  - \textbf{Low power} ROIC to avoid thermal drifts of IR sensors
ROIC Channel Module

- **Sub-Hz** high-pass pre-amplification

- **5-parameter** independent programmability per channel!

- Dedicated **blind channel** for cancellation of common disturbing signals

- ADC with **digital lock-in** demodulation
Low-Power Channel Circuits

- Fully integrated sub-Hz variable corner & gain pre-amplifier
- Highly linear differential transconductor with soft limiter
- Integrate & fire PDM with 3-level quantizer
32-Channel ROIC

- 0.35μm 2P4M CMOS technology
  - 350μm-pitch
  - 11mm x 1.6mm (17.6mm²)
  - Direct **wire-bonded** to IR μbolometer array
Experimental Results

▲ **120μA/ch at +3.3V**

▲ **Full programmability**

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<thead>
<tr>
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<tbody>
<tr>
<td>$I_{sens}$</td>
<td>1 to 10</td>
<td>μA</td>
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<tr>
<td>$f_c$</td>
<td>0.75±0.10</td>
<td>Hz</td>
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<tr>
<td></td>
<td>3.6±0.4</td>
<td></td>
</tr>
<tr>
<td></td>
<td>49±8</td>
<td></td>
</tr>
<tr>
<td></td>
<td>389±76</td>
<td></td>
</tr>
<tr>
<td>$G$</td>
<td>26±0.1</td>
<td>dB</td>
</tr>
<tr>
<td></td>
<td>34±0.1</td>
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<td></td>
<td>40±0.1</td>
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<td></td>
<td>45±0.1</td>
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<tr>
<td>$G_m$</td>
<td>18</td>
<td>μS</td>
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<tr>
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<td>25</td>
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<tr>
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<td>36</td>
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</tr>
<tr>
<td></td>
<td>45</td>
<td></td>
</tr>
<tr>
<td>$1/C_{int}V_{th}$</td>
<td>1.7</td>
<td>Hz/pA</td>
</tr>
<tr>
<td></td>
<td>0.8</td>
<td></td>
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<tr>
<td>$V_{sensneq}@10Hz$</td>
<td>250</td>
<td>nV/$\sqrt{Hz}$</td>
</tr>
<tr>
<td>THD $V_{amp}&lt;300mV_{pp}$</td>
<td>&lt;0.1</td>
<td>%</td>
</tr>
<tr>
<td>Crosstalk</td>
<td>&lt;0.5</td>
<td>LSB</td>
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Massive Parallel Processing

- Connectivity issues for large **sensory arrays**

- **Multi-channel**
  ROIC architecture?

- Parallel A/D conversion reduces equivalent **noise bandwidth**

- Early A/D conversion avoids **inter-symbol crosstalk**

- Dedicated ADC per sensor increases **area** and **power** (temperature)
High-Speed Uncooled IR Digital Imager

- Applications in strategic equipment, production quality control...
- Photoconductive **PbSe MWIR** sensors post-processed by VPD on top of CMOS
  - High **frame rate** achievable at room temperature
  - High fixed pattern noise (**FPN**)
  - High speed **multiplexing** spec at focal plane array (**FPA**) level
- **Low power** digital pixel sensor (**DPS**) to not increase sensor temperature
ROIC Pixel Circuits

- **Sensor** capacitance compensation
- **FPN** offset (dark current) and **gain** (sensitivity) digital compensation
- In-pixel **A/D** conversion
- **Local bias** generator and **asynchronous** operation to minimize inter-pixel **crosstalk**
- **Daisy-chain** digital read-out and simultaneous program-in
- **Sub-μW/pix** static power
- **135μm-pitch** in 0.35μm 2P4M CMOS technology
ROIC Pixel Circuits

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Sensor Integration at Wafer Level

- **Au** deposition and patterning for contacts + active layer by **PbSe** VPD
- Sapphire window on top + **wire-bonding** to chip-carrier

- Access to sensor common bias terminal through ROIC pads
In-pixel **full FPN** compensation

**High speed** digital frame mux for both read-out and program-in

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[J. Margarit et al., A 2-kfps Sub-uW/Pix Uncooled-PbSe Digital Imager with 10-bit DR Adjustment and FPN Correction for High-Speed and Low-Cost MWIR Applications, IEEE Journal of Solid-State Circuits, 2015, accepted](#)
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Power-Aware Design

▼ Smart sensor **ubiquity** means limited power source!

► Analog circuit techniques for **low-power**?

▼ **Low-voltage** design (supply or technology specs)
  - Charge-pump supply multipliers
  - Bulk-driven transistors
  - Current-domain processing
  - Inverter-based amplifiers
  - ...

▼ **Low-current** design (life-time or thermal specs)
  - Class-AB amplifiers
  - Noise-shaping architectures
  - Asynchronous operation
  - Short duty-cycles
  - ...

► **Local energy source** solution (or combination) for each scenario?

![Stability vs. Autonomy diagram]
Remote Powered Impedimetric Sensor

- Applications in chemical industry control and biosensors...
- 13.56MHz ISM near field inductive coupling for **remote power** supply
- **Power ASK** for program-in
- **Load PWM** for read-out

- Complex I/Q impedance measurements for solution **conductivity** and **permittivity** monitoring

- Contact-less and **package-less**
CMOS Integration

- **0.35μm 2P4M high-voltage** CMOS technology
  - 3.5mm x 3.5mm (12.25mm²)
  - 3M power coupling coil (L~8μH, Q~1) and supply capacitor (C~2nF) at periphery

- Number of turns optimized for maximum supply voltage and out-band self-resonant frequency

- Pads for prototype testing purposes only
Lithography-Less Post-Processing

- Poly-Silicon material + native oxidation (3nm) to improve microelectrode reliability

- **4-microelectrode** by CHF$_3$-based reactive ion etching (**RIE**)
Lithography-Less Post-Processing

- Poly-Silicon material + native oxidation (3nm) to improve microelectrode reliability

- **4-microelectrode** by CHF₃-based reactive ion etching (RIE)

- **Interdigitated** 2-microelectrode by RIE + ‘piranha’ (H₂SO₄) solution
Experimental Results

▲ Remote power **5mW** at **3mm** (up to >10cm with external resonator)

▲ Complex impedance measurement at **13kHz** (10kHz to 100kHz)

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When Package Matters

- Packaging costs can be dominant in **hybrid** smart sensors!

**Sensor** needs?
- Signal integrity and parasites
- Pitch matching
- Filling factor
- Exposure window
- ...

**Application** requirements?
- Sensing area
- Environment compatibility
- ...

**Modular** ROIC design + **MCM** packaging?
2D Modular Direct X-Ray Imager

- Applications in mammography, defect detection...

- CdTe or Si **direct X-ray** pixelated detectors

- Hybrid imager packaging by **bump-bonding** (bump growing + flip-chip)

- Fully autonomous **DPS** with:
  - Charge-integration ADC
  - Dark current cancellation
  - Gain FPN compensation
  - Built-in test
  - Local bias generator

- **55μm-pitch** detectors with high fill-factors
Packaging for Seamless 2D Image

- Pixel detector-to-circuit rerouting...

52μm pitch

55μm pitch

CMOS ROIC Module

- 0.18μm 1P6M CMOS technology
- 94 x 94 pixel (5mm x 5mm) module
- 52μm-pitch
- 6μW/pix at +1.8V
Wafer-Level Sensor Integration

- 4”-wafer 55μm-pitch **Si X-ray detectors** from IMB-CNM(CSIC) to be tested...
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My Nice Smart Sensor

- **Custom** + standard chip set
- Single **ROIC** design to cover a full family of sensors (e.g. chemical)
- **Local energy** harvesting + storage for ROIC + controller memory
- **Wireless** communications and remote power

Thanks for your attention!