How to Make Your Integrated Sensor Smarter

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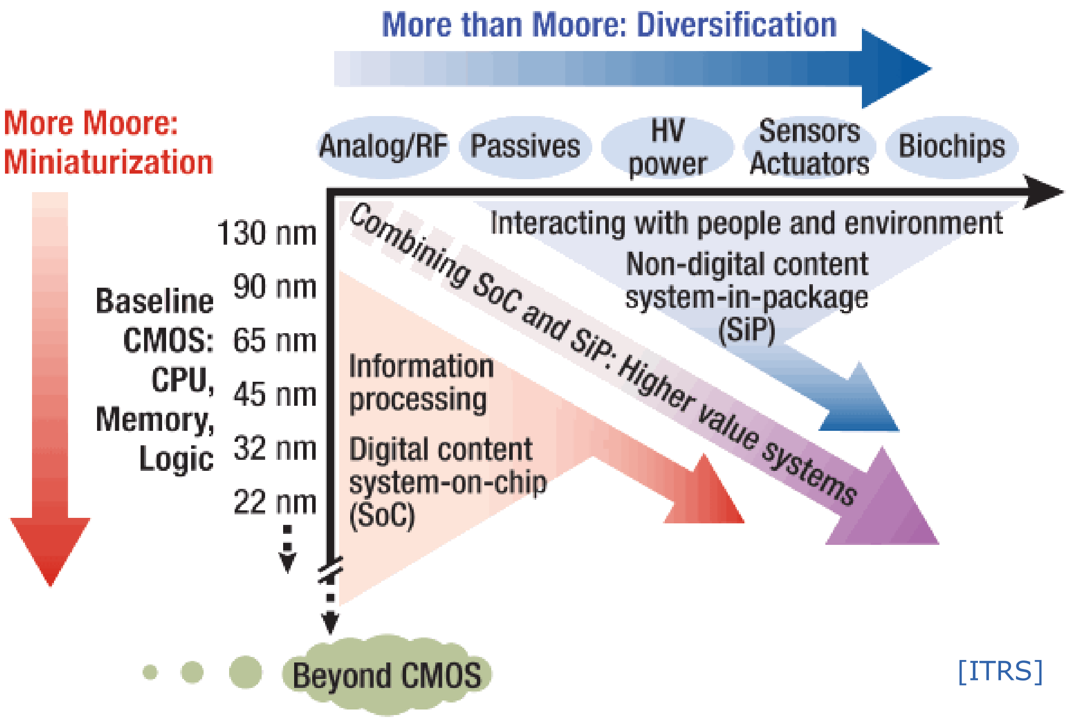
More than Moore

- 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...)



[ITRS]

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

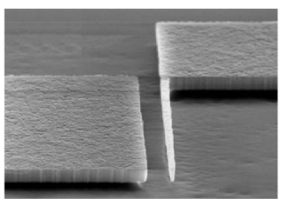
What is Missing

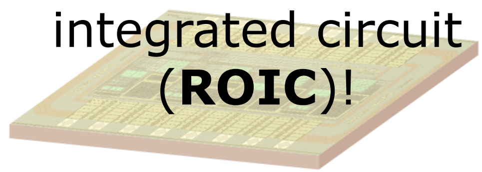
- Why some sensors are not smart enough to reach **application** stage?

device ⟶ **circuit** ⟶ **system**

100nm 1µm 10µm 100µm 1mm 10mm 100mm

1µW 10µW 100µW 1mW 10mW 100mW 1W





Micro world

signal **integrity**

sensor **biasing**

sensor **calibration**

PVT compensation

power management

signal **processing**

multi-sensor muxing

communications

Macro world

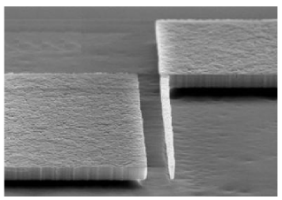
What is Missing

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

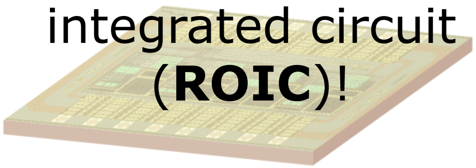
device ⟶ circuit ⟶ system

100nm 1µm 10µm 100µm 1mm 10mm 100mm

1µW 10µW 100µW 1mW 10mW 100mW 1W

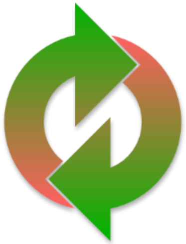


Missing read-out integrated circuit (**ROIC**)!



Micro world

- Technology compatibility
- Device modeling
- Yield optimization



- Apps specs
- Controllability & observability
- Packaging strategy

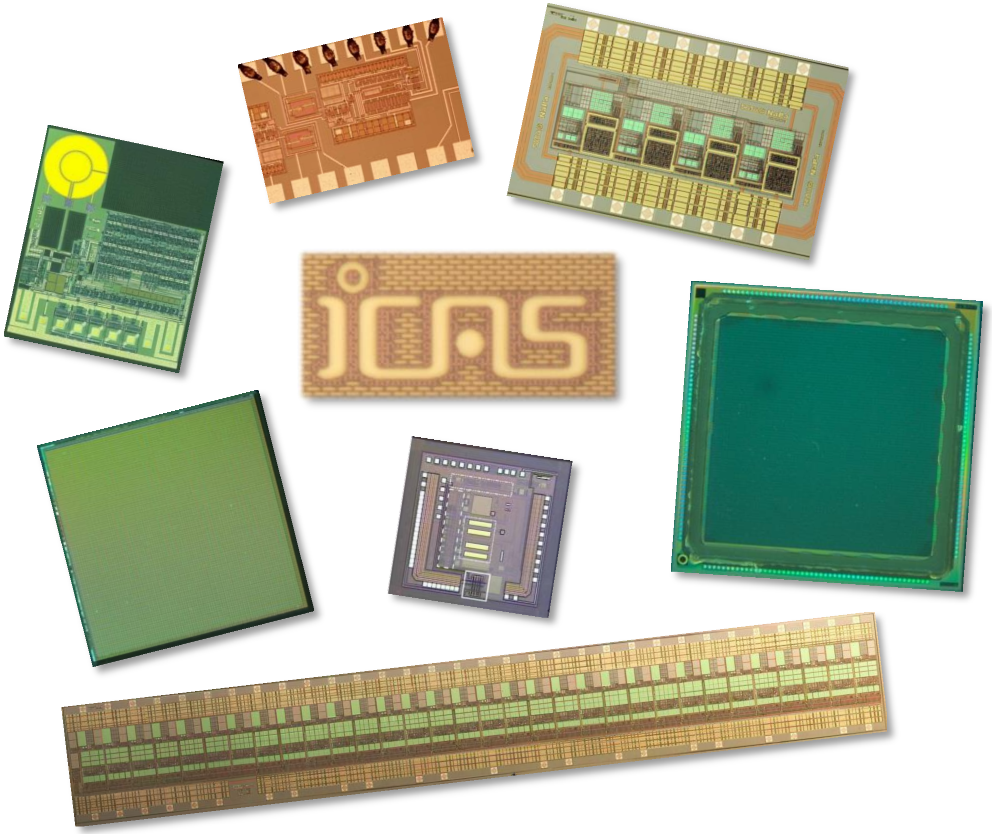
Macro world

- **Multi-disciplinary** design work can be a hard task

Filling the Gap

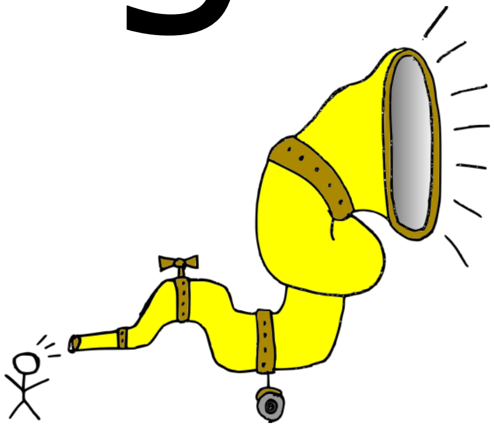
- Each smart sensor usually requires its own **custom ROIC**!
- General ROIC figures of merit (**FOMs**):
  - **Small size** for light packaging, aggressive system scaling and ubiquity
  - **Low power** for extended operative life, minimum overheating and local energy harvesting
  - **Low cost** for mass production, disposable products and multi-sensory applications

- **Real smart sensor examples** developed by ICAS group at IMB-CNM(CSIC):

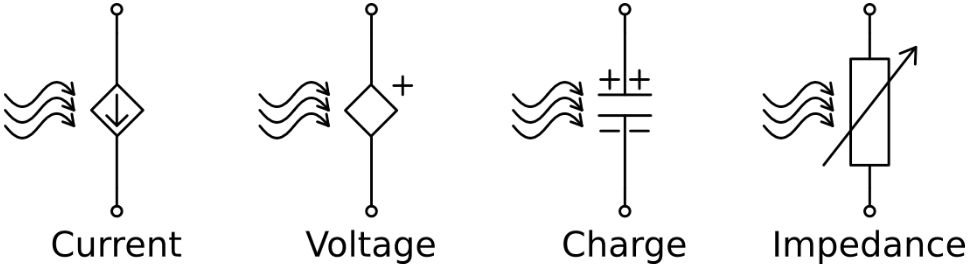


Too Tiny to Be Touched

- **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.:

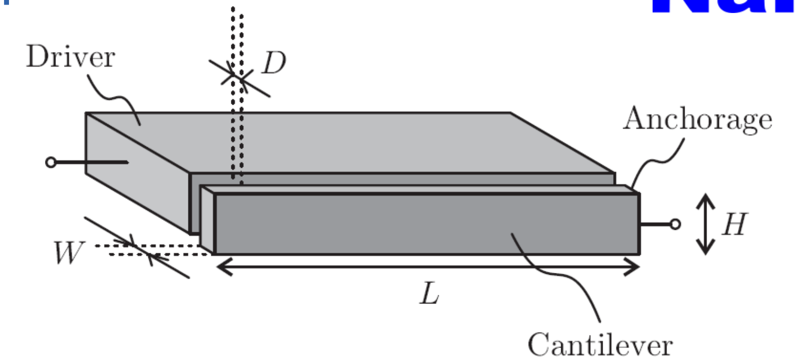


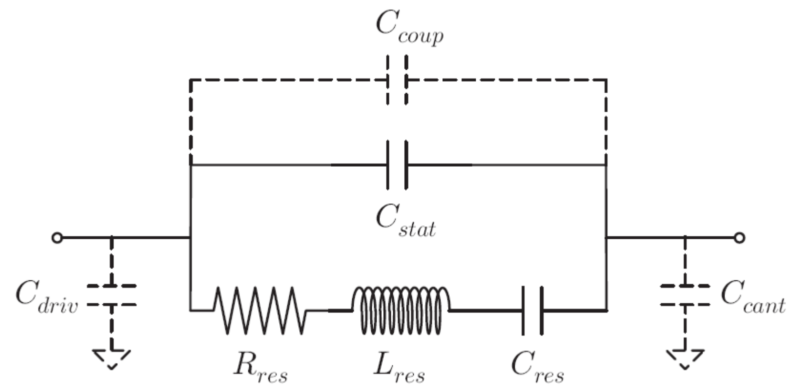
NEMS Resonator Characterization

NaPa

- 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**



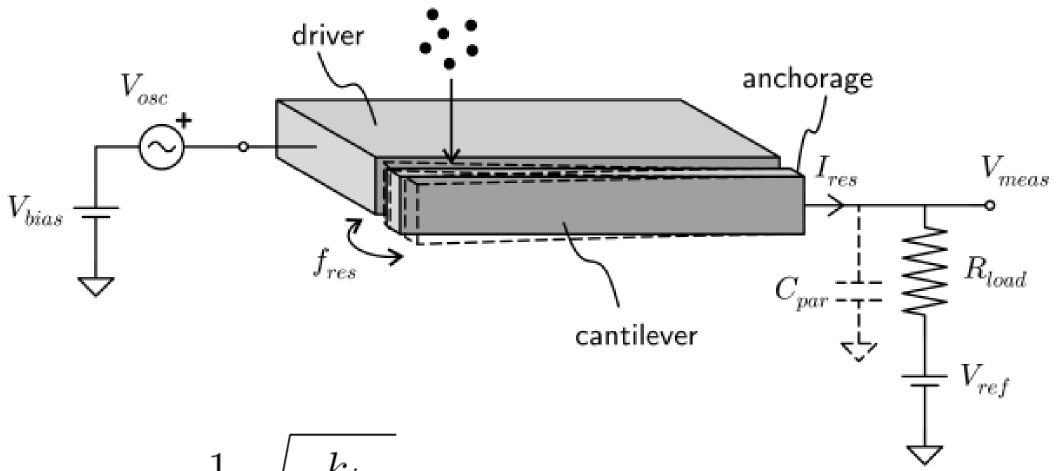


$$f_{res} = \frac{1.015}{2\pi}\sqrt{\frac{E}{\rho}}\frac{W}{L^2}$$

Parameter	Value	Units
W	265	nm
L	14.5	μm
H	580	nm
D	650	nm

NEMS Resonator Characterization

- ROIC designed for the solely purpose of sensor **characterization**
- **Interface** challenge:
  - Current-mode read-out
  - Weak signal (nA)
  - Parasitic capacitance



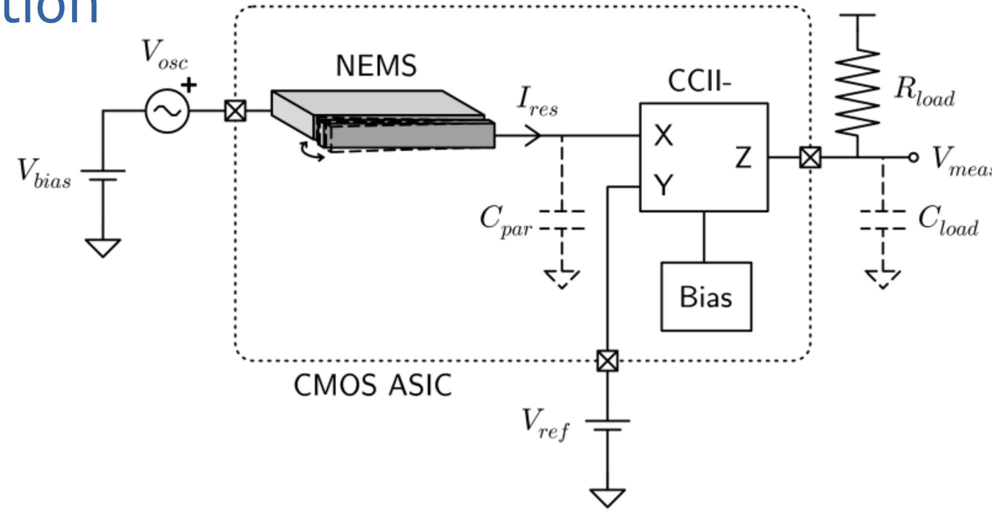
$$f_i = \frac{1}{2\pi}\sqrt{\frac{k_i}{m_{eff}}}$$

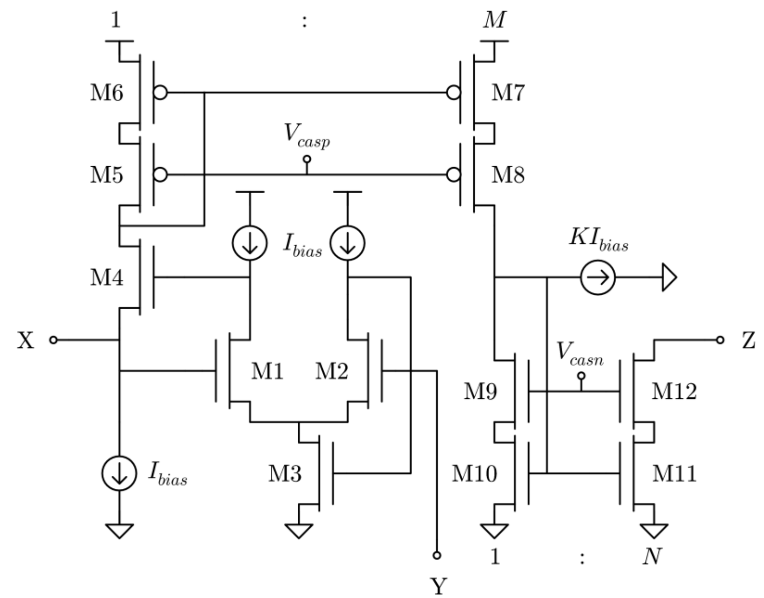
$$I_{res} = \frac{dQ_{res}}{dt} \simeq C_{stat}\frac{dV_{osc}}{dt} + (V_{bias} - V_{ref})\frac{dC_{mot}}{dt}$$

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

$$\begin{bmatrix} I_Y \\ V_X \\ I_Z \end{bmatrix} = \begin{bmatrix} 0 & 0 & 0 \\ 1 & 0 & 0 \\ 0 & -MN & 0 \end{bmatrix} \begin{bmatrix} V_Y \\ I_X \\ V_Z \end{bmatrix}$$

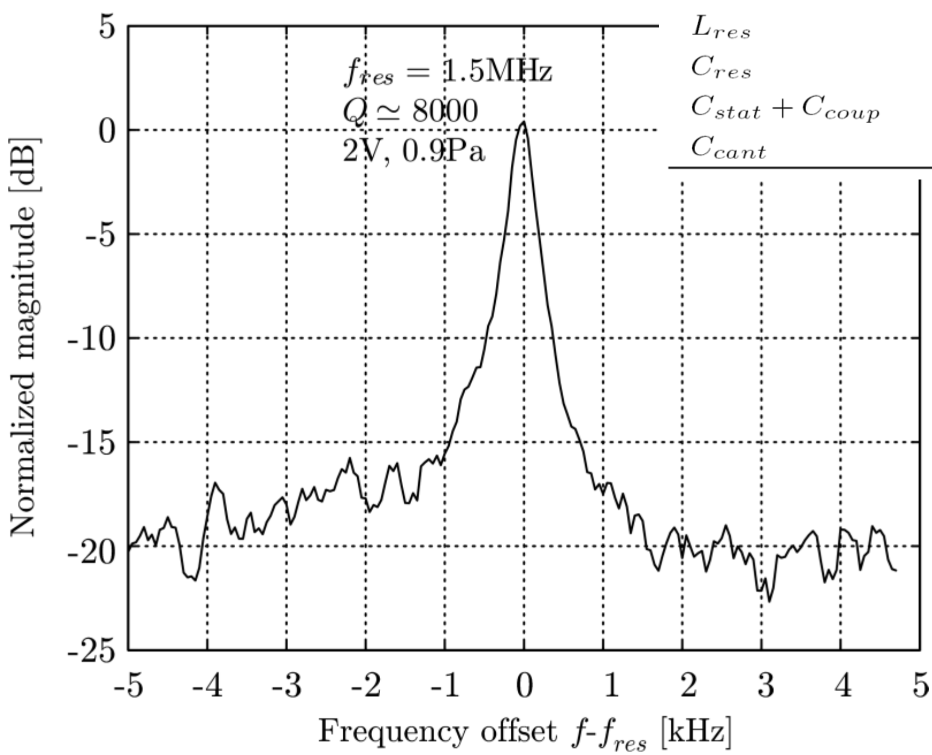


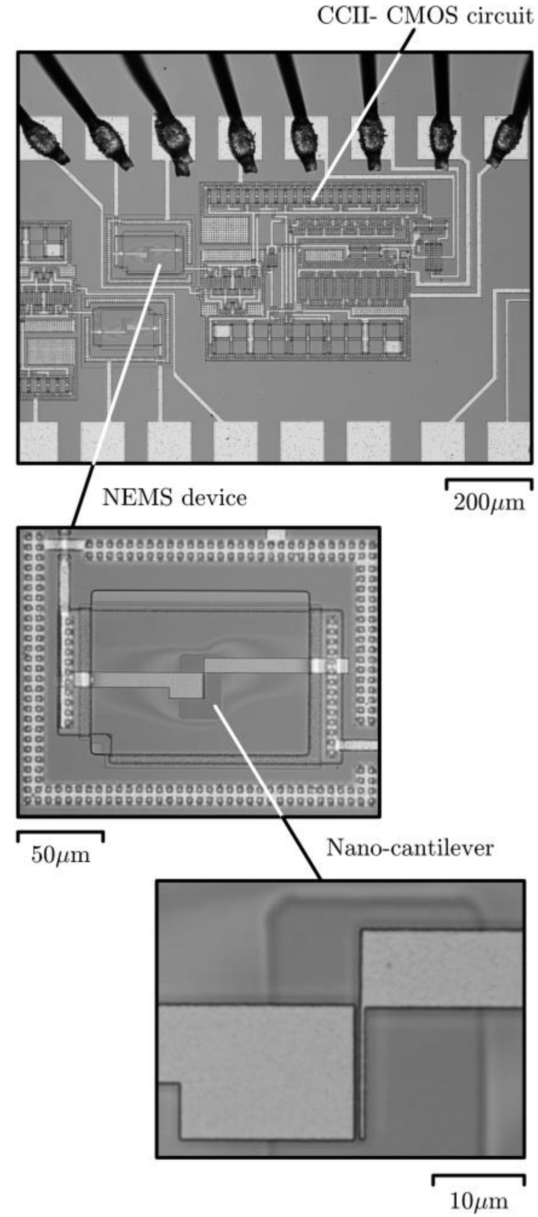


NEMS Resonator Characterization

- Monolithic integration at IMB-CNM(CSIC) and experimental **results**:

Parameter	Value	Units
R_{res}	40	MΩ
L_{res}	33	kH
C_{res}	0.34	aF
$C_{stat} + C_{coup}$	275	aF
C_{cant}	<50	fF





NEMS Resonator Characterization

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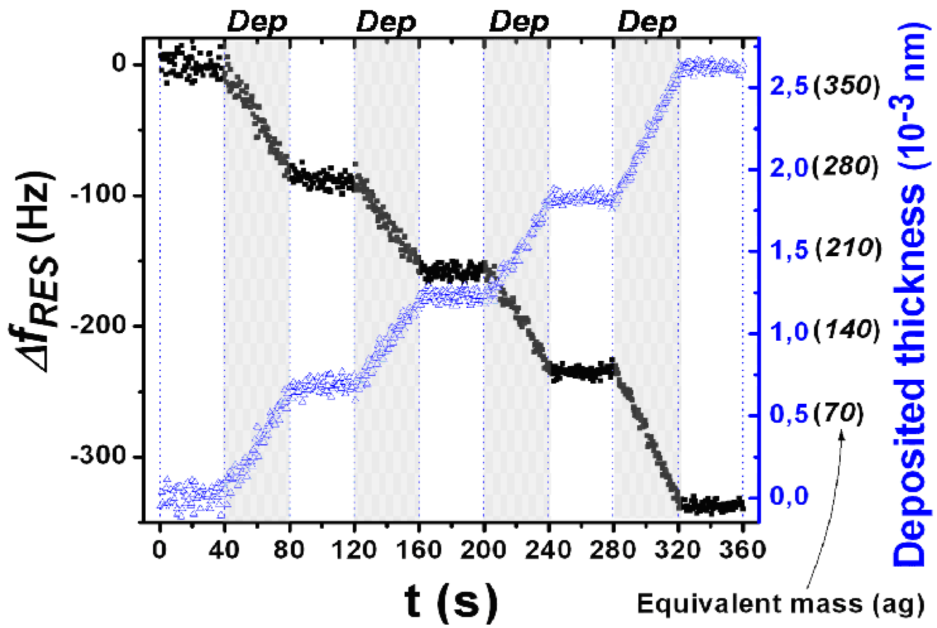
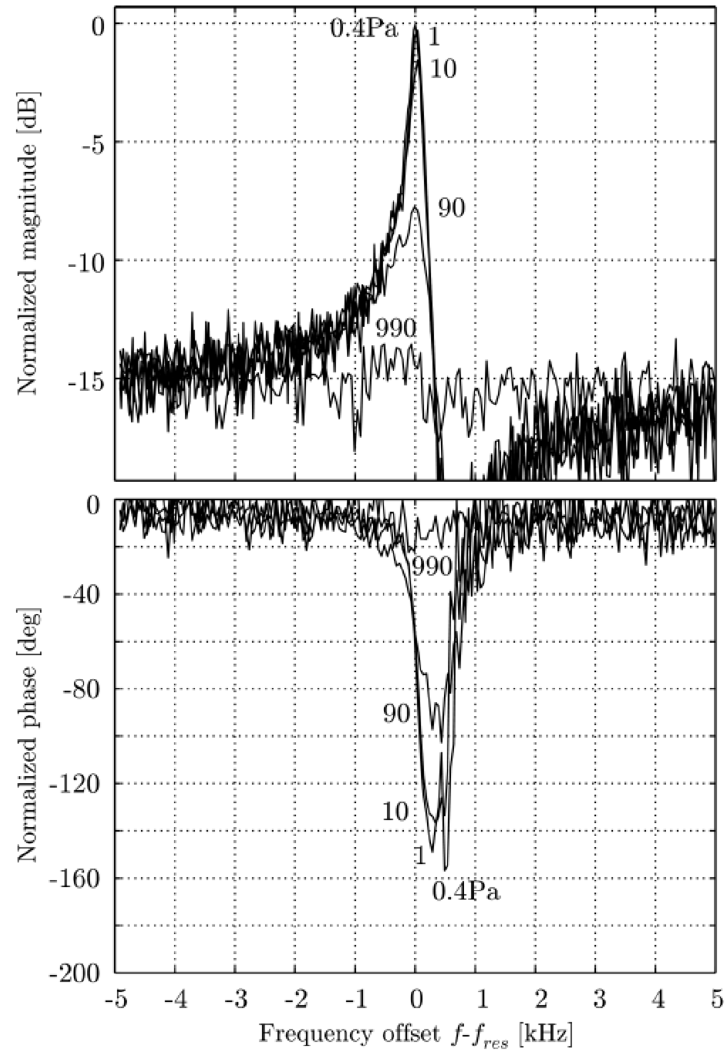
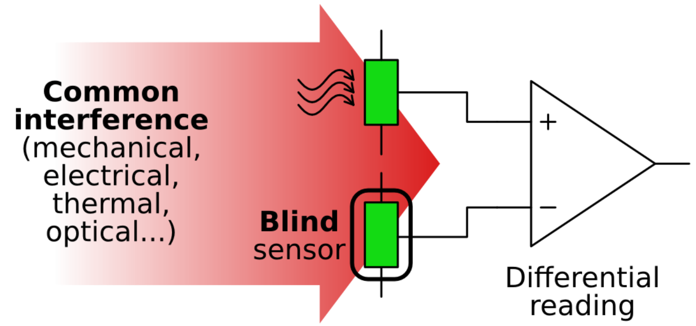




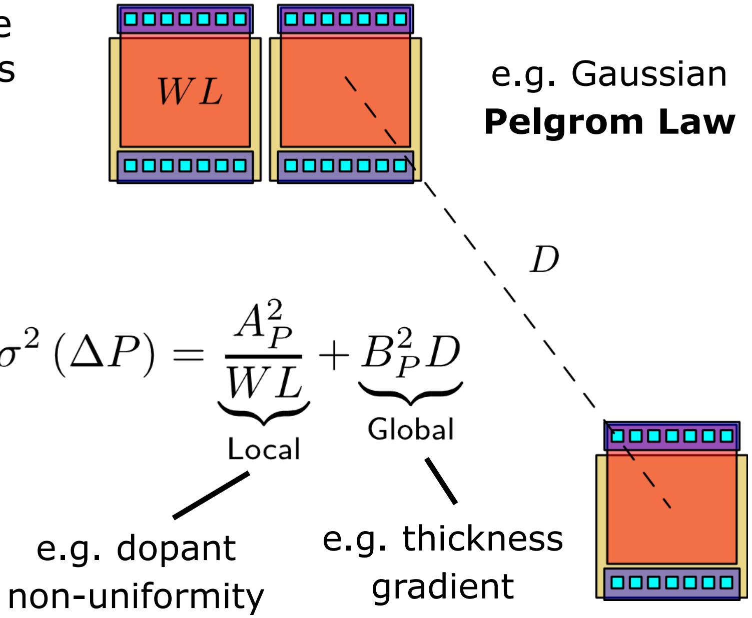
J. Arcamone et al., *A Compact and Low-Power CMOS Circuit for Fully-Integrated NEMS Resonators*, IEEE Transactions on Circuits and Systems-II, Vol.54:5, pp.377-381, May 2007

Process & Matching Nightmares

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



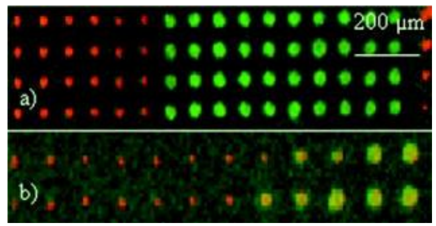
- Countermeasures at ROIC level?
  - **Blind sensor** for process and interference cancellation in differential read-out, but its effectiveness can be limited by mismatching itself
  - Large **area**, minimum **distance** and **symmetrical** layout design
  - **Calibration** mechanism (automatic or with external control)
  - Digital **post-processing** may be too late to recover dynamic range!



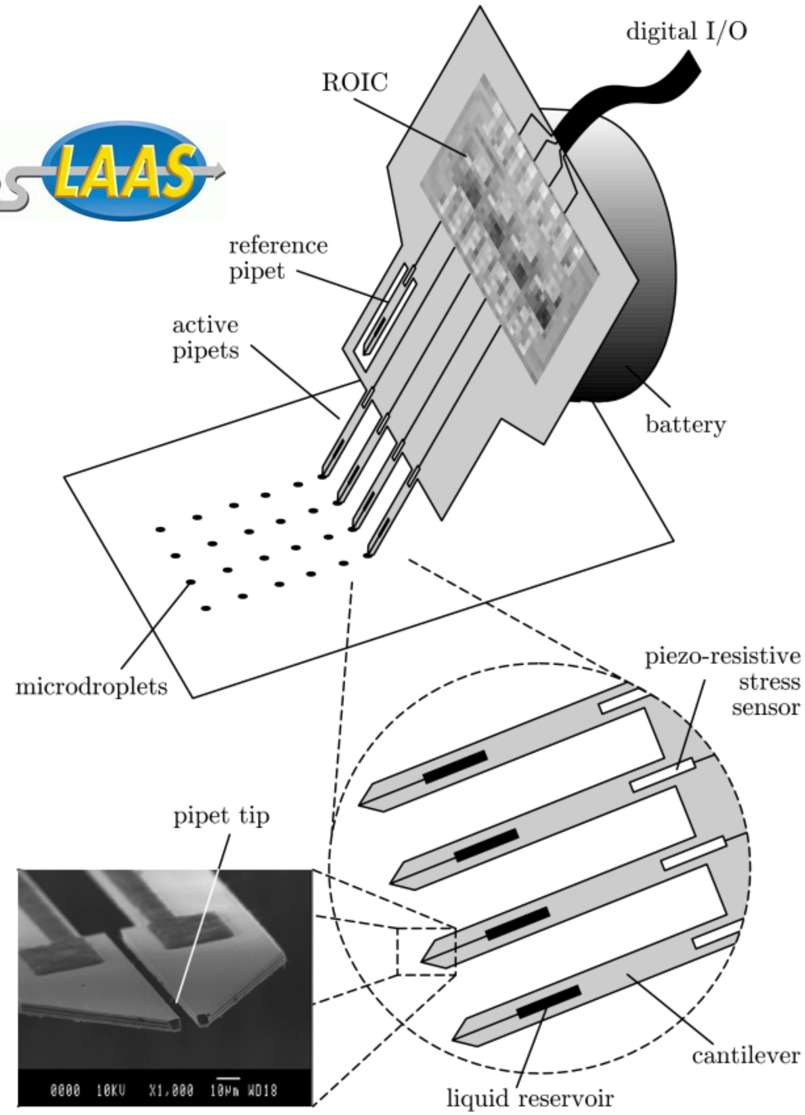
$$\sigma^2(\Delta P) = \underbrace{\frac{A_P^2}{WL}}_{\text{Local}} + \underbrace{B_P^2 D}_{\text{Global}}$$

A Microdroplet Dispensing System

- Applications in photonics, molecular electronics, biosensors...
- Fluidic NEMS operated as a **bioplume**



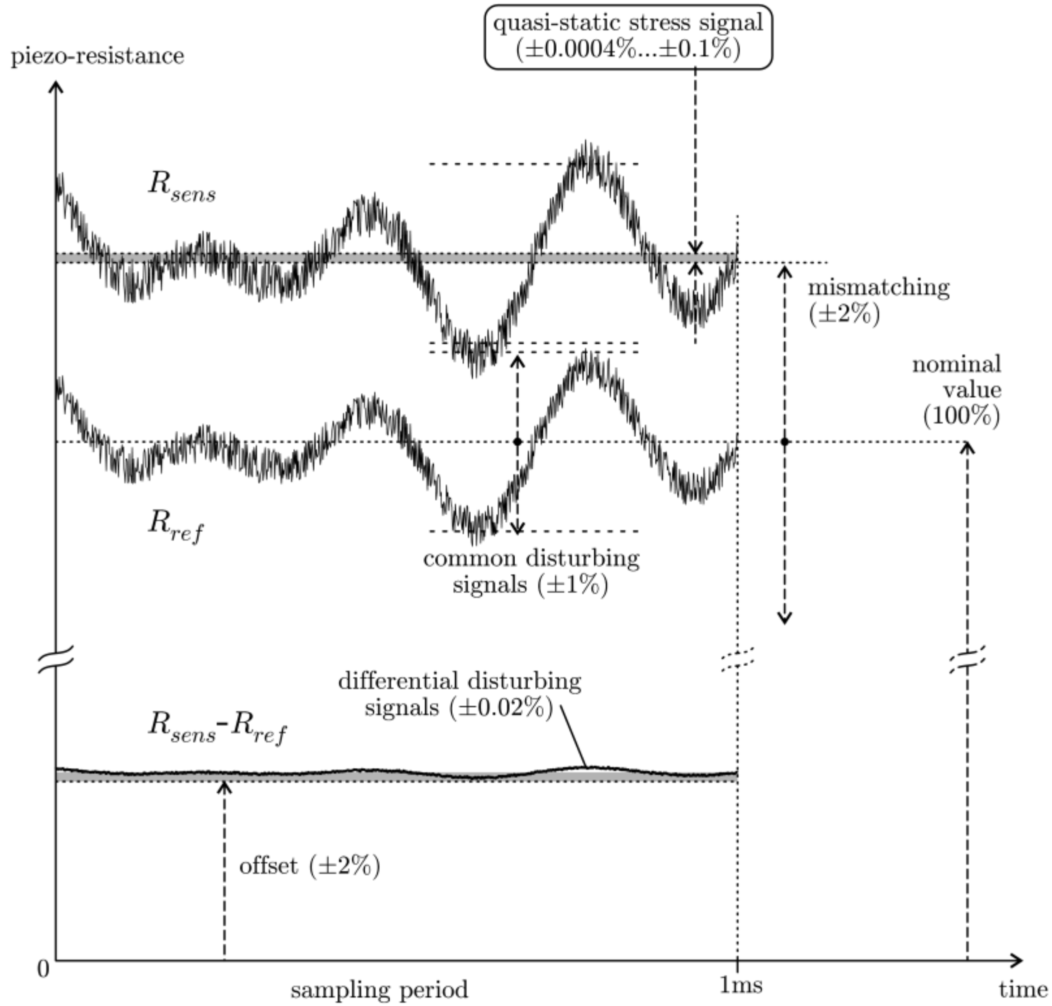
- Accurate **positioning** for microdoplet high uniformity
- Multi-channel digital ROIC for integrated **piezo-resistive** stress sensors:
  - **Low power** to prevent drying
  - **Low voltage** for single cell battery supply
- **Blind sensor** against interferences



Integrated Piezo-Resistors

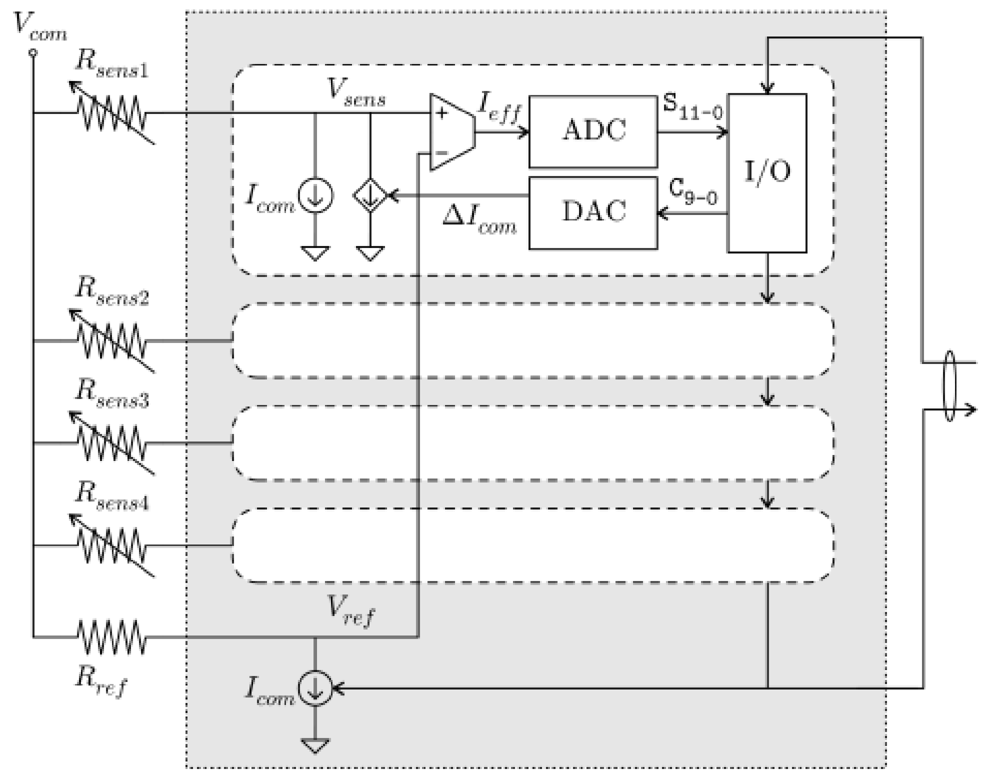
- **Differential** read-out of weak stress signal ±0.1% / ±0.0004% = 9bit
- **Process** corners ±20%

- 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



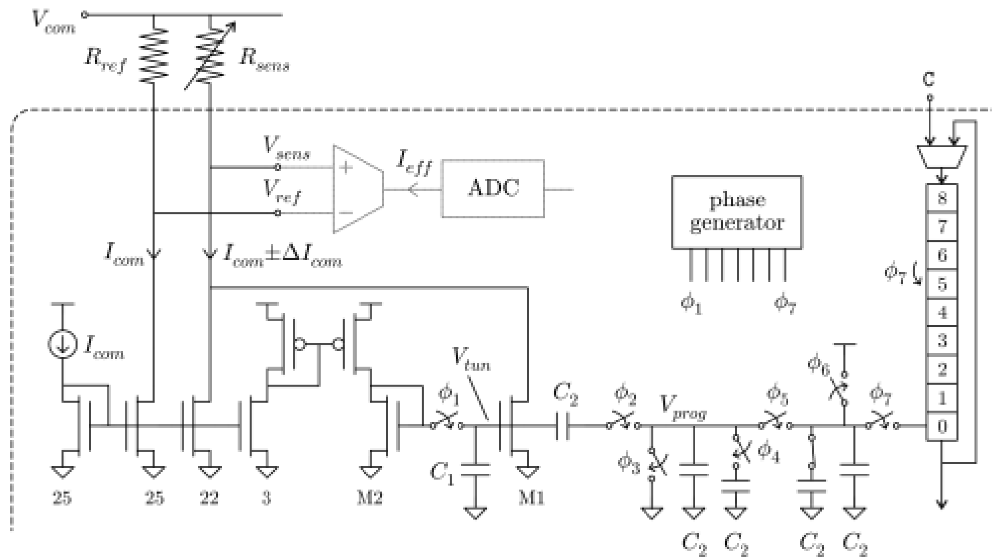
Multichannel ROIC Architecture

- Overall programmable **sensitivity** (I_{com})
- Differential **gain balancing** through sensor bias (ΔI_{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

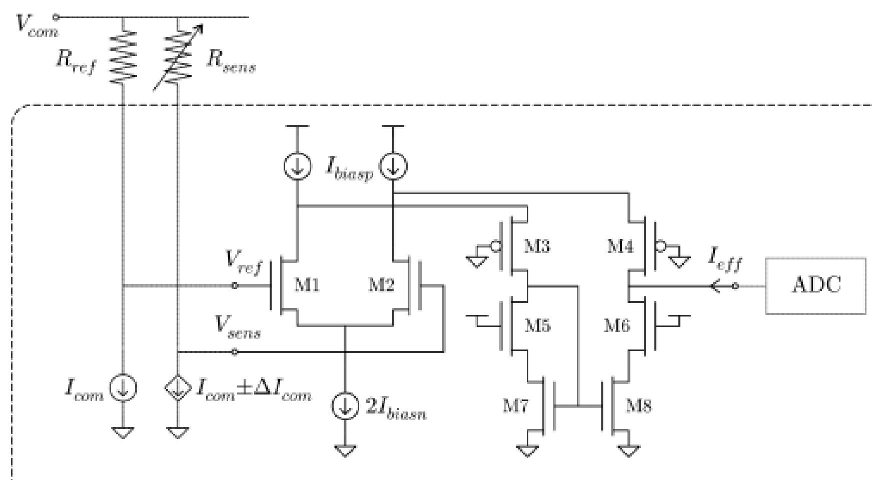


Low-Voltage and Low-Power CMOS Circuits

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

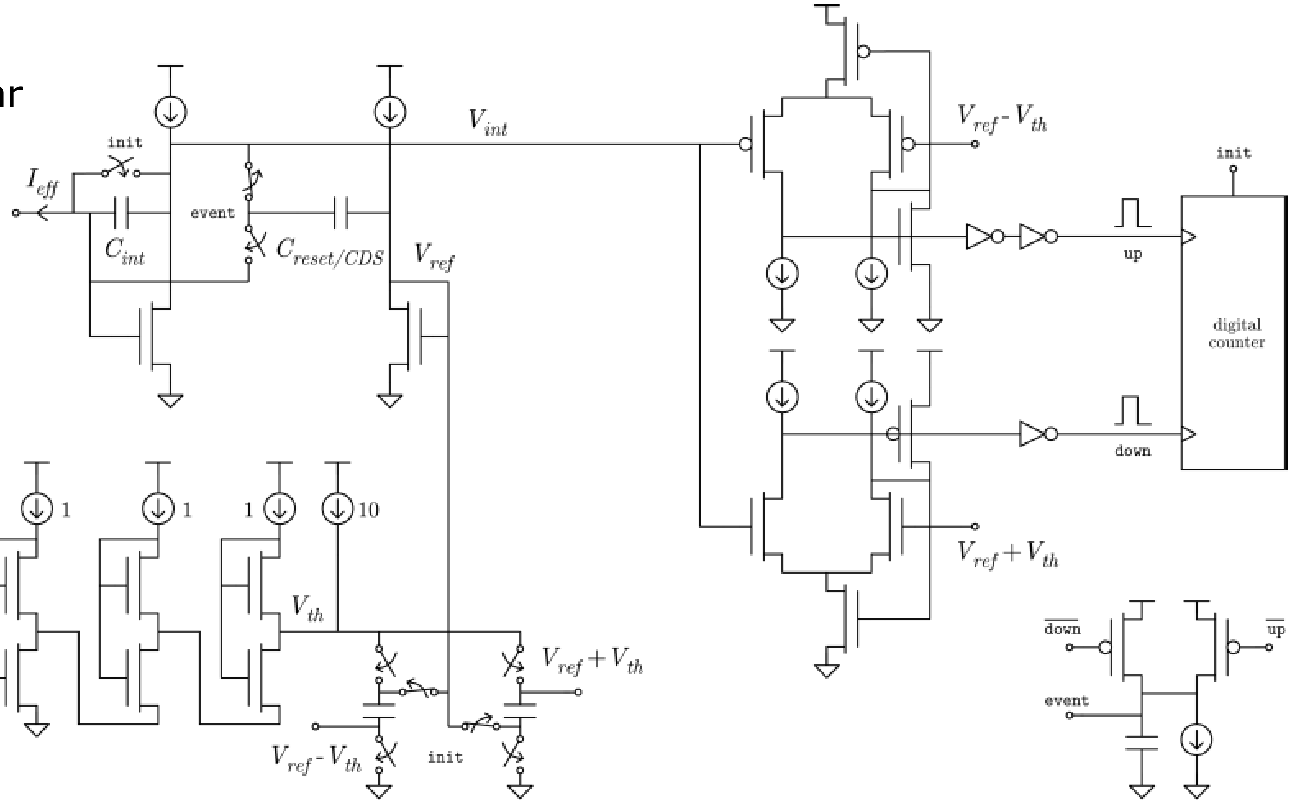


- Differential V to **single ended** I conversion:
  - Biased in weak inversion for best G_m/I_D and lowest technology sensitivity
  - Low equivalent input **noise** and high **CMRR**



Low-Voltage and Low-Power CMOS Circuits

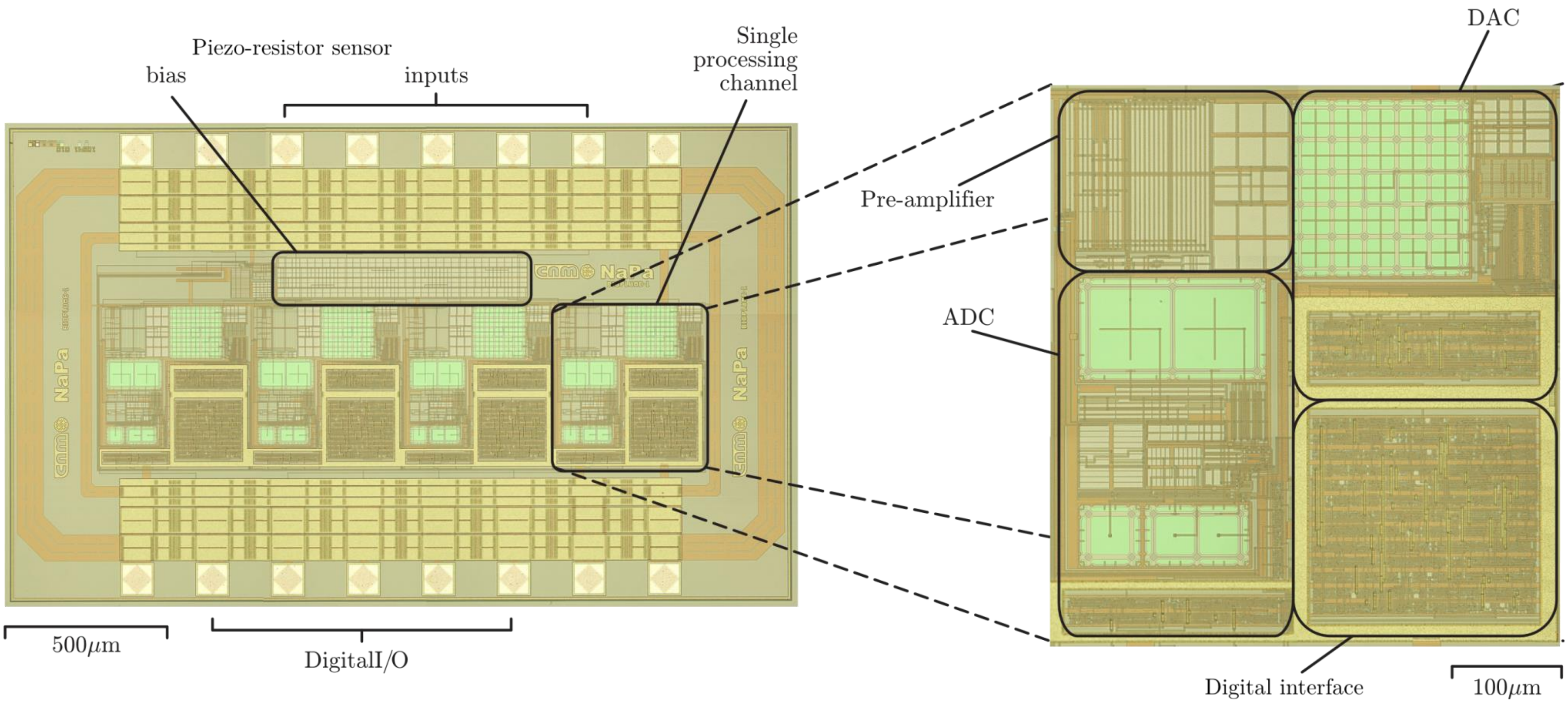
- **Spike-counting** ADC:
  - **Class-AB** window comparator
  - Built-in modular and **floating** threshold generator
  - **Compact** CTIA with correlated double sampling (**CDS**) for low-frequency noise reduction



Quad ROIC CMOS Integration

- 0.35µm 2P4M CMOS technology

2.4mm x 1.3mm (3.1mm^2)

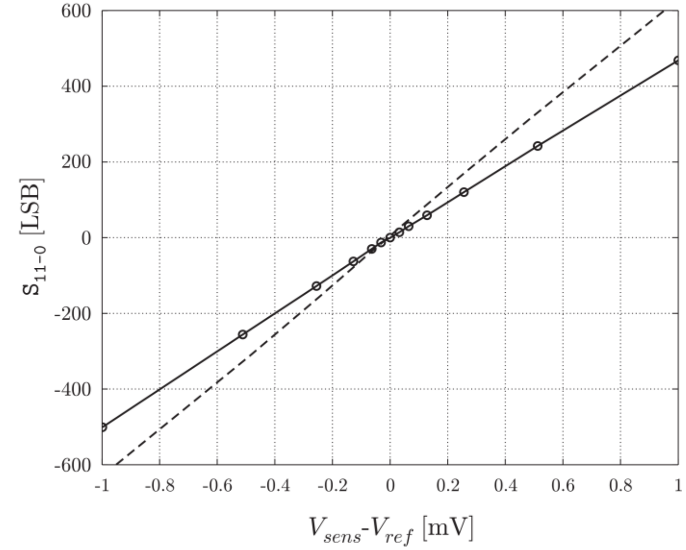


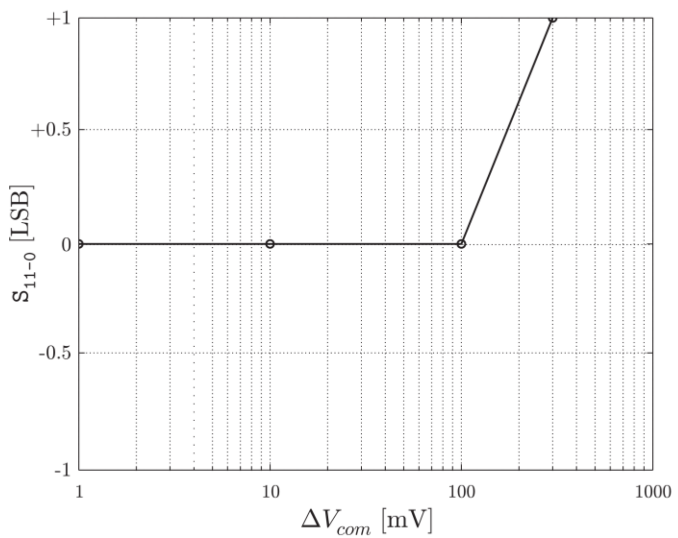
- Direct **wire-bonded** to integrated piezo-resistors substrate

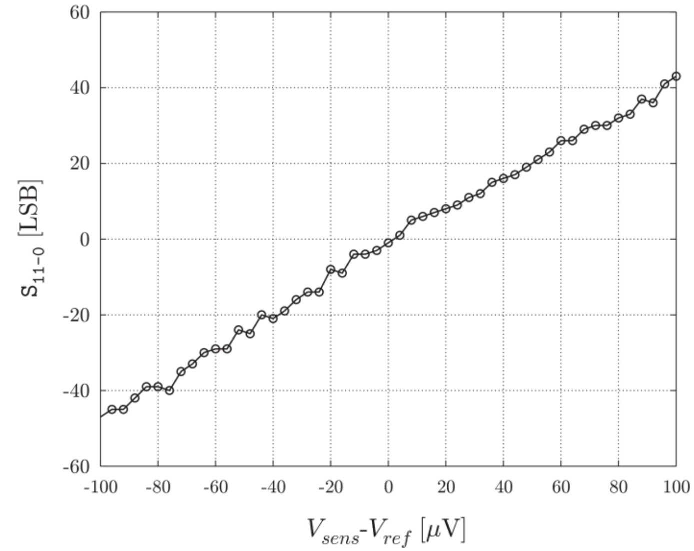
Experimental Results

$$\left|\frac{s_{11\text{-}0}}{\Delta R_{sens}/R_{sens}}\right| = \frac{G_m T_{int}}{C_{int} V_{th}} I_{com} R_{sens} \simeq 6\text{kLSB}/\%$$

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



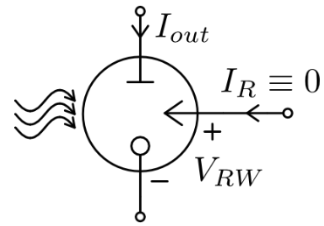




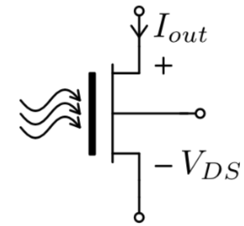
R. Durà et al., *A 0.3mW/Ch 1.25V Piezo-Resistance Digital ROIC for Liquid Dispensing MEMS,* IEEE Transactions on Circuits and Systems-I, 56:5(957-65), May 2009

Biasing Specials

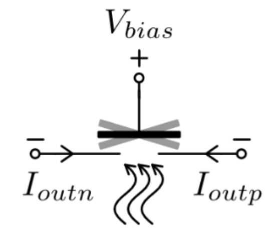
- Some sensors require ROIC to incorporate **control loops** for their proper DC biasing
- **Multiple ports** may be needed by ROIC to compensate for unavoidable parasitics
- When possible, **lock-in** operation is advised to strongly reduce equivalent noise bandwidth
- Indirect measurement through **time-domain** processing is a promising alternative



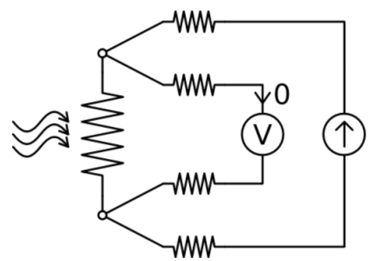
Electrochemical



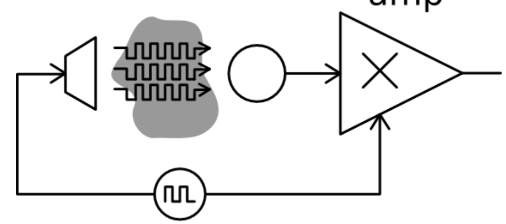
ISFET

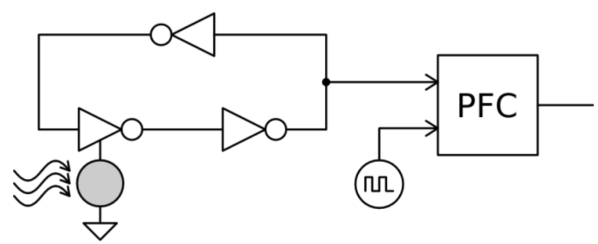


MEMS resonators



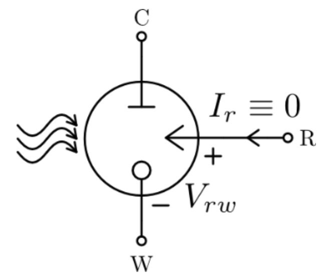
lock-in amp

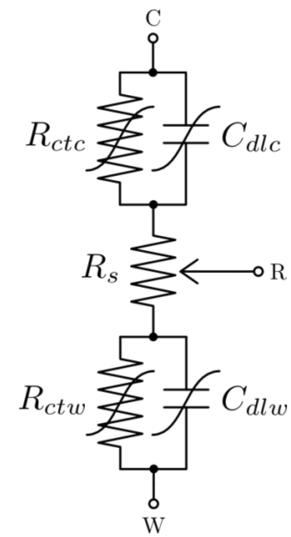


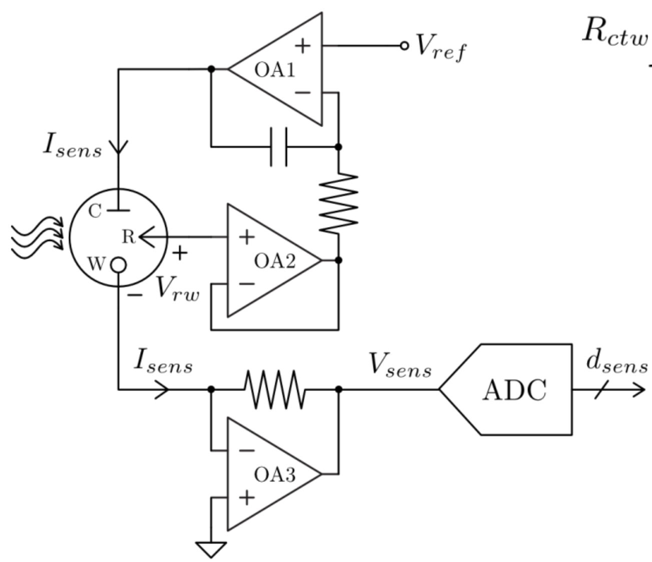


Integrated Electrochemical Sensors

- ▶ 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

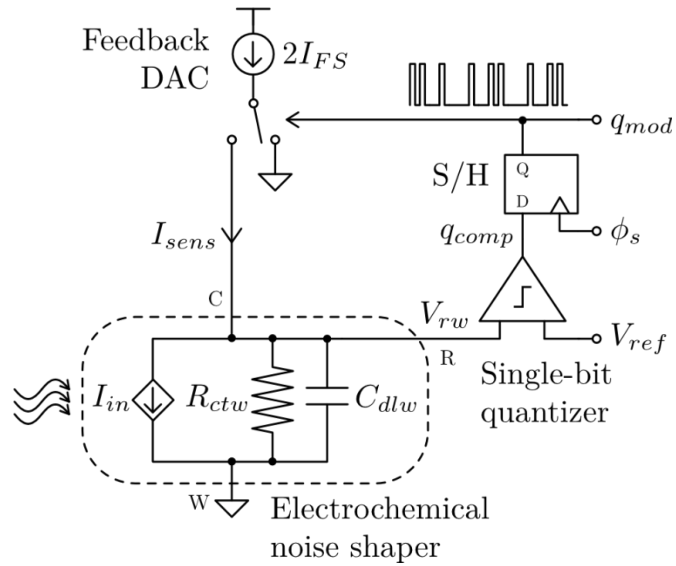


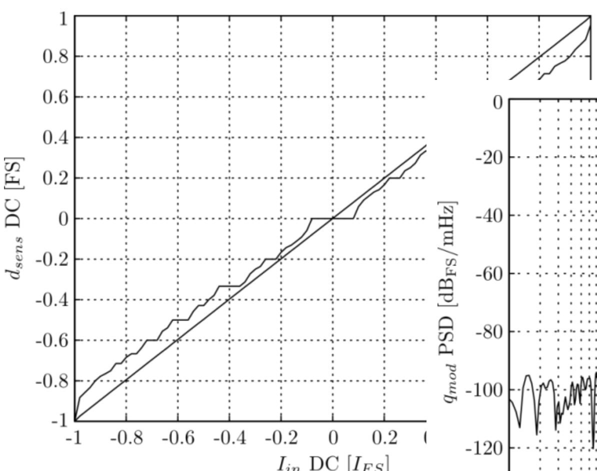




Mixed Electrochemical ROIC Architecture

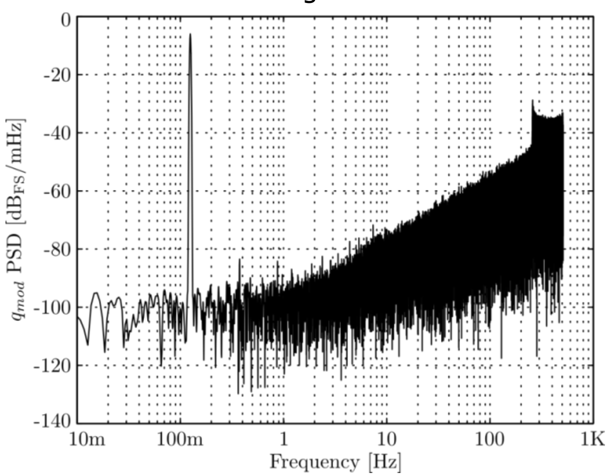
- Low-pass first-order single-bit CT **ΔΣ A/D modulator** with sensor in the loop:
  - Minimalistic **analog** circuits
  - **Low power** ROIC overhead respect to sensor itself
  - Accurate sensor dynamic **modeling** needed

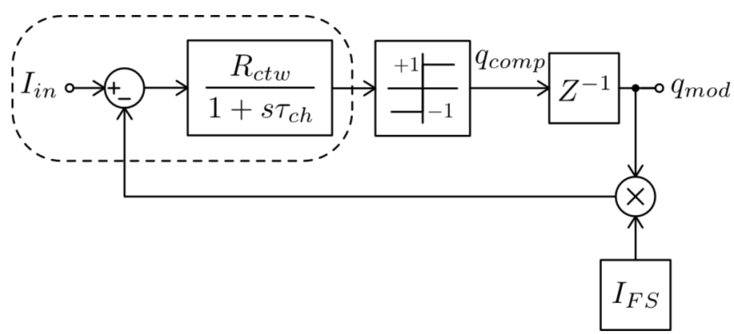




High oversampling against dead zones

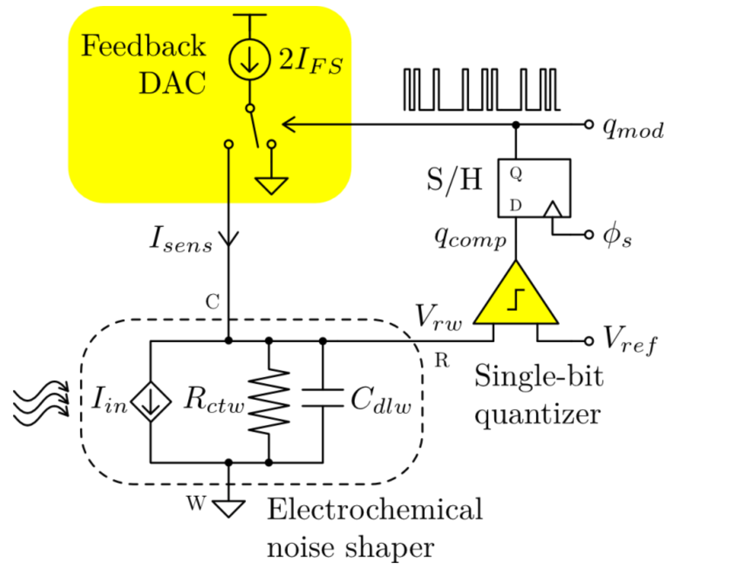
Thermal noise dithering against tonal behavior

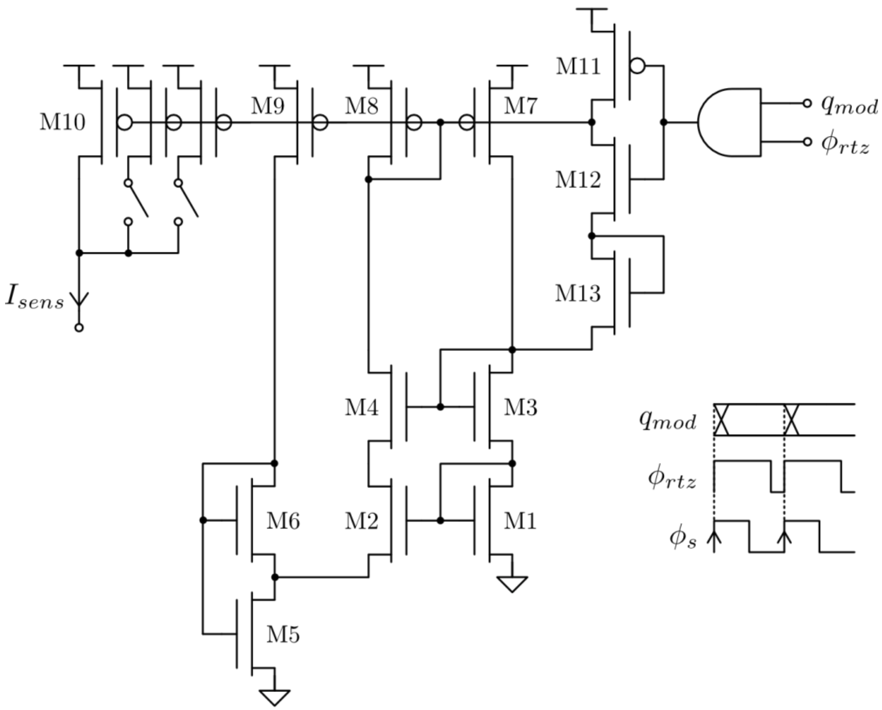


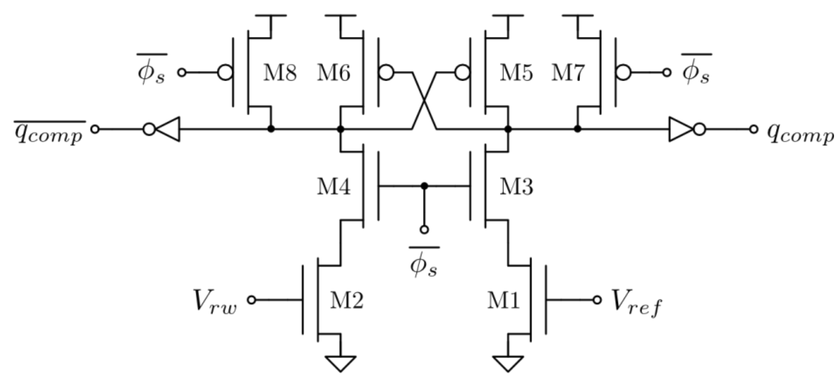


Low-Power All-MOS Circuits

- Two **analog blocks** only
- **Latched comparator** for 1bit quantization + **current reference** for 1bit feedback DAC



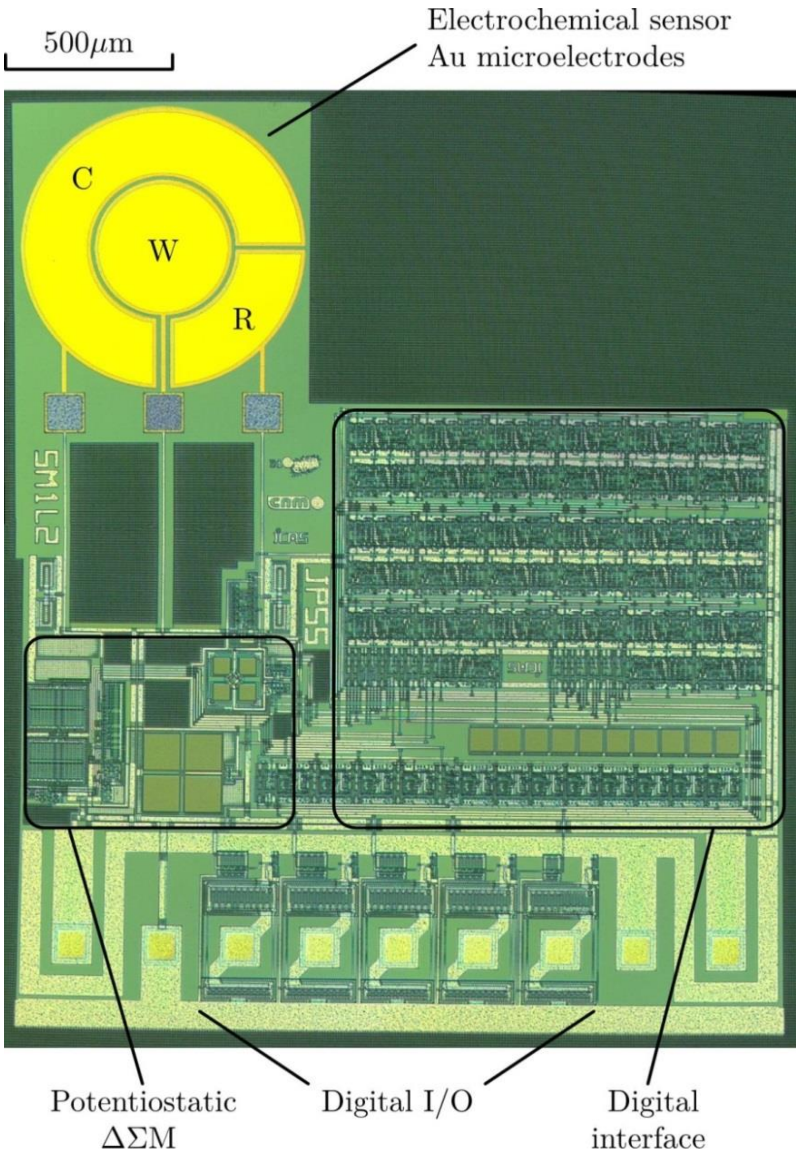




Monolithic CMOS Integration

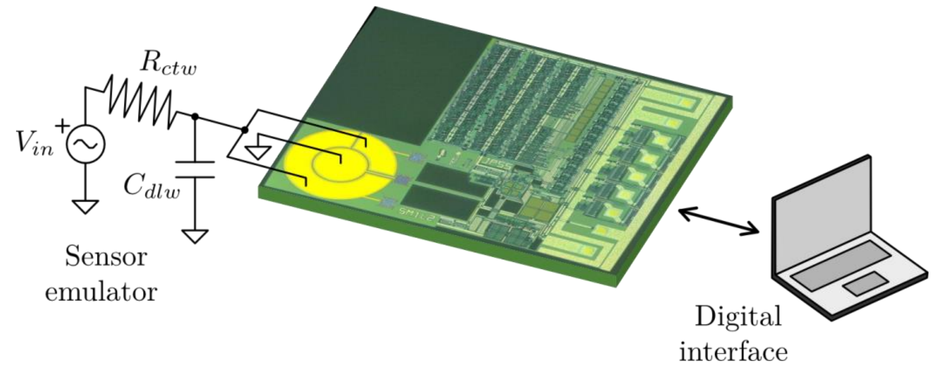
- IMB-CNM(CSIC) inexpensive 2.5µm 1M CMOS technology (**CNM25**)
- In-house sensor **Au post-processing** at wafer level
- 2.3mm x 2.8mm (6.4mm²)

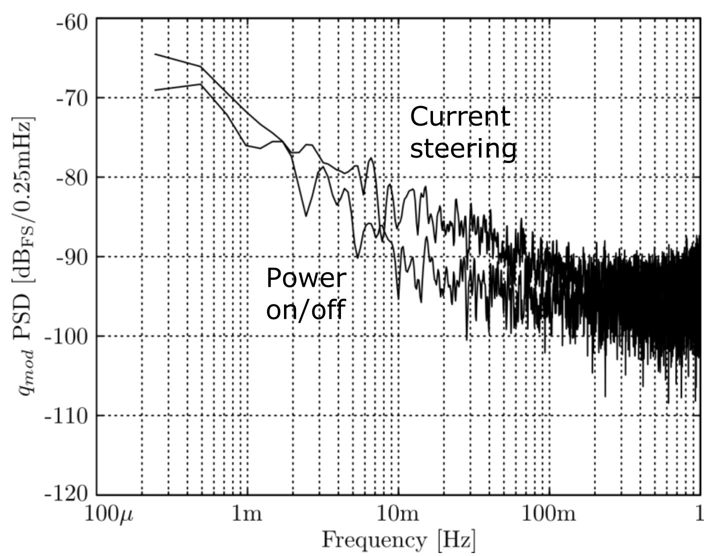
- **Low area** overhead of ΔΣ ADC
- **Digital only interface** for low-pass filtering and programming of potentiostatic voltage and current full-scale
- Overall **25µW** at **+5V**

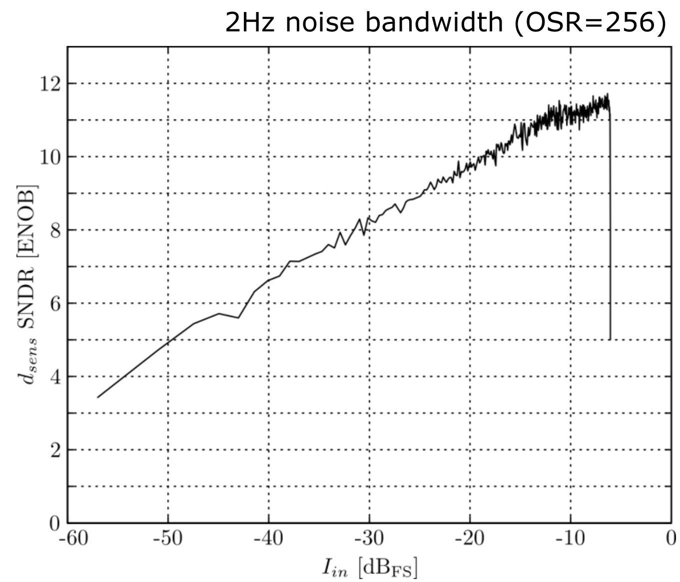


Experimental Results

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

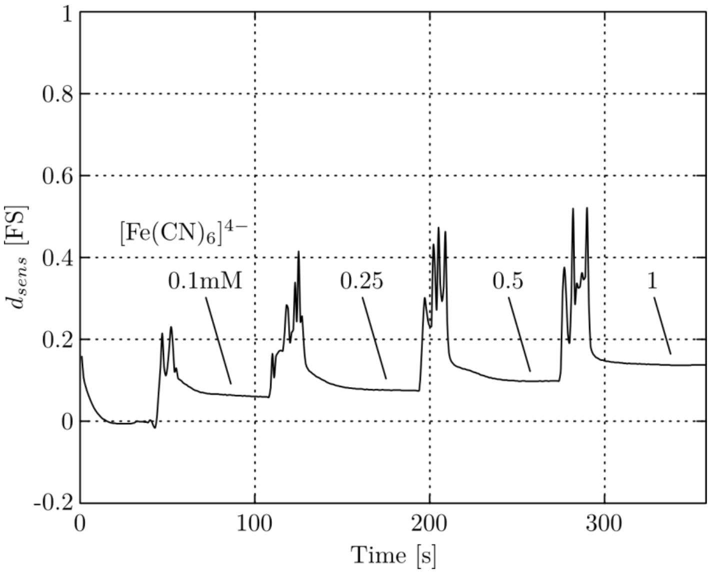


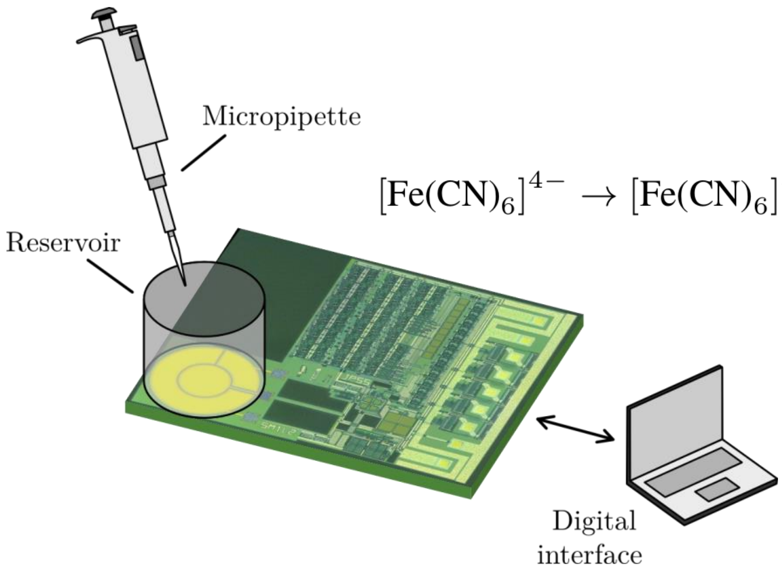




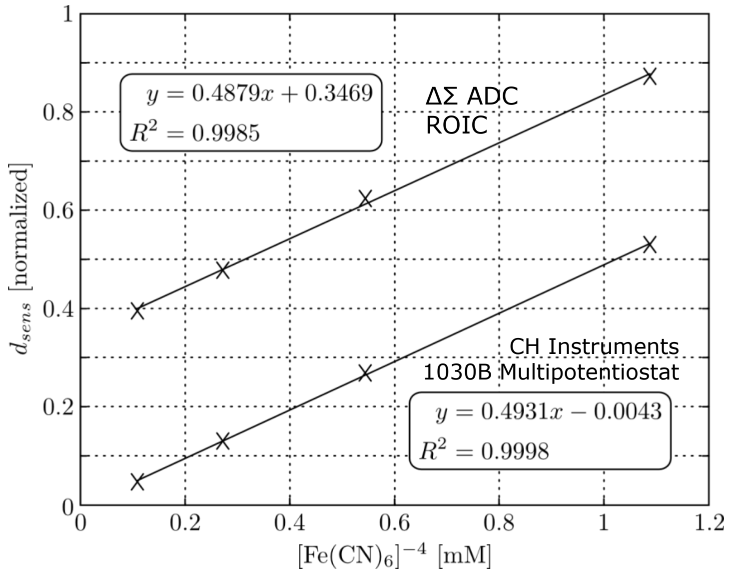
Experimental Results

- **Electrical** tests show good enough dynamic range to not limit measurements
- **Electrochemical** tests return comparable performance to lab desktop equipment





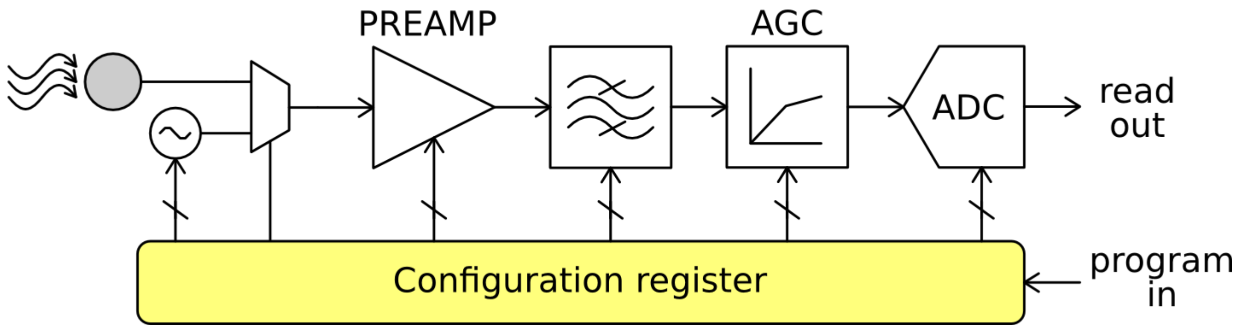
$$[Fe(CN)_6]^{4-} \rightarrow [Fe(CN)_6]^{3-} + 1e^-$$



S. Sutula et al., *A 25-uW All-MOS Potentiostatic Delta-Sigma ADC for Smart Electrochemical Sensors*, IEEE Transactions on Circuits and Systems-I, 61:3(671-679), Mar 2014

Flexibility as a Must

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

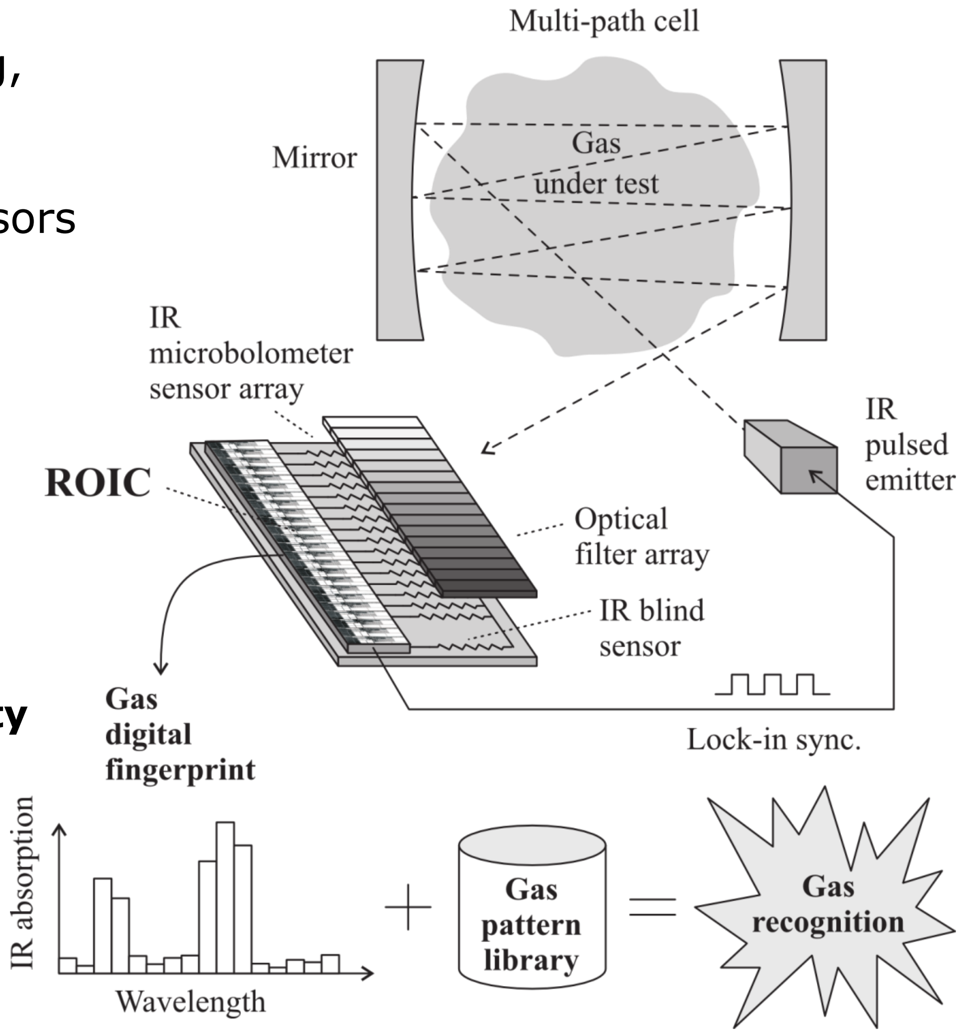


- **Single** ROIC can fit several sensor designs
- **Built-in test** mechanism to screen smart sensors before post-processing or packaging
- Compensate for **sensor aging**
- Independent optimization of **dynamic range** for each stage
- If available, **non-volatile** memory (Flash, OTP...) to store configuration
- Specially useful when sensor or application **specifications** are incomplete!
- **Extra design** work for making each stage configurable

IR Spectroscopic Gas Recognition System

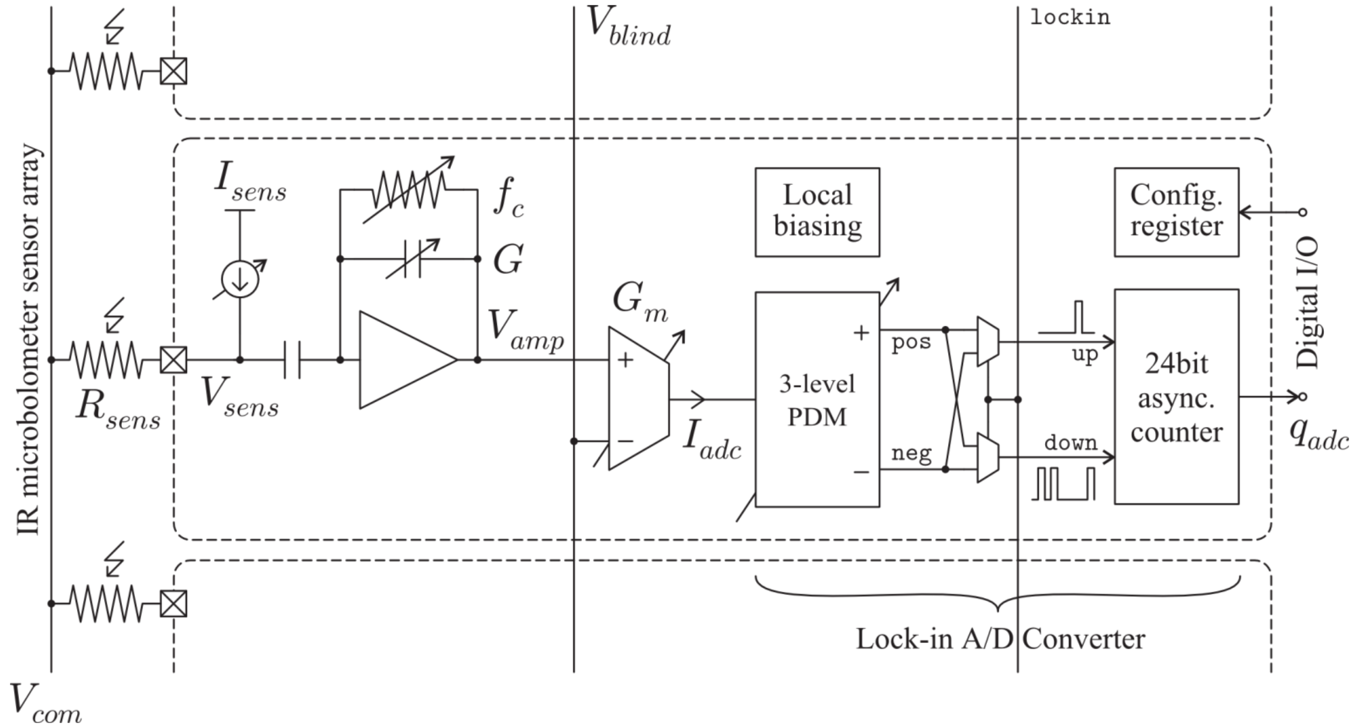
- Applications in toxic gas warning, environmental monitoring…
- Thermal **µbolometer** LWIR sensors
- Multipath optical cell to amplify gas IR **absorption** effect

- Blind reference and lock-in demodulation for **high accuracy** read-out
- Sensor deviations and mixed IR technologies need **high flexibility** for each channel
- **Low power** ROIC to avoid thermal drifts of IR sensors



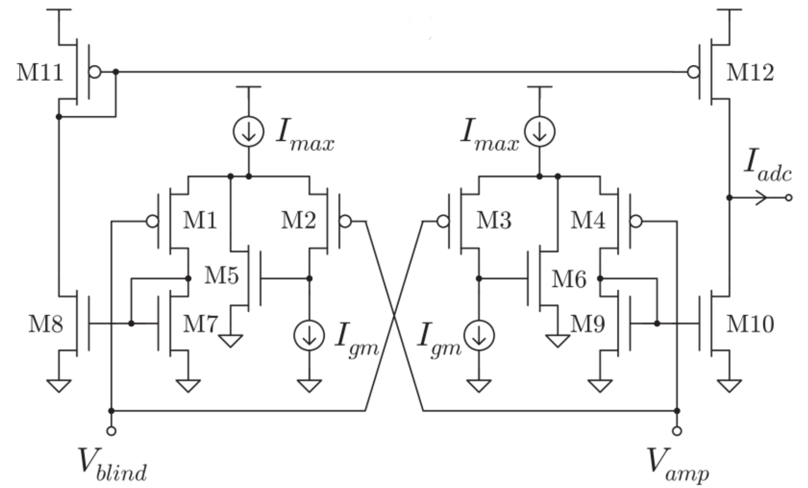
ROIC Channel Module

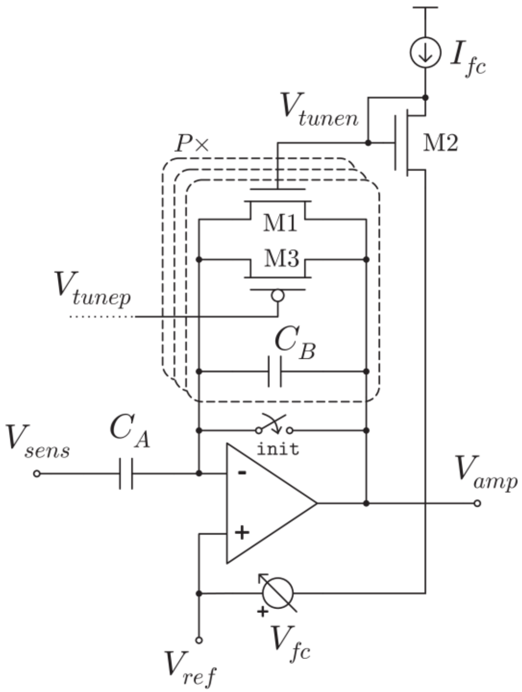
- **Sub-Hz** high-pass pre-amplification
- **5-parameter** independent programmability per channel!
- Dedicated **blind channel** for cancellation of common disturbing signals
- ADC with **digital lock-in** demodulation



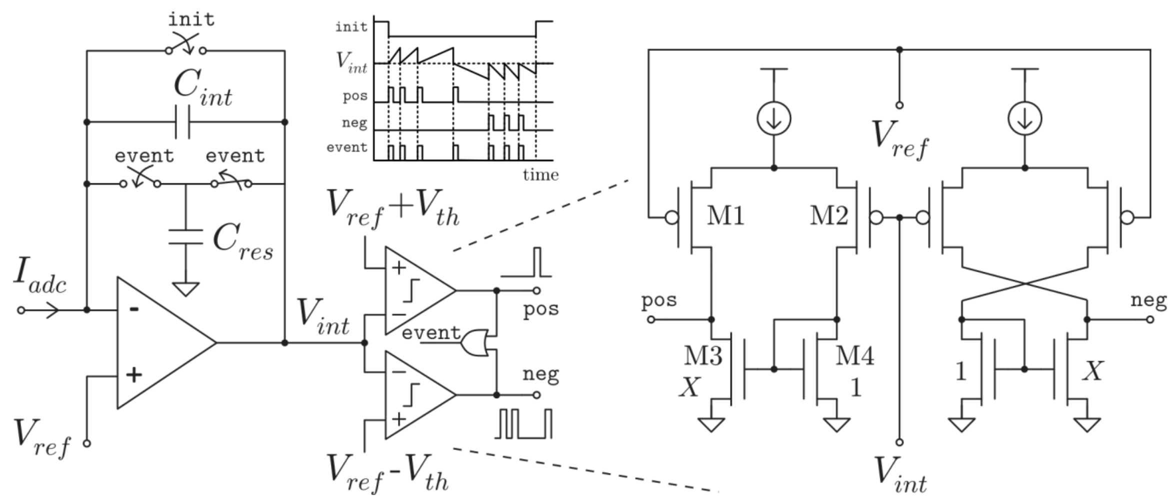
Low-Power Channel Circuits

- Fully integrated sub-Hz variable **corner** & **gain** pre-amplifier
- **Highly linear** differential transconductor with soft limiter



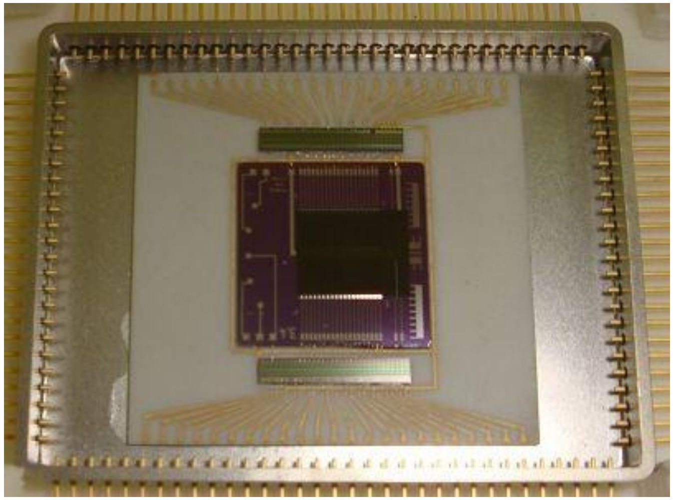


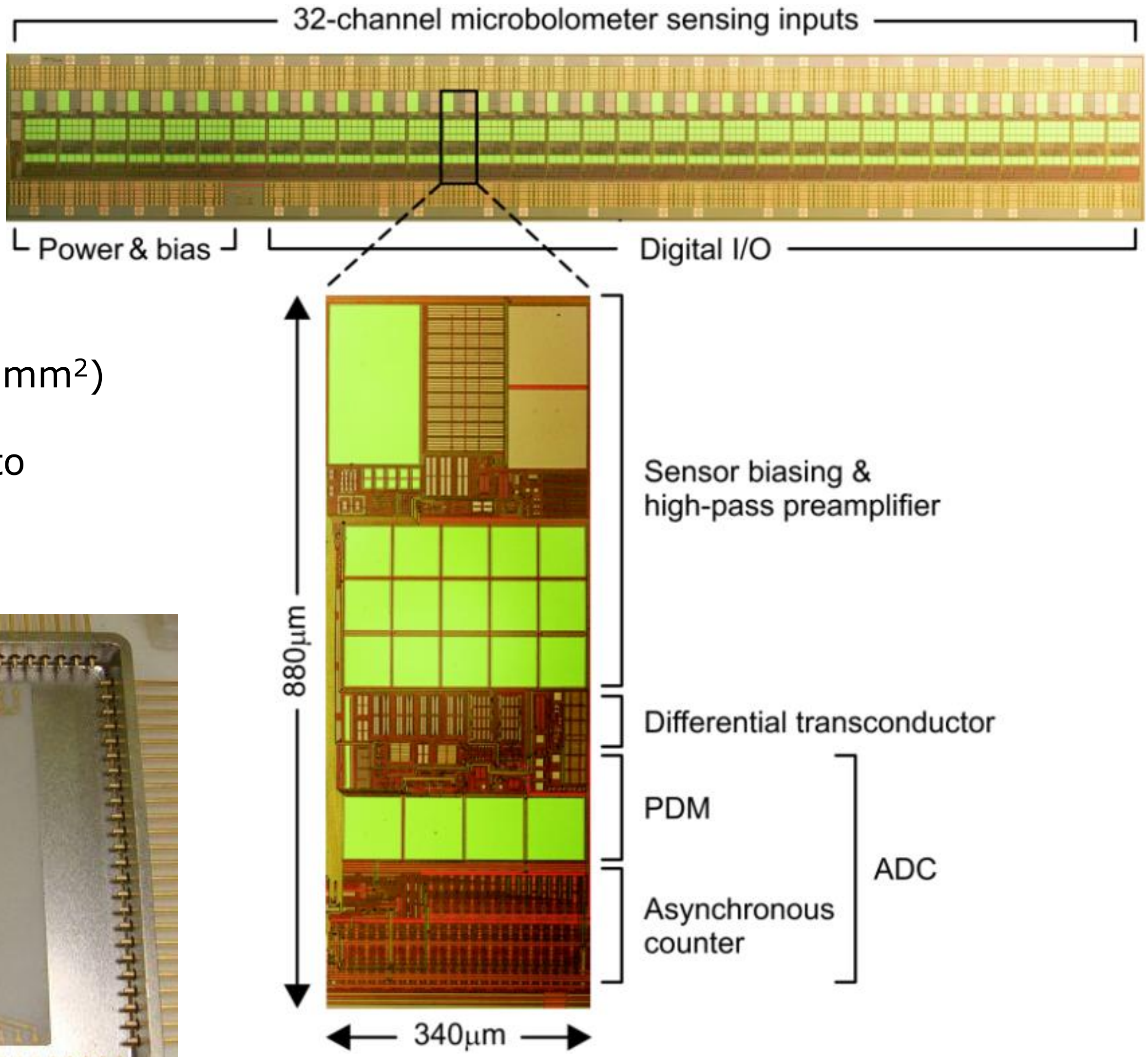
- Integrate & fire PDM with **3-level** quantizer



32-Channel ROIC

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

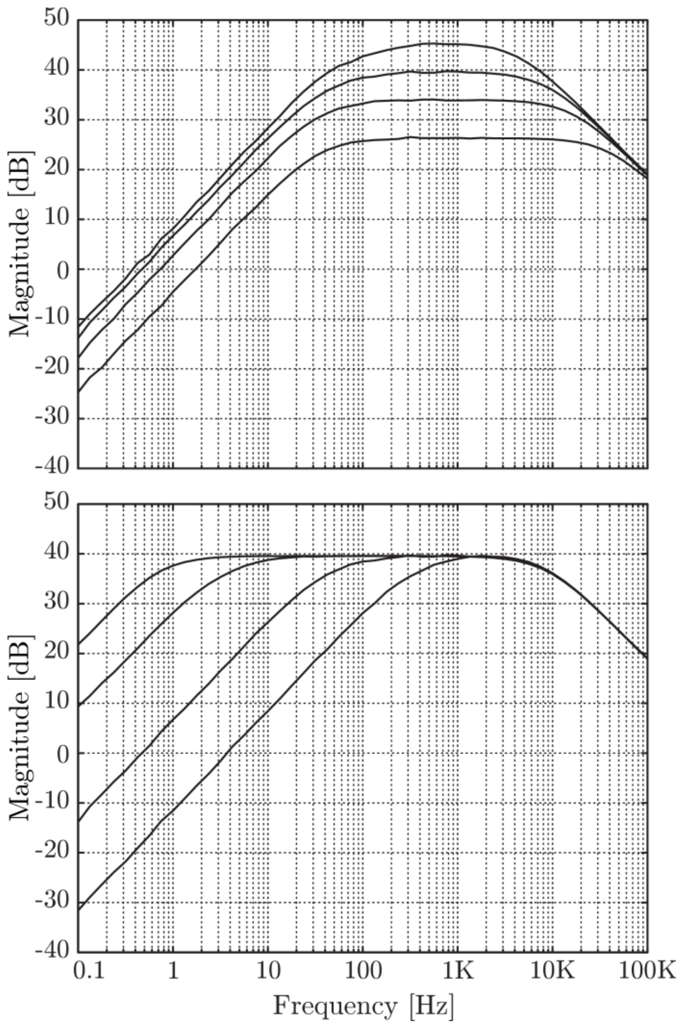




Experimental Results

- **120µA/ch** at +3.3V
- Full **programmability**

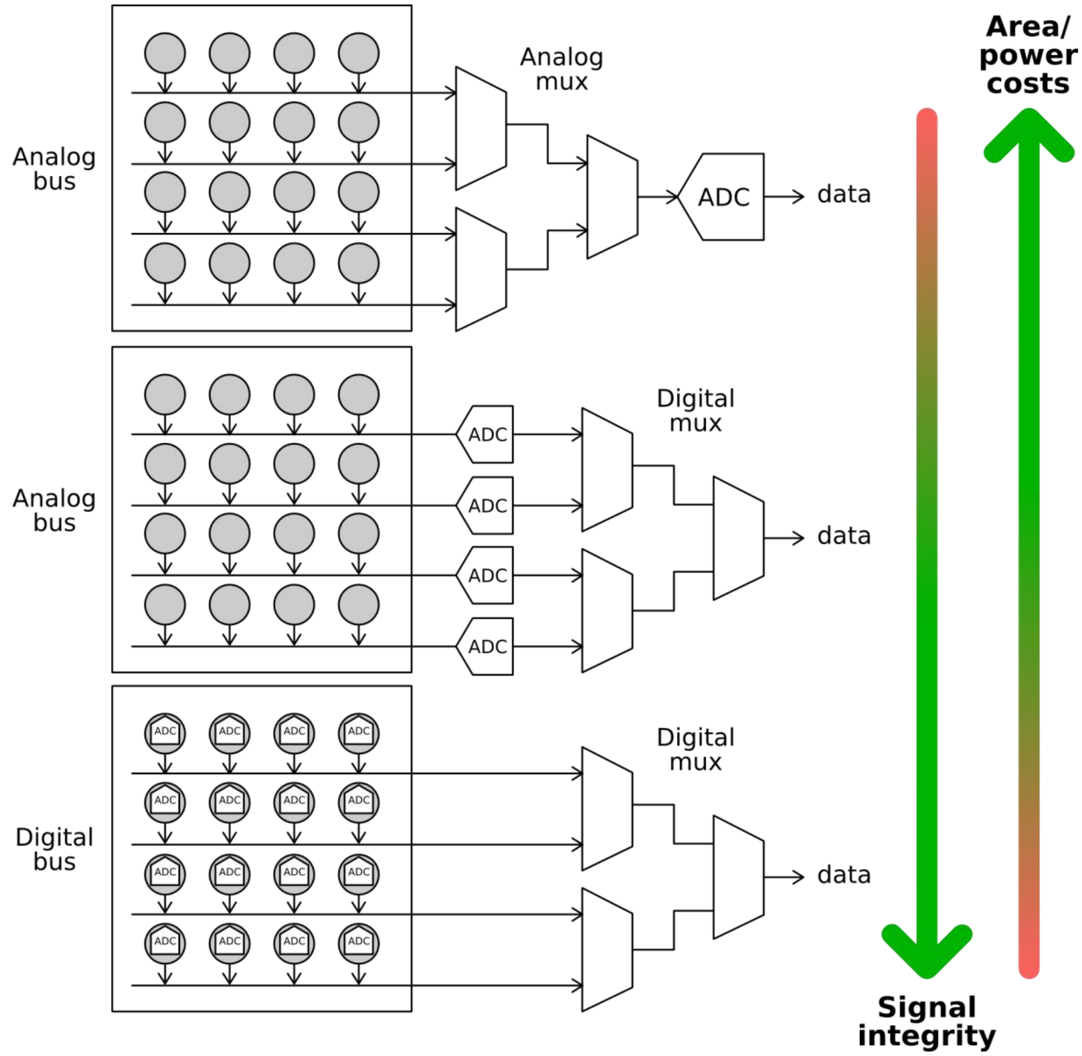
Parameter	Value	Units
I_{sens}	1 to 10	μA
f_c	0.75±0.10 3.6±0.4 49±8 389±76	Hz
G	26±0.1 34±0.1 40±0.1 45±0.1	dB
G_m	18 25 36 45	μS
$1/C_{int}V_{th}$	1.7 0.8	Hz/pA
$V_{sensneq}$@10Hz	250	$nV_{rms}/\sqrt{Hz}$
THD V_{amp}<300mV$_{pp}$	<0.1	%
Crosstalk	<0.5	LSB



S. Sutula et al., *A 400uW Hz-Range Lock-In A/D Frontend Channel for Infrared Spectroscopic Gas Recognition*, IEEE Transactions on Circuits and Systems-I, 58:7(1561-8), Jul 2011

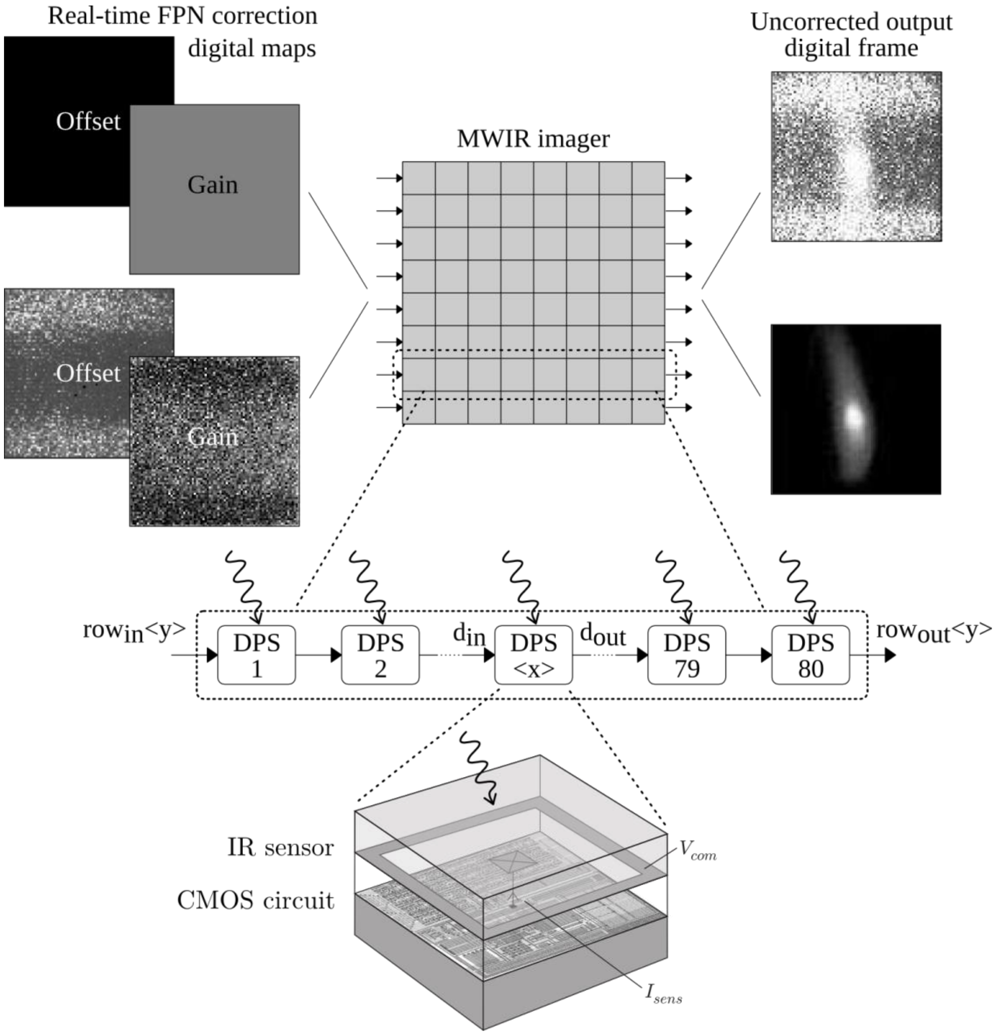
Massive Parallel Processing

- 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)



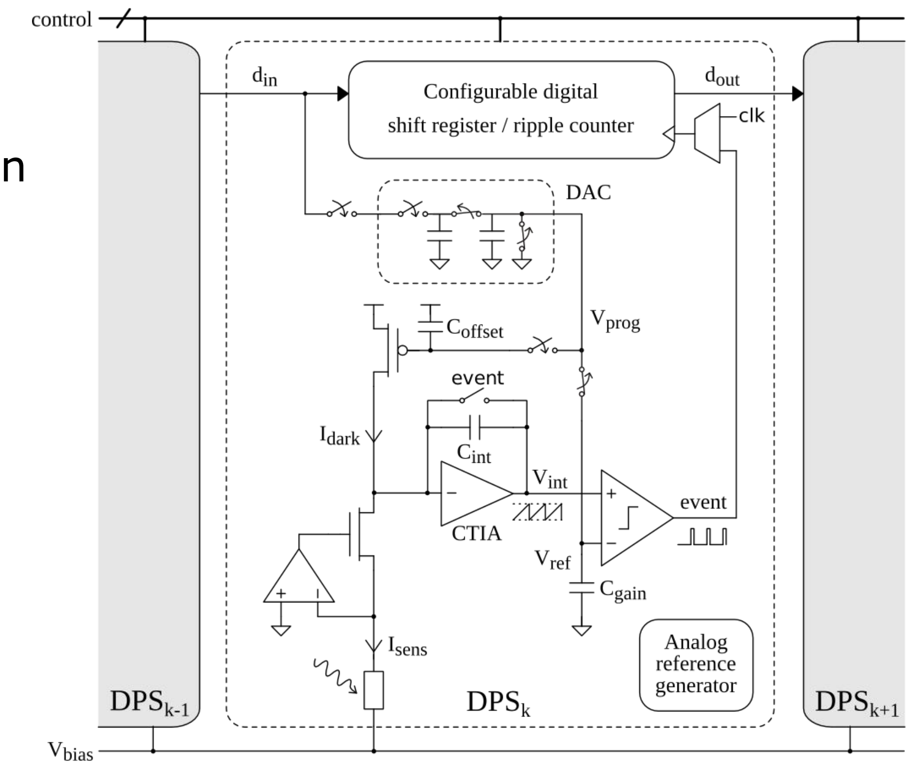
High-Speed Uncooled IR Digital Imager

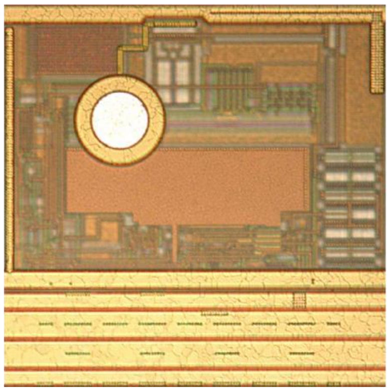
- Applications in strategic equipment, production quality control...
- Photoconductive **PbSe MWIR** sensors post-processed by VPD on top of CMOS
  - High **frame rate** achievable at room temperature
  - High fixed pattern noise (**FPN**)
  - High speed **multiplexing** spec at focal plane array (FPA) 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





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- ▲ Sensor **capacitance** compensation
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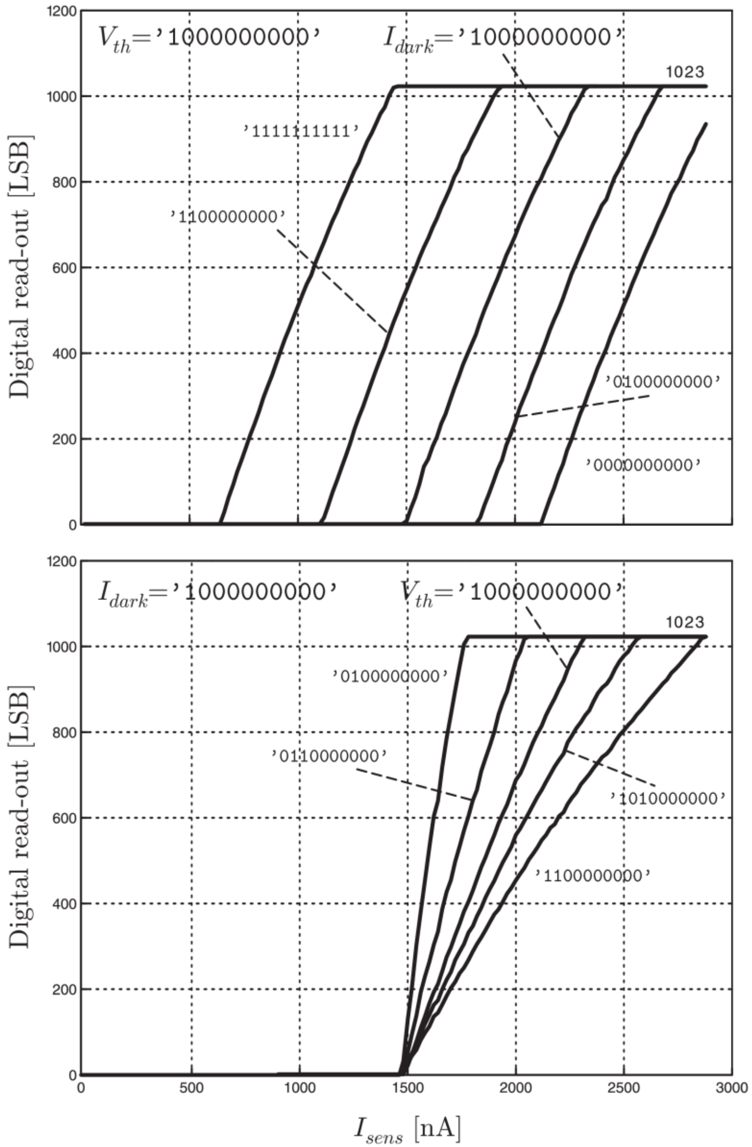
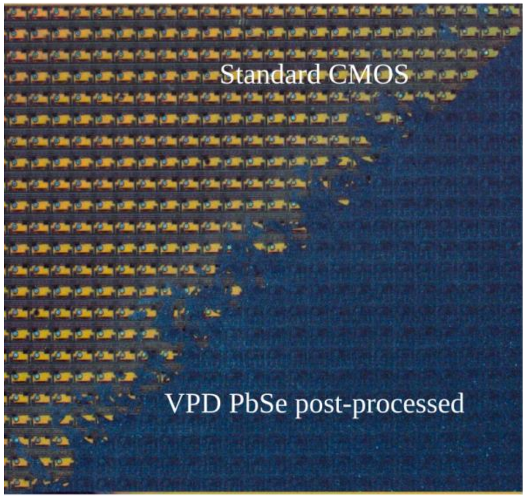
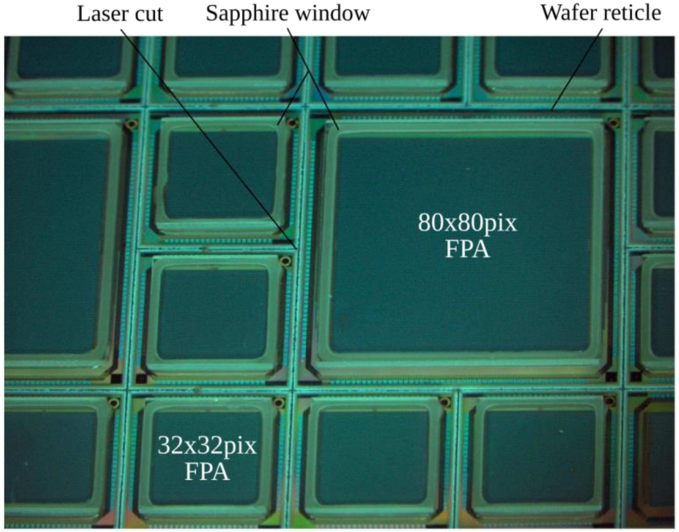
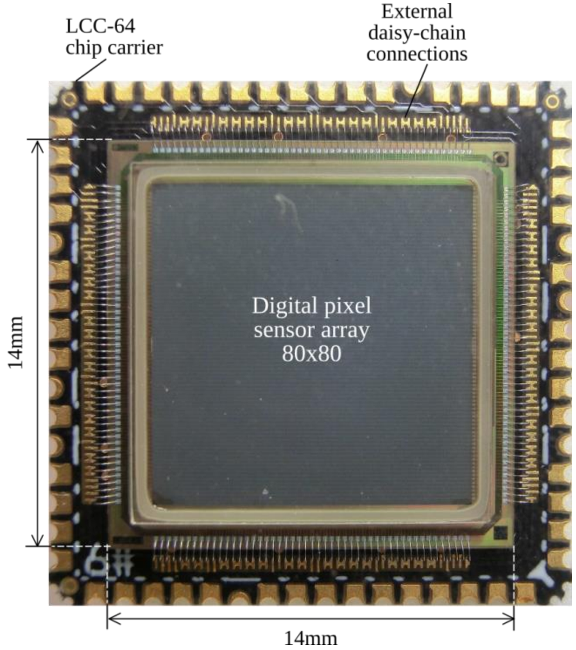


Sensor Integration at Wafer Level

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



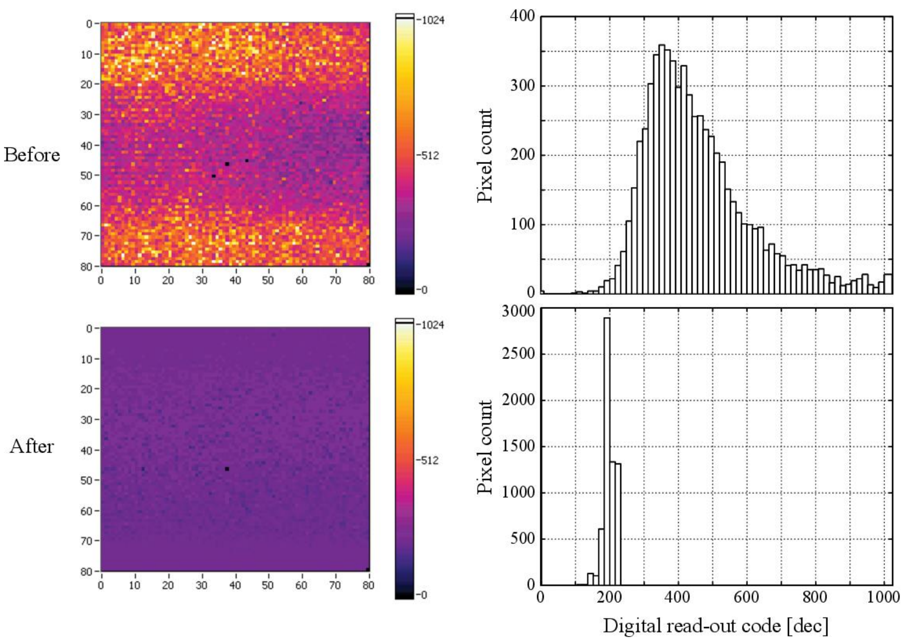




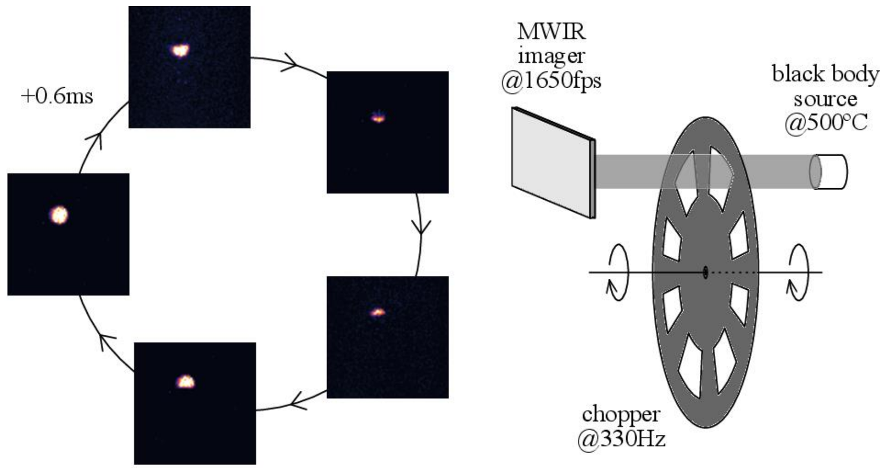
- Access to sensor common bias terminal through ROIC pads

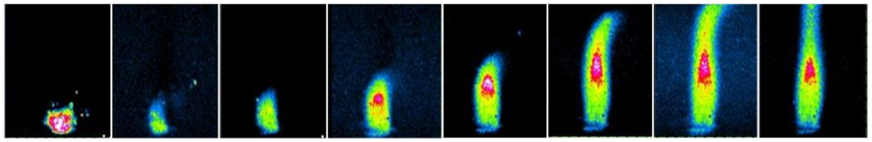
IR Test Results

- In-pixel **full FPN** compensation



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

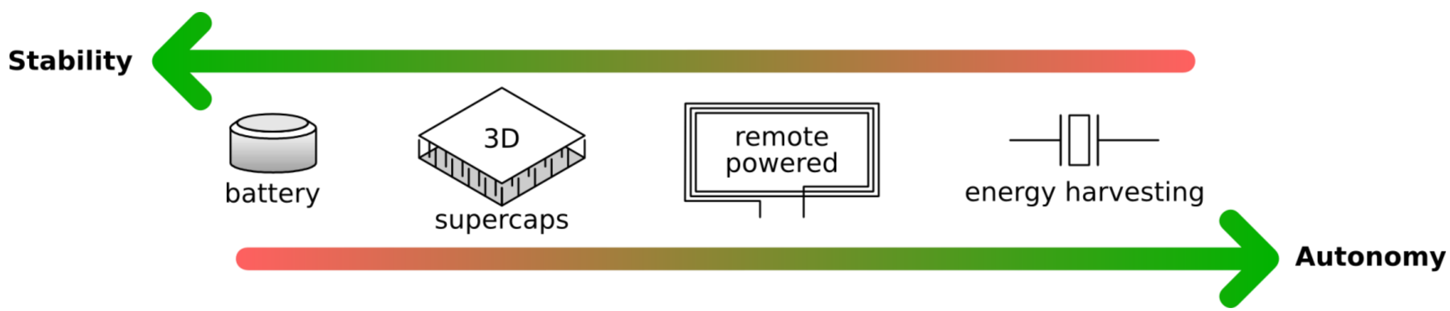




J. Margarit et al., *A 2-kfps Sub-uW/Pix Uncooled-PbSe Digital Imager with 10-bit DR Adjustment and FPN Correction for High-Speed and Low-Cost MWIR Applications,* IEEE Journal of Solid-State Circuits, 2015, accepted

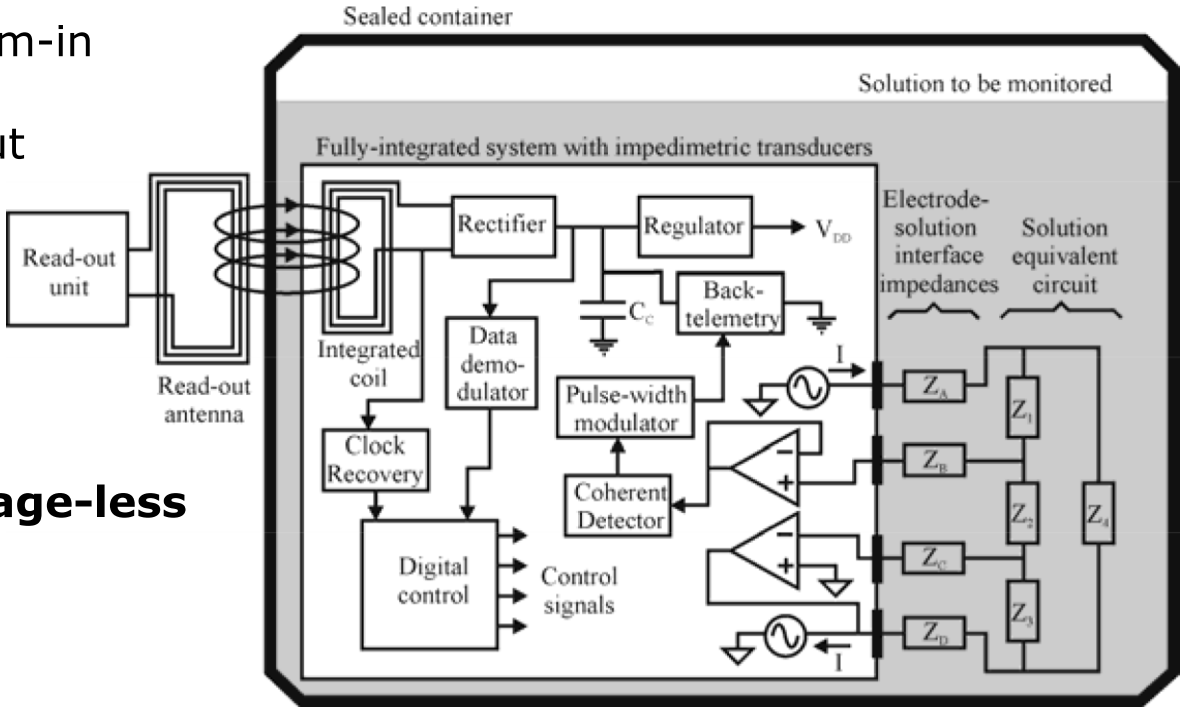
Power-Aware Design

- 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?



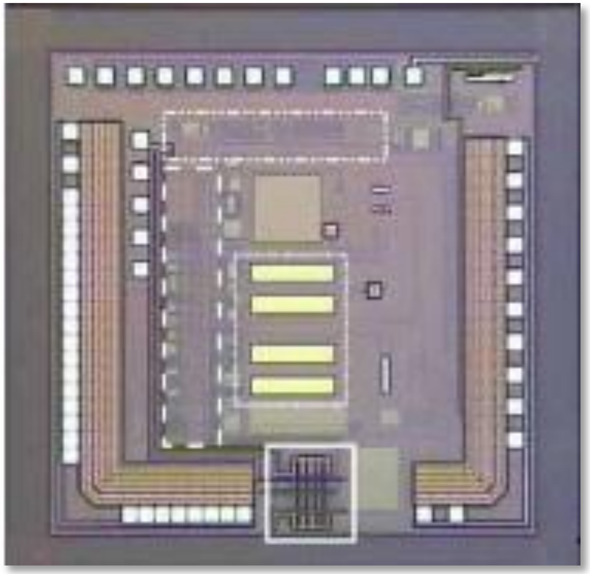
Remote Powered Impedimetric Sensor

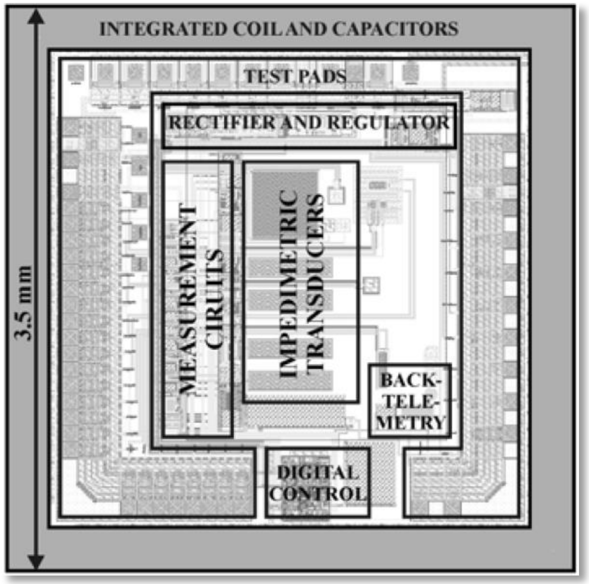
- Applications in chemical industry control and biosensors...
- 13.56MHz ISM near field inductive coupling for **remote power** supply
- **Power ASK** for program-in
- **Load PWM** for read-out
- Complex I/Q impedance measurements for solution **conductivity** and **permittivity** monitoring
- Contact-less and **package-less**



CMOS Integration

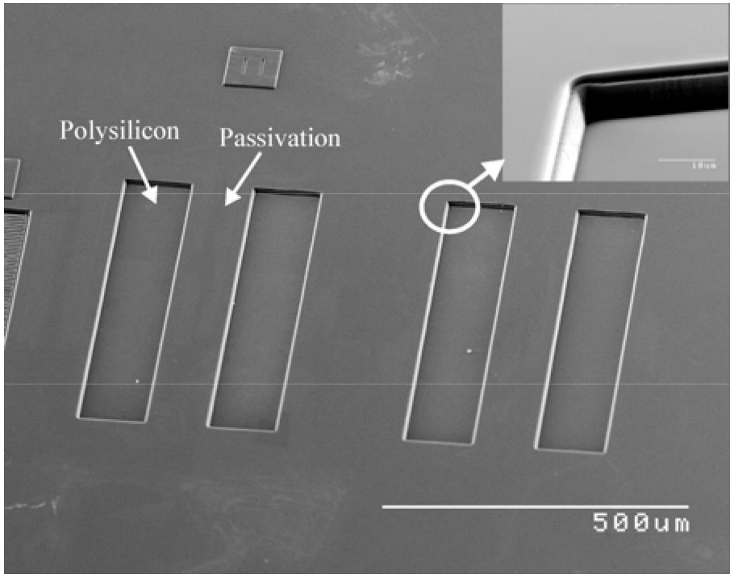
- 0.35μm 2P4M **high-voltage** CMOS technology
  - 3.5mm x 3.5mm (12.25mm^2)
  - 3M **power coupling** coil (L~8μH, Q~1) and supply capacitor (C~2nF) at periphery
- Number of turns optimized for maximum **supply voltage** and out-band **self-resonant** frequency
- Pads for prototype testing purposes only

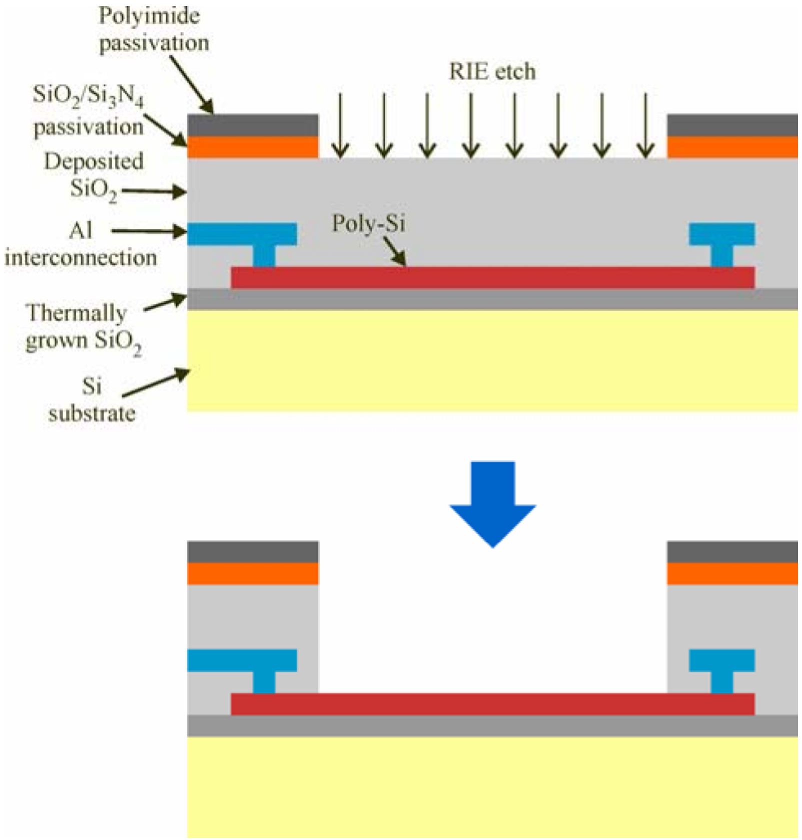




Lithography-Less Post-Processing

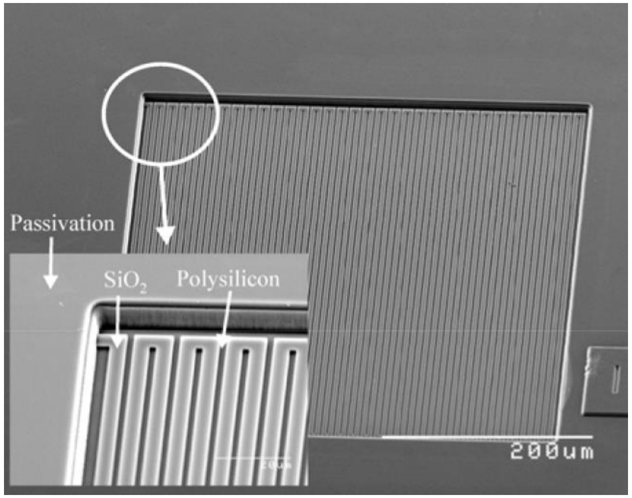
- Poly-Silicon material + native oxidation (3nm) to improve microelectrode **reliability**
- **4-microelectrode** by CHF_3-based reactive ion etching (**RIE**)

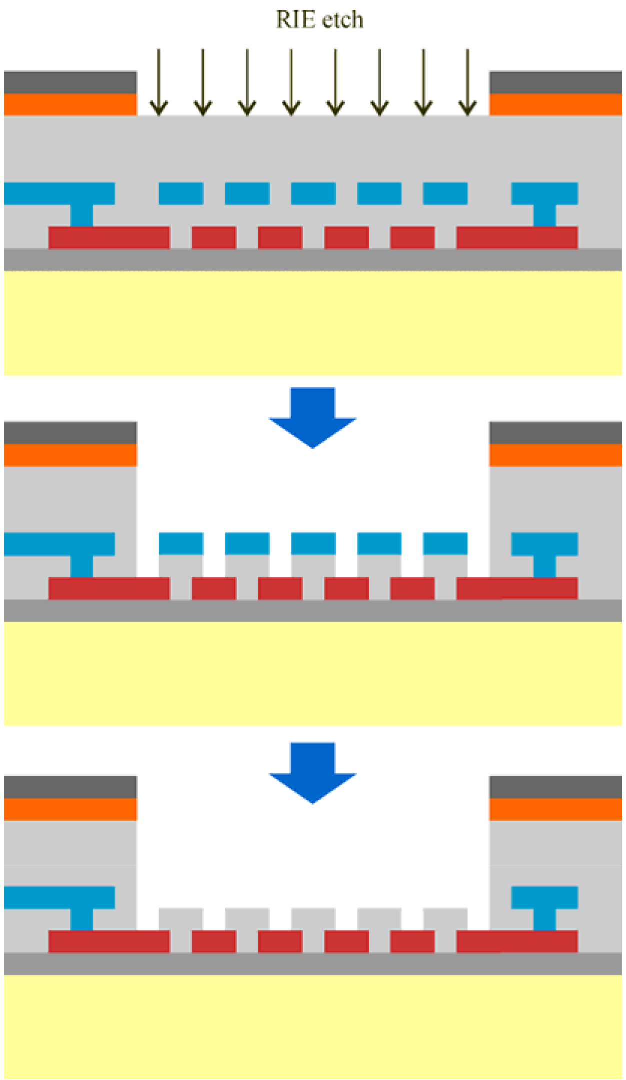




Lithography-Less Post-Processing

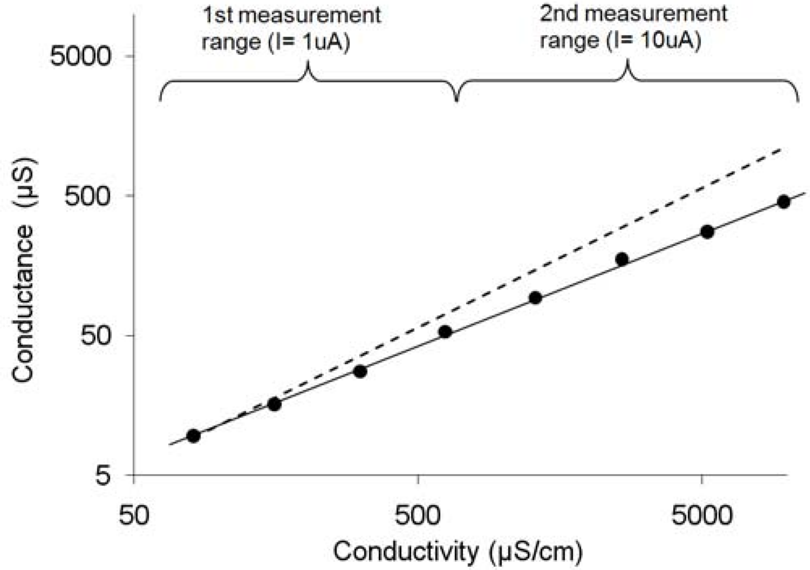
- Poly-Silicon material + native oxidation (3nm) to improve microelectrode **reliability**
- **4-microelectrode** by CHF_3-based reactive ion etching (**RIE**)
- **Interdigitated** 2-microelectrode by RIE + 'piranha' (H_2SO_4) solution



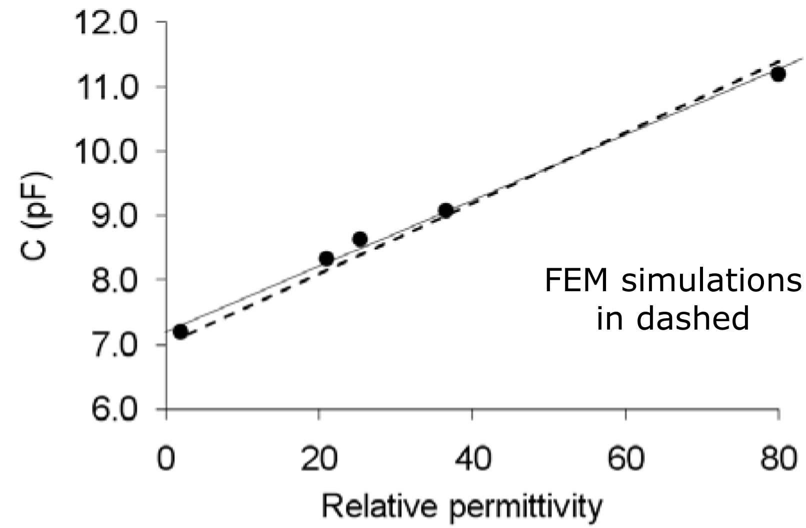


Experimental Results

- Remote power **5mW** at **3mm** (up to>10cm with external resonator)
- Complex impedance measurement at **13kHz** (10kHz to 100kHz)



4-microelectrode



Interdigitated
2-microelectrode

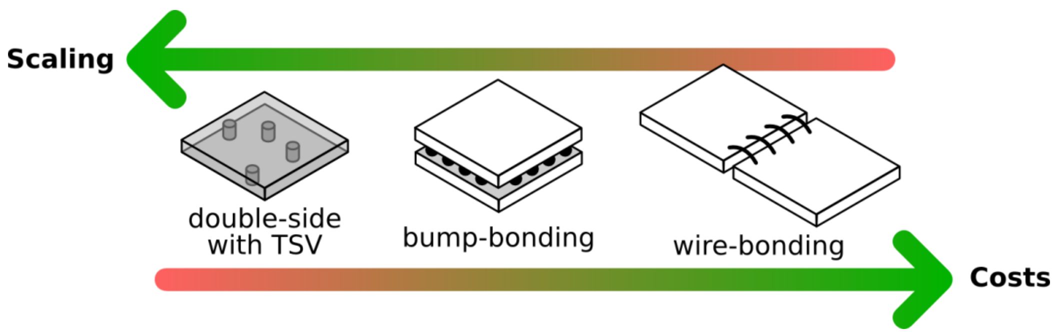
F. Segura-Quijano et al., *Towards Fully Integrated Wireless Impedimetric Sensors*, MDPI Sensors, 10:4(4071-82), Apr 2010

When Package Matters

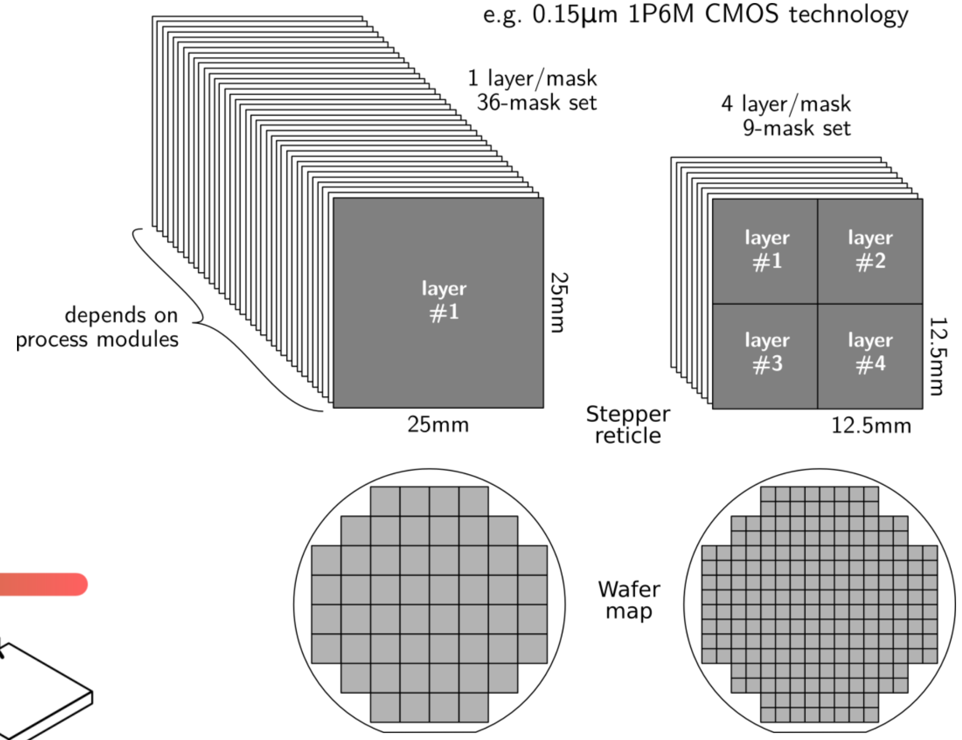
- Packaging costs can be dominant in **hybrid** smart sensors!

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

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



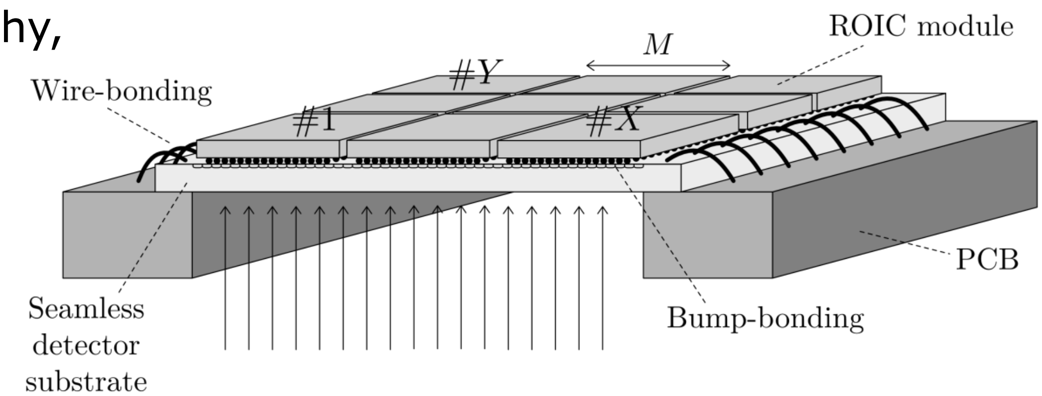
- **ROIC** optimum size



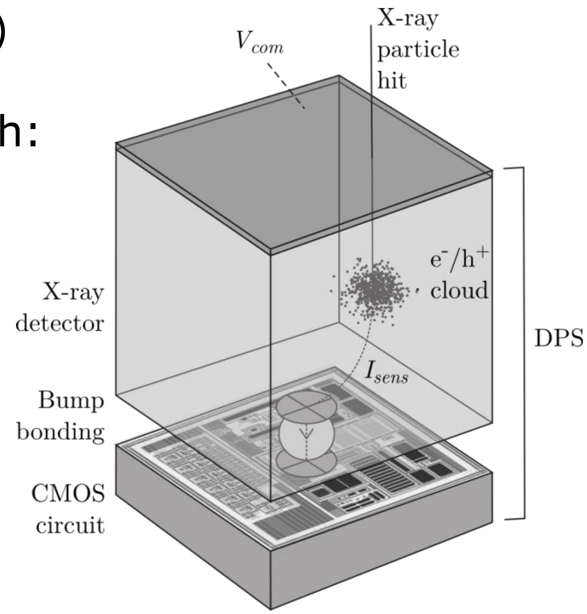
- **Modular** ROIC design + **MCM** packaging ?

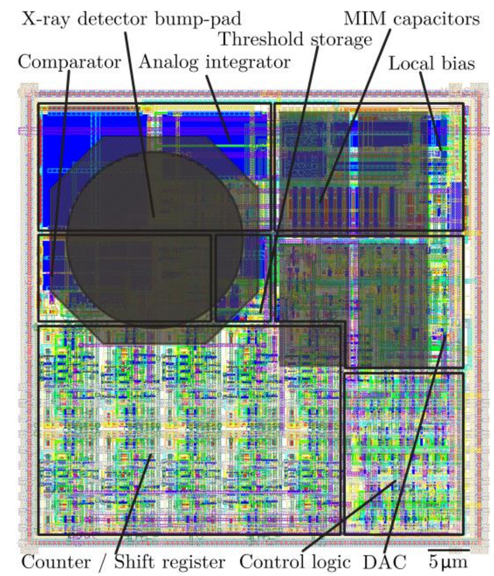
2D Modular Direct X-Ray Imager

- 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



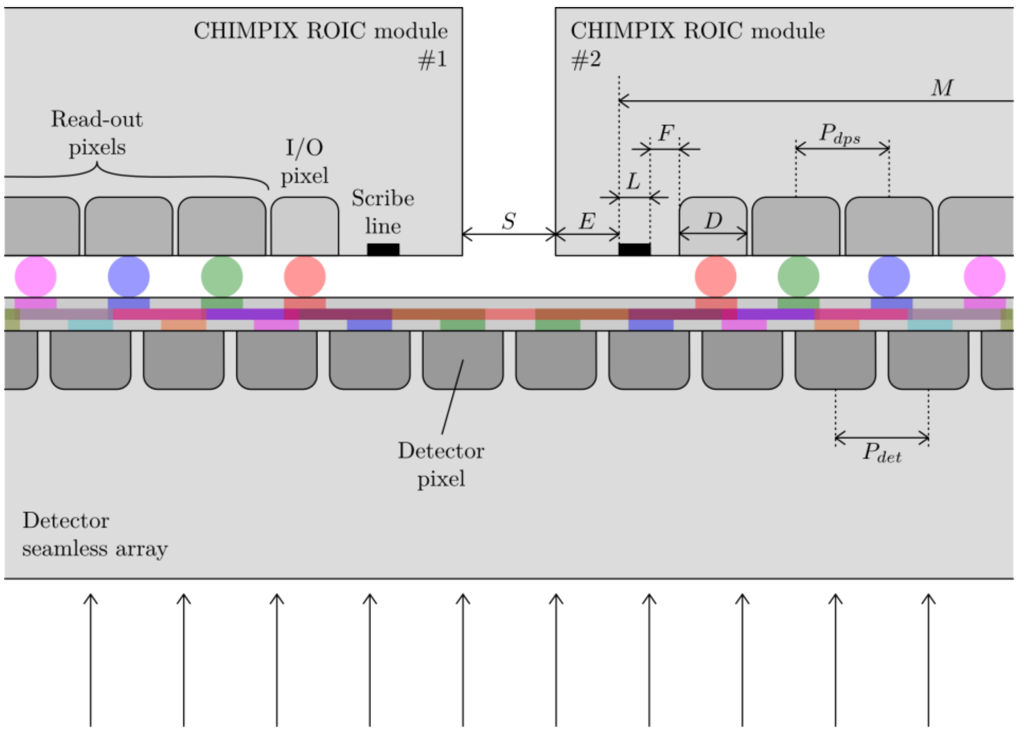


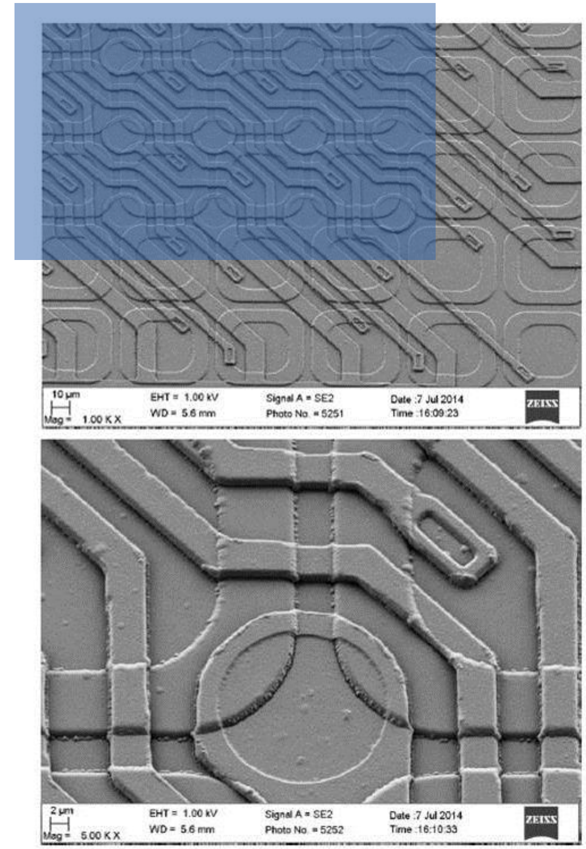
Packaging for Seamless 2D Image

- Pixel detector-to-circuit **rerouting**...

52µm pitch

55µm pitch



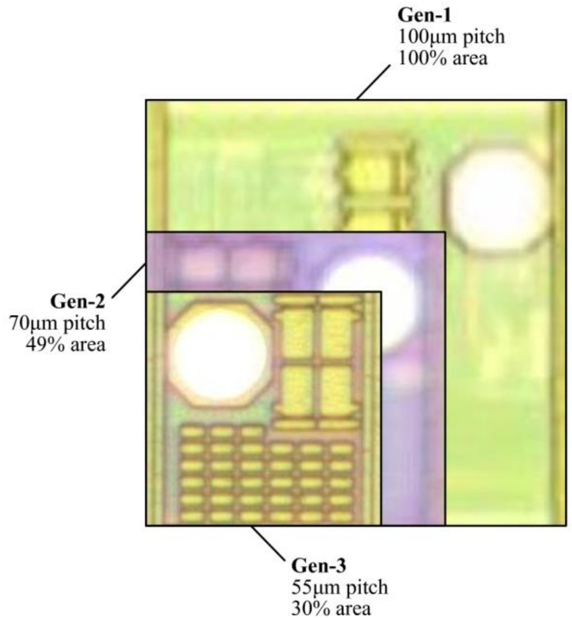


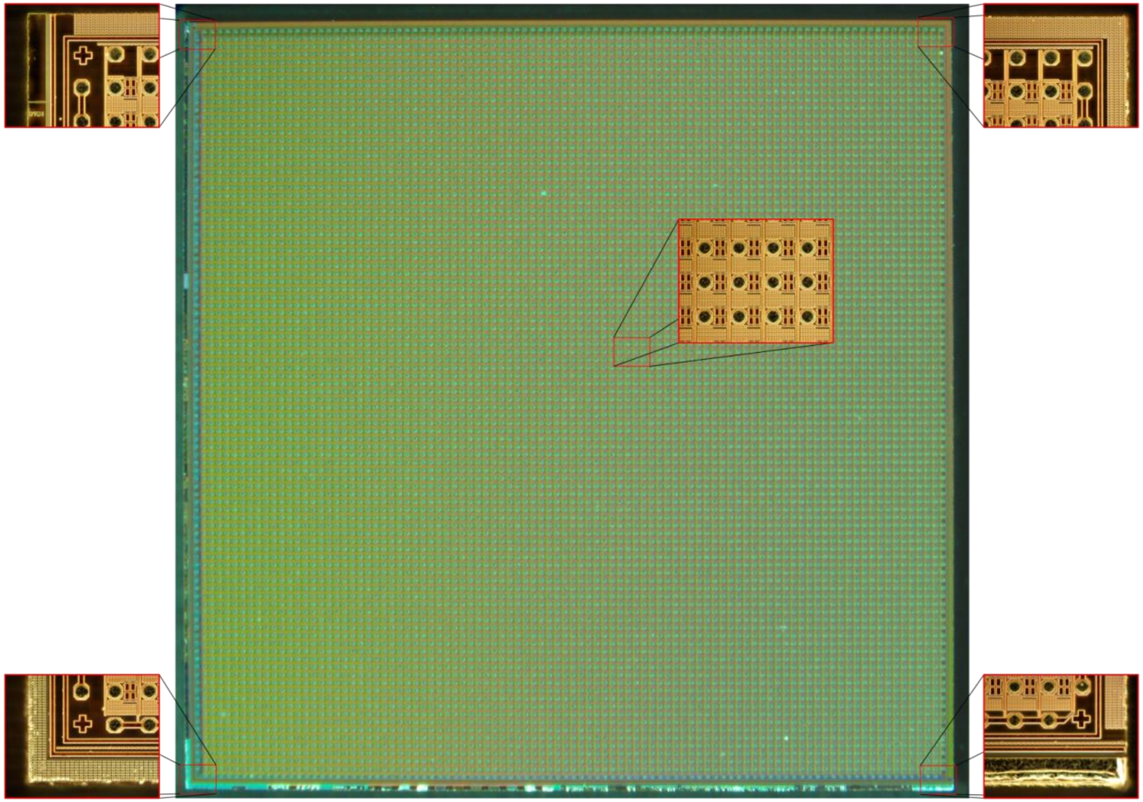
- Inter-pixel **crosstalk**?

R. Figueras et al., *A 70-um Pitch 8-uW Self-Biased Charge-Integration Active Pixel for Digital Mammography*, IEEE Transactions on Biomedical Circuits and Systems, 5:5(481-489), Oct 2011

CMOS ROIC Module

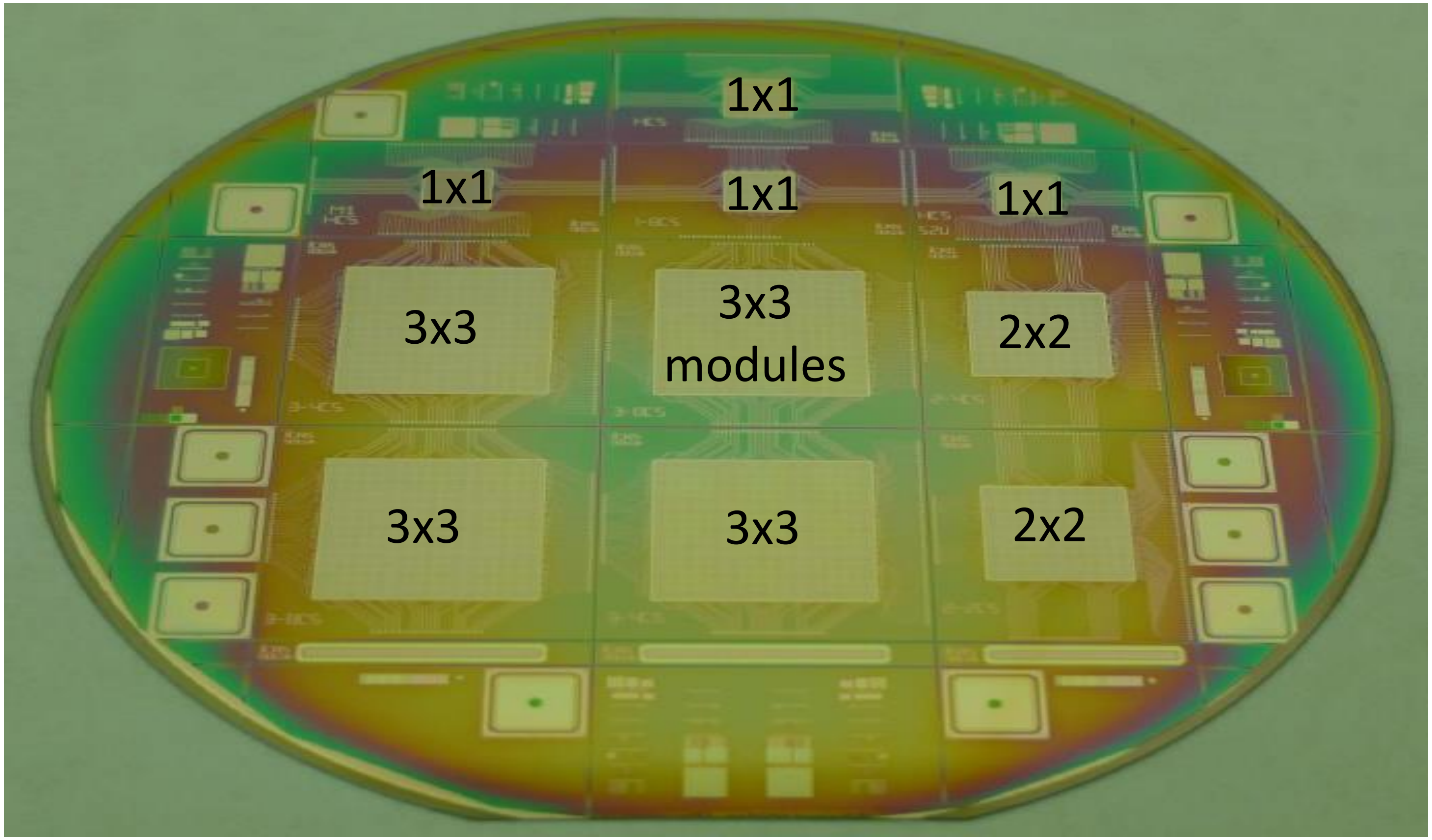
- 0.18µm 1P6M CMOS technology
- 94 x 94 pixel (5mm x 5mm) **module**
- **52µm-pitch**
- **6µW/pix** at +1.8V





Wafer-Level Sensor Integration

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



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