# Multi-modal Sensors and Integrated Circuits for Smart Connected Health

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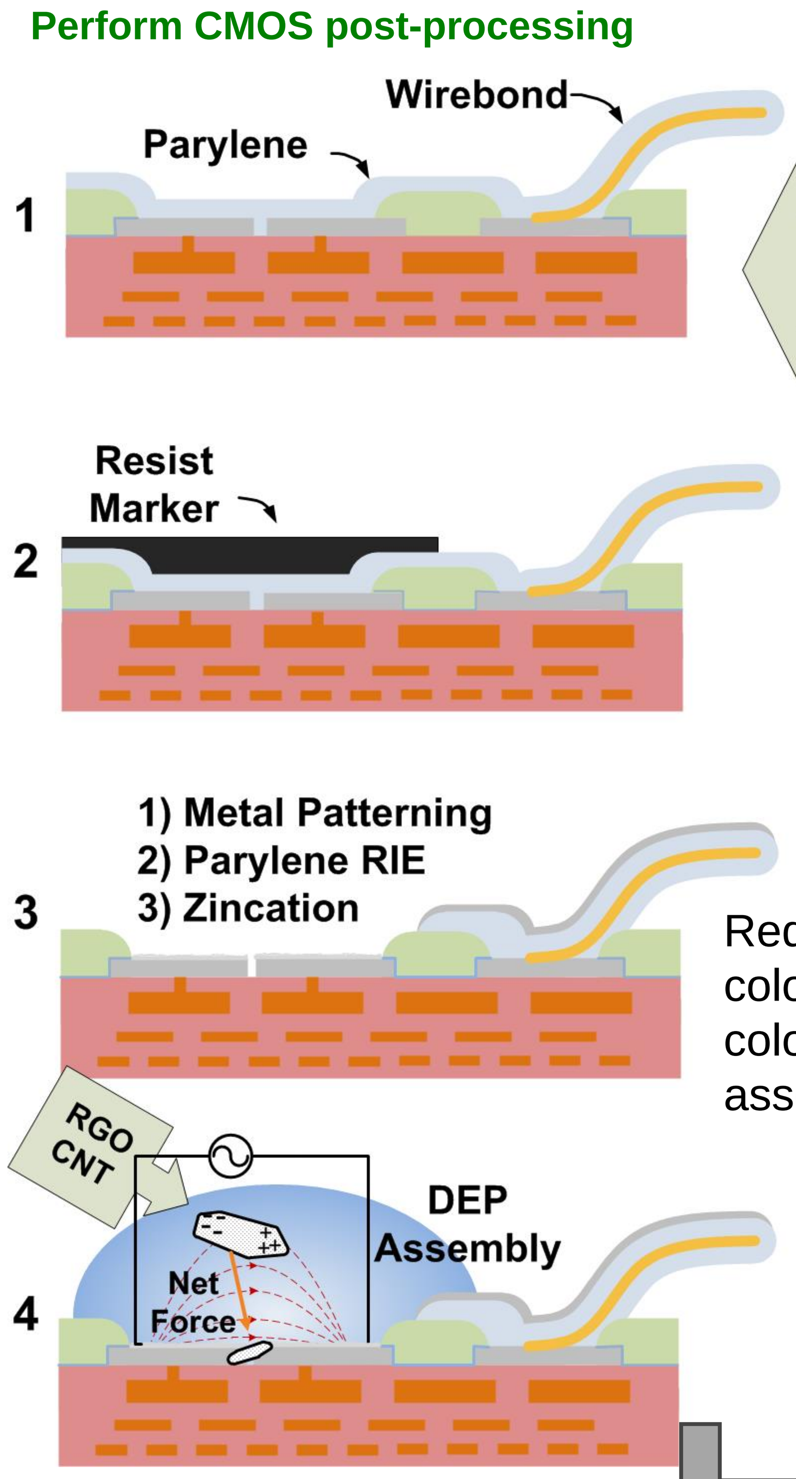
NANOLAB

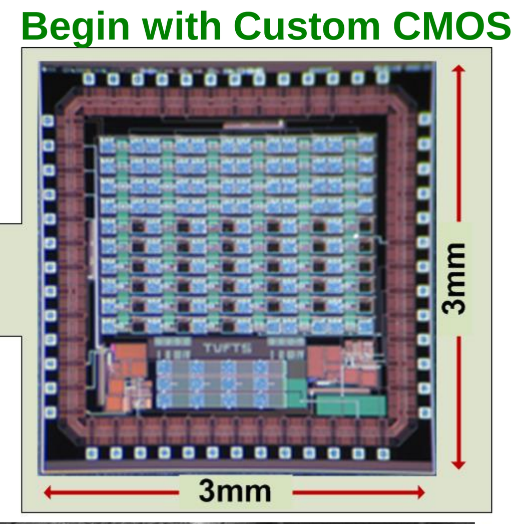
## Vision: Smart and Connected Health

**To make low-cost high-performance self-powered disposable sensors for smart and connected health**

- **What can we sense?**
  - Chemicals: Volatile organic compounds, Toxic chemicals, Gases, Air quality
  - Physical: Motion, Physical Activity
  - Physiological: Heart rate, ExG (ECG, EMG, EEG), Other Biopotentials
- **How do you make them low cost and disposable?**
  - Sensors on substrates like paper or textile which are ubiquitous, inconspicuous and environment friendly
  - Printed circuit on paper or textile for electronics
  - Ease to fabricate and easy to dispose of
- **Almost zero power how?:**
  - Use energy contained in the signal itself (e.g. galvanic electrochemical configuration for chemicals, piezoelectric for motion, biopotentials)
  - CMOS circuits that operate at the threshold voltage of a transistor (< 0.25V)
  - Nanowatt power dissipation (~ 10 – 20nW continuous)

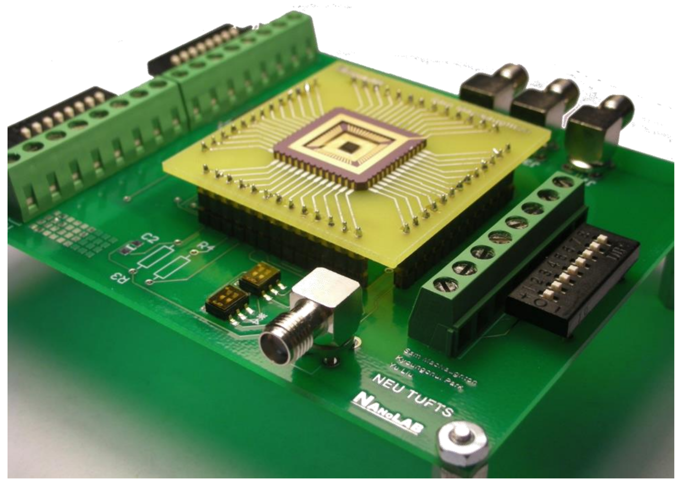
## Topic 1: Nano-enabled Electronic Nose on CMOS




**Assemble Diverse Nanomaterials as Chemical Sensors on CMOS**

Reduced graphene oxide (RGO) flakes (left, false color green) and carbon nanotubes (right, false color red) as representative nanomaterials assembled on the CMOS die.



The resulting chip is ready for sensing on test PCB shown at right

Magnitude response of four different nanomaterials for gases

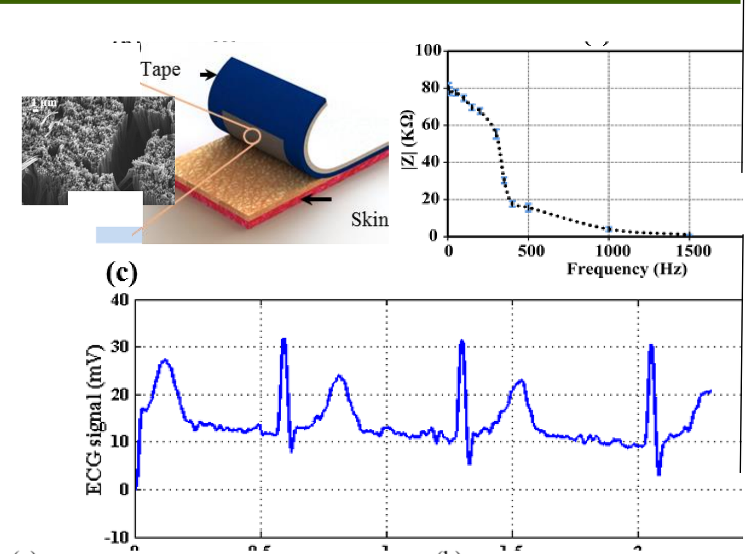
| Analyte | CNT | rGO | Copper Oxide | Polypyrrole |
|---|---|---|---|---|
| Ethanol | 7.5% | 7.5% | 2.5% | 2.5% |
| Acetone | 15% | 20% | 7.5% | 5% |
| Ammonia | 22.5% | 32.5% | 10% | 7.5% |

**Sensitivity to vapors of the order of 100ppb!**

## Topic 2: Disposable Nanowire on Paper Devices

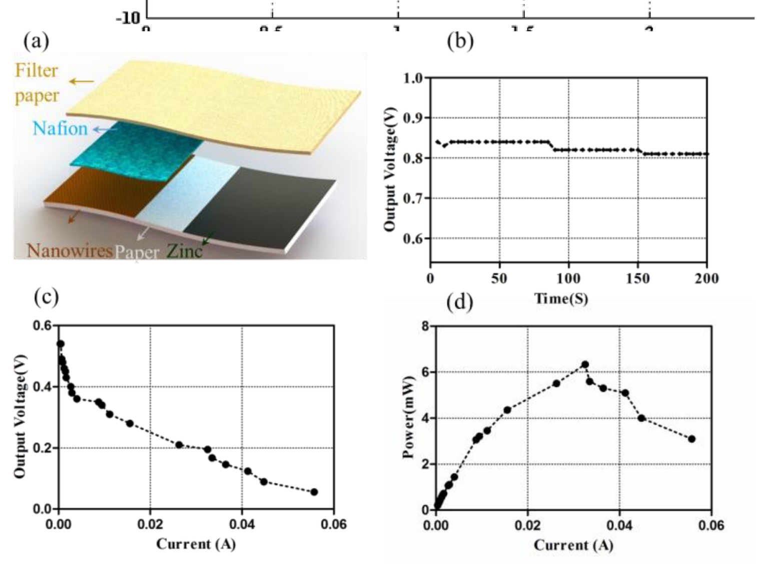
### Biopotential Recording

- **Pt Nanowires on paper**
- **No need for wet-gel adhesives**
- **Low-moderate impedance**
- **Long term wearability**



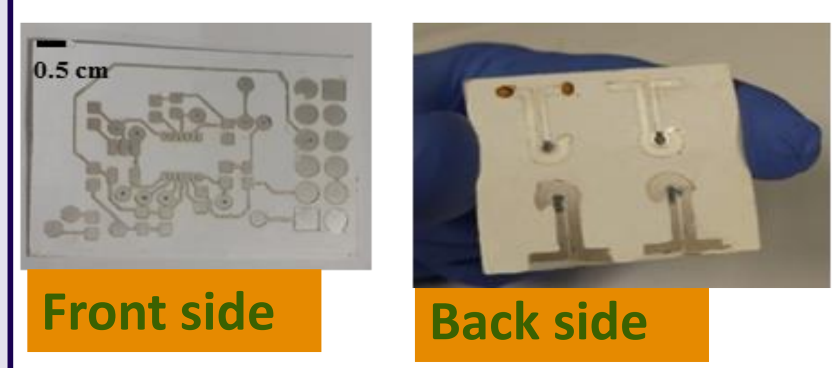

### Biological Battery

- **Harvesting power from acidic environment (pH 1 ~ 4)**
- **Zn and Pt nanowires on paper serve as anode and cathode**
- **Planar geometry**
- **0.84V/ 6.3mW/ 32mA/ 6ohms**



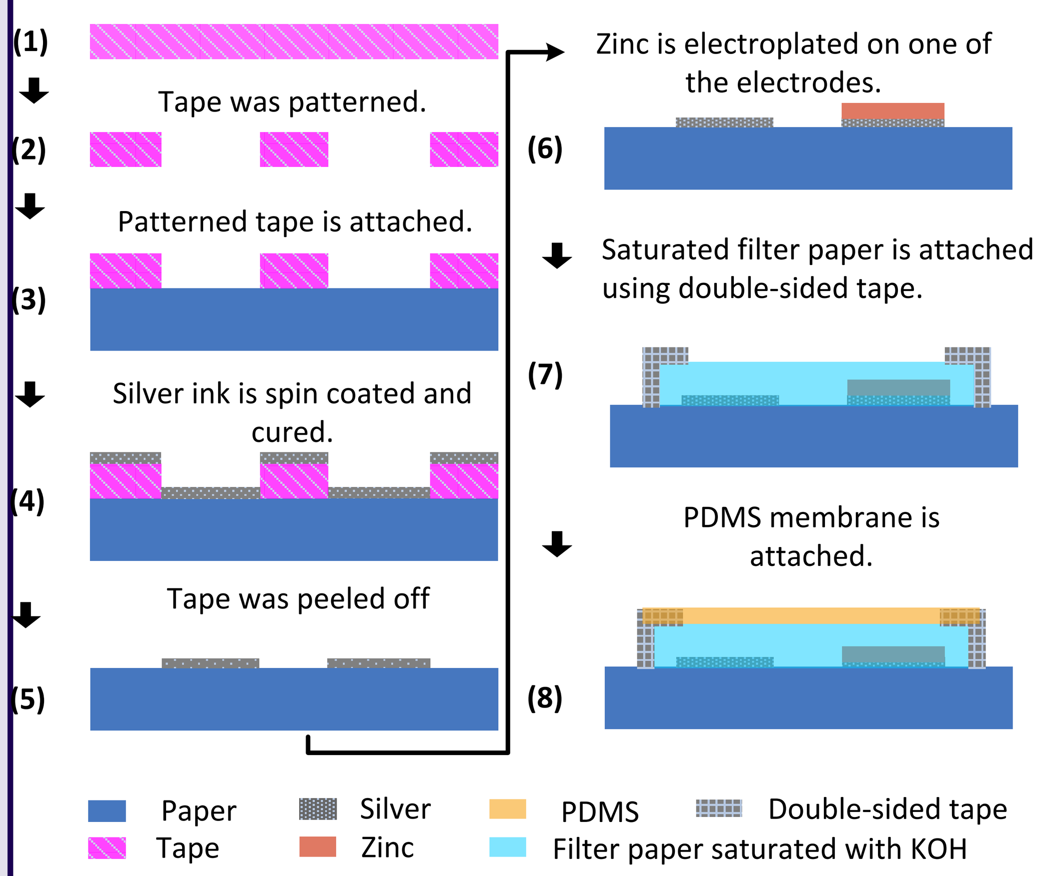

## Topic 3: Disposable Printed Circuit Boards

**Disposable paper based oxygen (and other electrochemical) sensor**

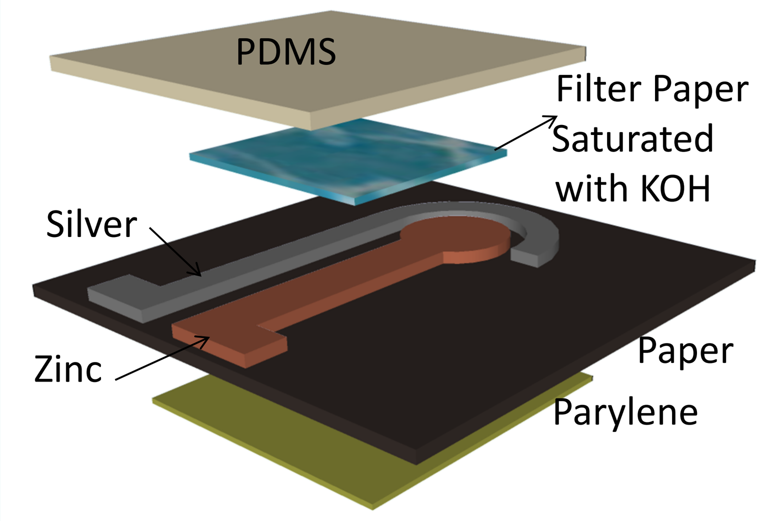



- **Two pieces of paper for four layer PCB all on paper**
- **Screen printing for interconnects and punching for via**
- **Galvanic electrochemical sensor to measure oxygen**

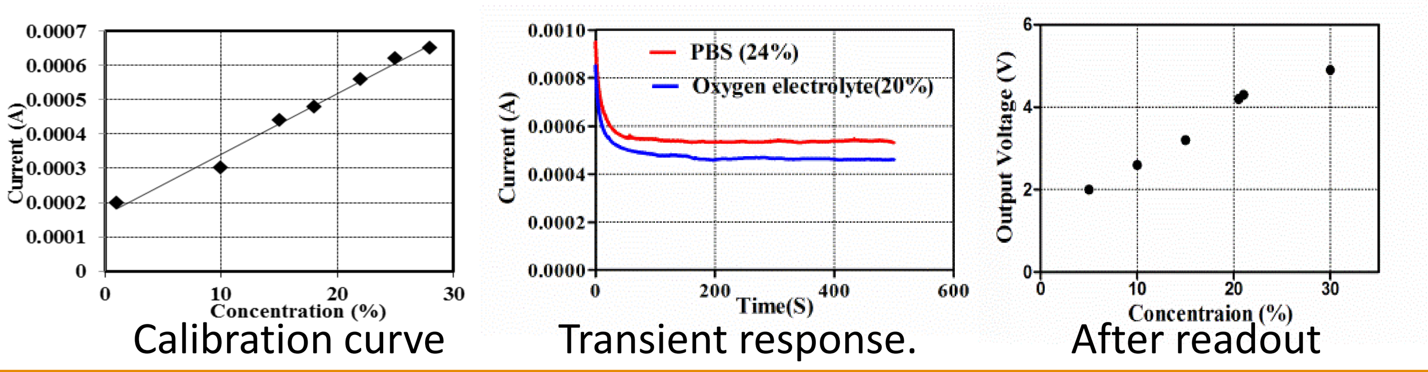
**Fabrication Process**




**Oxygen Sensor Structure**




Oxidation at Zn anode: $2Zn \rightarrow 2Zn^{2+} + 4e^-$
Reduction at Ag cathode: $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$
Overall reaction: $O_2 + 2H_2O + 2Zn \rightarrow 2Zn(OH)_2$

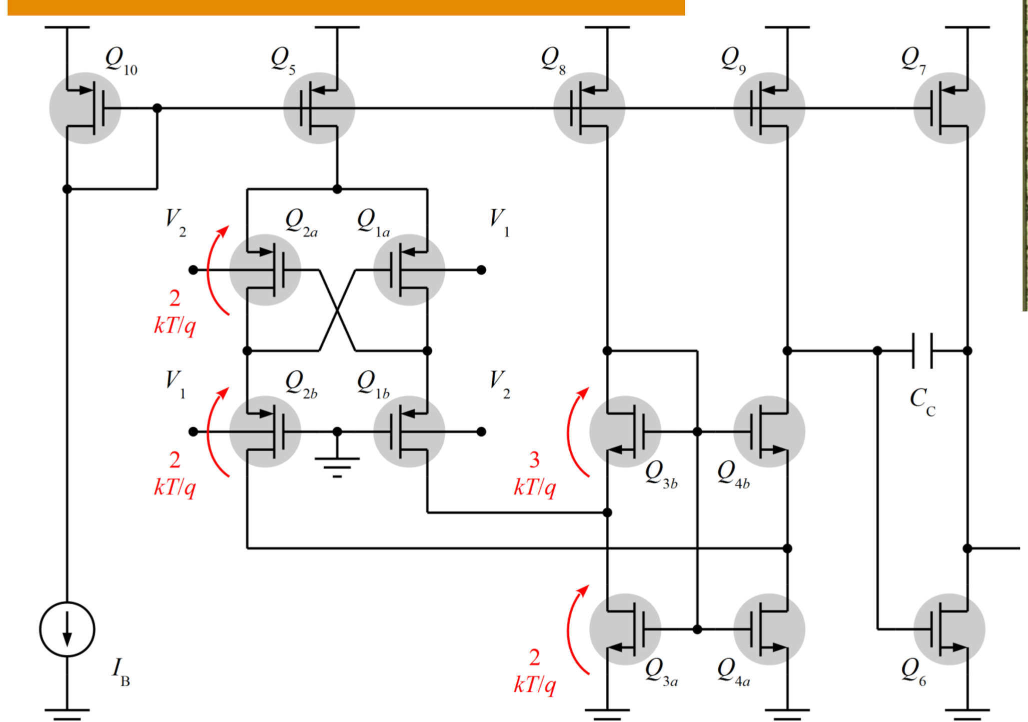


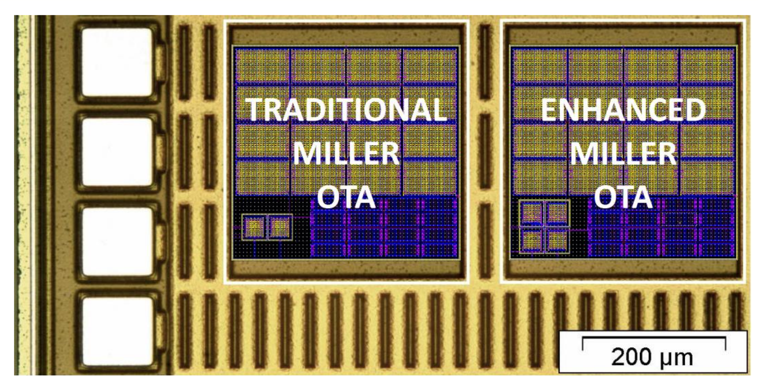

Calibration curve    Transient response.    After readout

**Electrodes, Sensors, Batteries, Electronics can all be built on paper using low cost approaches in resource-poor settings with applications in healthcare and environment**

## Topic 4: 0.25V Amplifier and Analog to Digital Converter

### 0.25V 18nW 60dB OTA



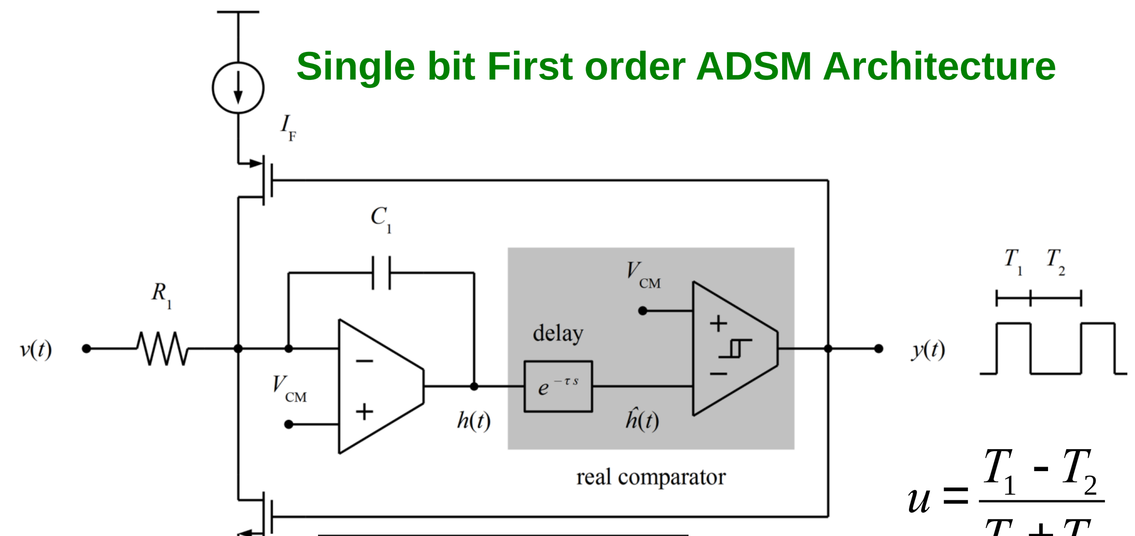



| | Traditional | Enhanced |
|---|---|---|
| Power supply | 0.25 V | 0.25 V |
| Technology | 130 nm | 130 nm |
| Transconductance | 2.8 nS | 9.3 nS |
| Maximum input current | < 3 pA | < 5 pA |
| Open loop gain | 40 dB | 60 dB |
| Unity gain frequency | 0.54 kHz | 1.88 kHz |
| Phase margin | 79.2° | 52.5° |
| Slew-rate + | 0.28 V/ms | 0.64 V/ms |
| Slew-rate − | 0.32 V/ms | 0.77 V/ms |
| THD @ 150 $mV_{PP}$ | 1.0 % | 0.2 % |
| Input referred thermal noise | $7.3 \frac{\mu V}{\sqrt{Hz}}$ | $3.3 \frac{\mu V}{\sqrt{Hz}}$ |
| Offset voltage standard deviation | 2.7 mV | 2.8 mV |
| Power consumption | 18 nW | 18 nW |
| OTA area | 0.083 $mm^2$ | 0.083 $mm^2$ |
| FOM = 100 x ($UGBW*C_L$)/I | 11.3 $V^{-1}$ | 39.2 $V^{-1}$ |

- **Bulk-driven input stage**
- **Sub-threshold operation**
- **Distributed layout for higher output impedance**
- **Negative impedance source degeneration**

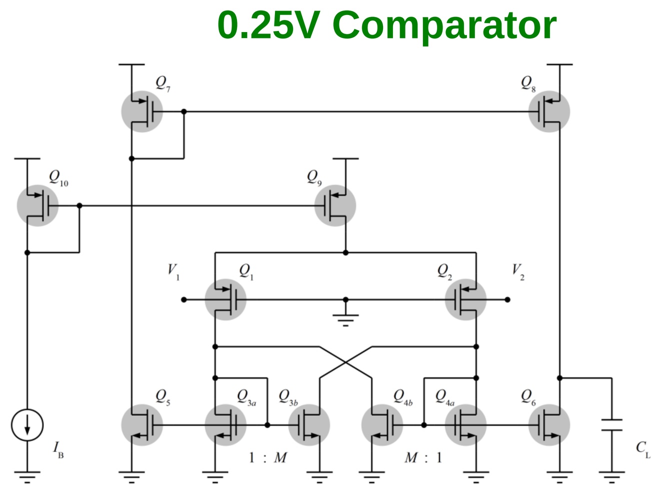
### 0.25V Async Delta Sigma Modulator

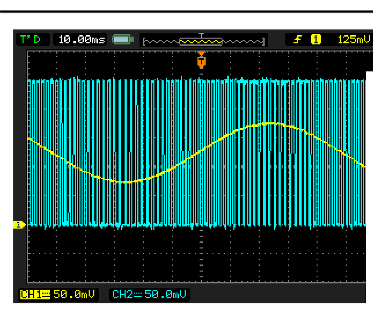
**Single bit First order ADSM Architecture**



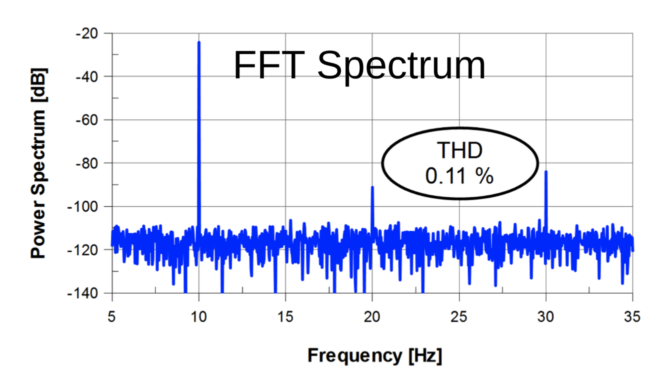

$$u = \frac{T_1 - T_2}{T_1 + T_2}$$

**0.25V Comparator**





Transient response

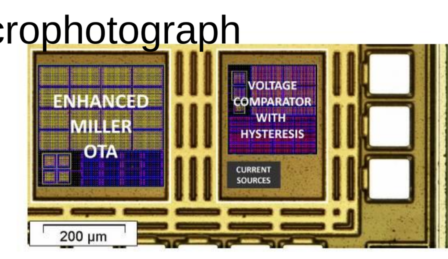



| | This work |
|---|---|
| Power supply | 0.25 V |
| Technology | 130 nm |
| Topology | ADSM |
| Order | 1 |
| Input type | single-ended |
| Modulator frequency | 630 Hz |
| Bandwidth | 30 Hz |
| SNR | 62 dB |
| SNDR | 58 dB |
| Dynamic range | 58 dB |
| Power consumption | 28 nW |
| Area | $0.141^{(3)}$ $mm^2$ |
| $FoM_1$ | 148 |
| $FoM_2$ | 0.8 pJ/step |

MEASURED HYSTERETIC COMPARATOR FEATURES.

| | |
|---|---|
| Power supply | 0.25 V |
| Biasing current | 10 nA |
| Hysteresis threshold | 1.25 mV |
| Time delay | 380 µs |
| Maximum input current | < 3 pA |
| Power consumption | 7 nW |
| Comparator area | 0.044 $mm^2$ |

Chip Microphotograph

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