A 0.3V Biofuel-Cell-Powered Glucose/Lactate Biosensing System Employing a 180nW 64dB SNR Passive ΔΣ ADC and a 920MHz Wireless Transmitter

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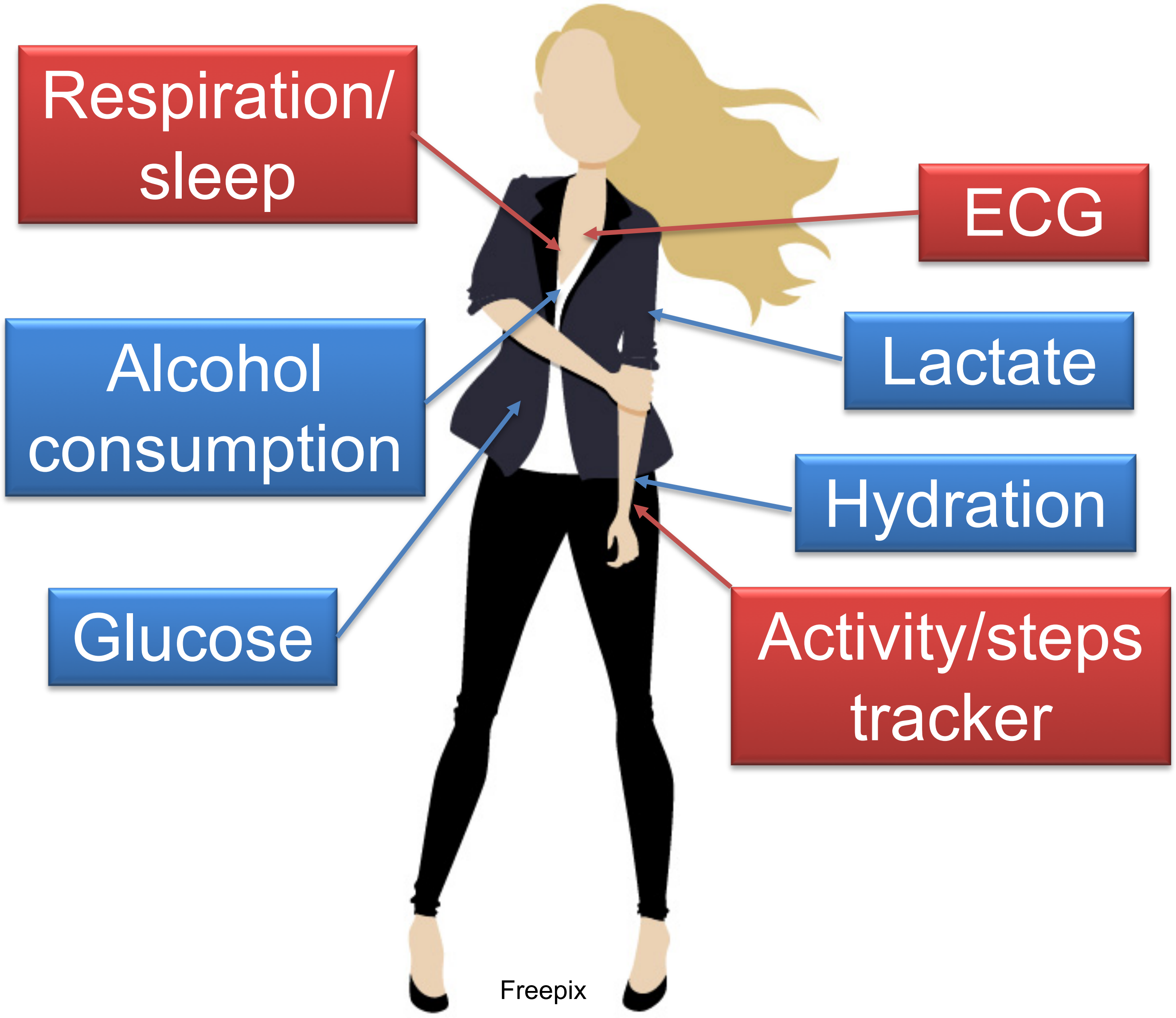
Next-Generation Wearable Sensors



SENSING TODAY:
- Physical parameters
- Electrophysiology

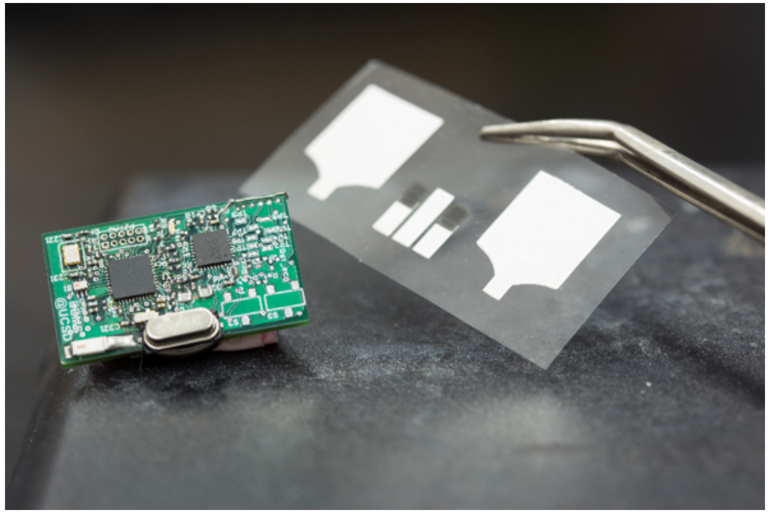
→ *Limited utility in daily life*

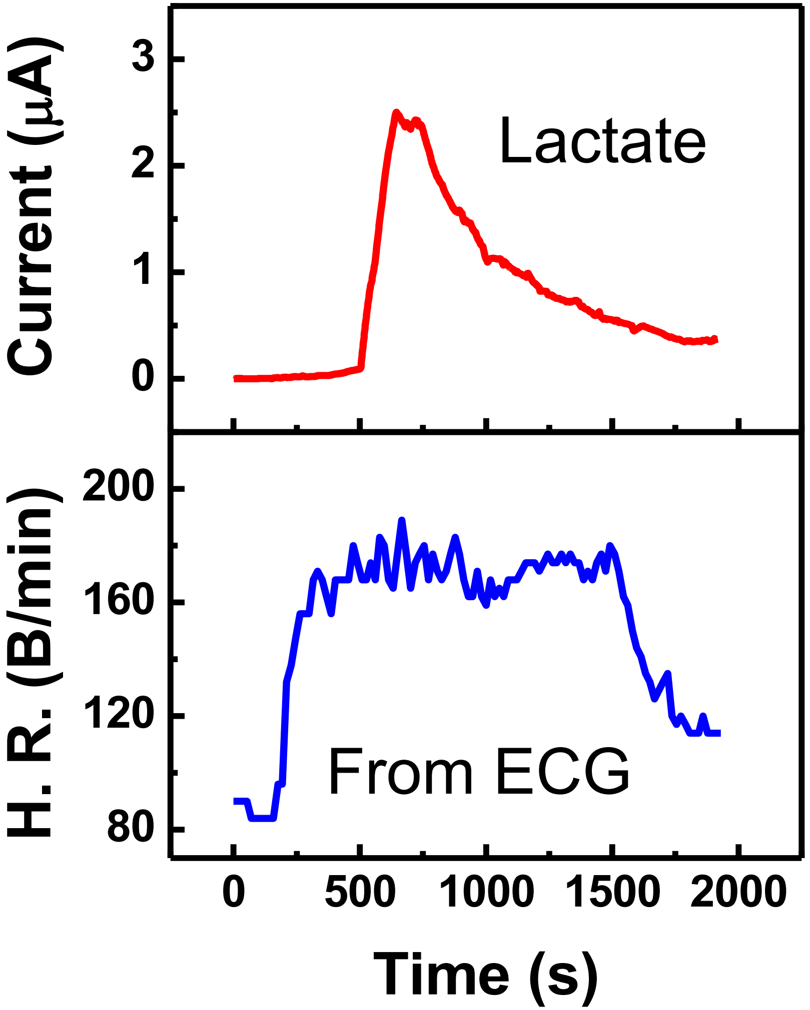
NEXT-GENERATION:
- Physiochemistry

→ *More actionable information for daily life improvement*

Research need: wireless physiochemical sensors

Wireless Physiochemical Sensing





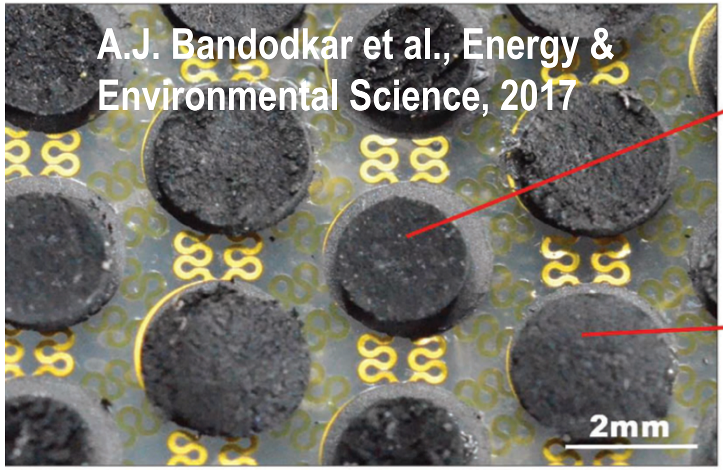
First demonstration of simultaneous real-time electrophysiology + physiochemical sensing

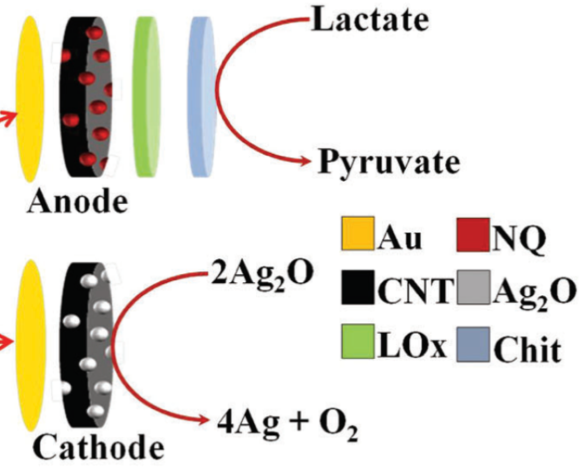
Requires battery, power management, user interaction

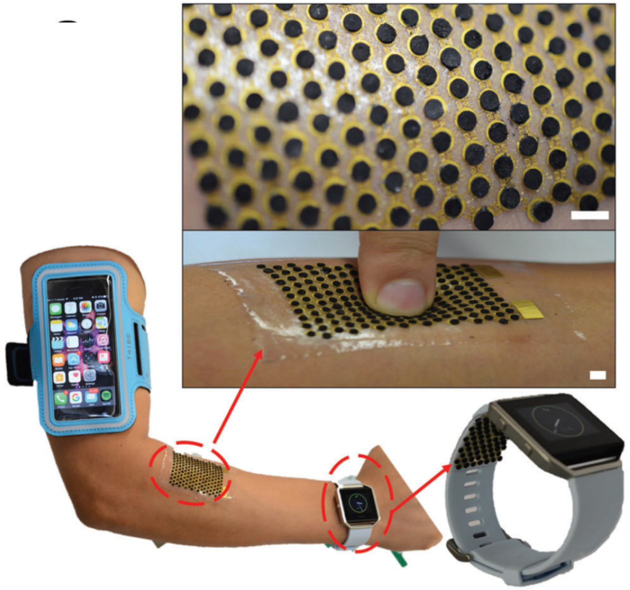
Research need: wireless physiochemical sensors that are small, unobtrusive and self-powered: "*unawearables*"

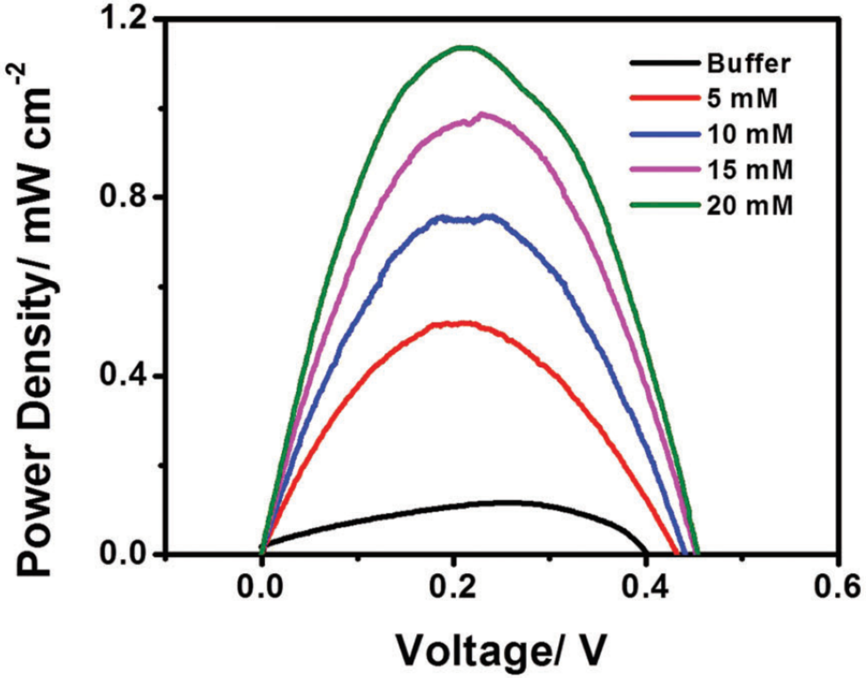
S. Imani et al., Nature Communications, May 2016

Physiochemical sensing and energy harvesting









- Biofuel cells (BFCs) convert biofuels (e.g., glucose, lactate) into electrical power
- Power ∝ fuel concentration

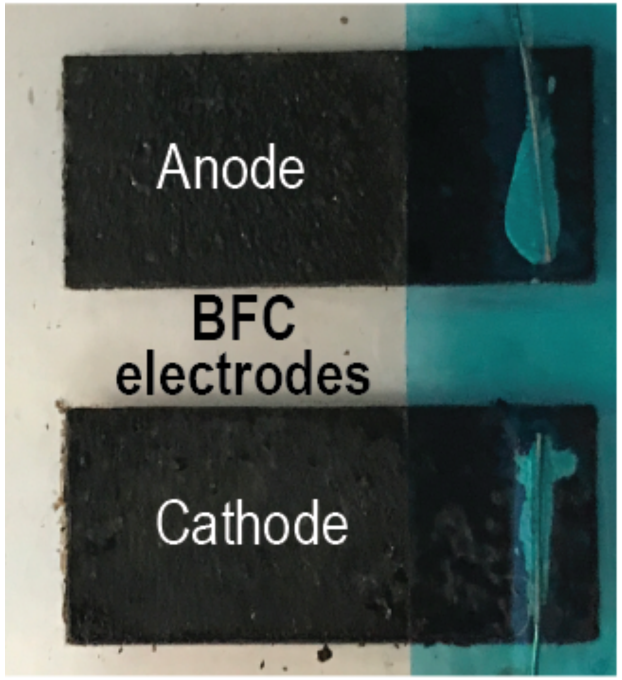
IDEA: utilize BFC power to create a self-powered physiochemical sensor

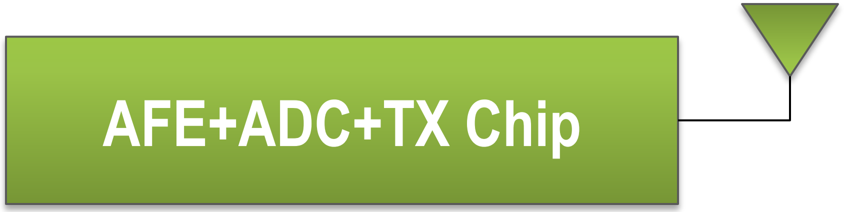
CHALLENGE: do so reliably, and in a small form factor (no DC-DC converter)

Outline of the Presentation

1. **Biofuel Cell Material Composition**
2. **Proposed Biosensing System Architecture**
3. **System Implementation**
   - **AFE**
   - **ΔΣ ADC**
   - **Wireless Transmitter**
4. **In-Vitro Experimental Results**
5. **Conclusions**

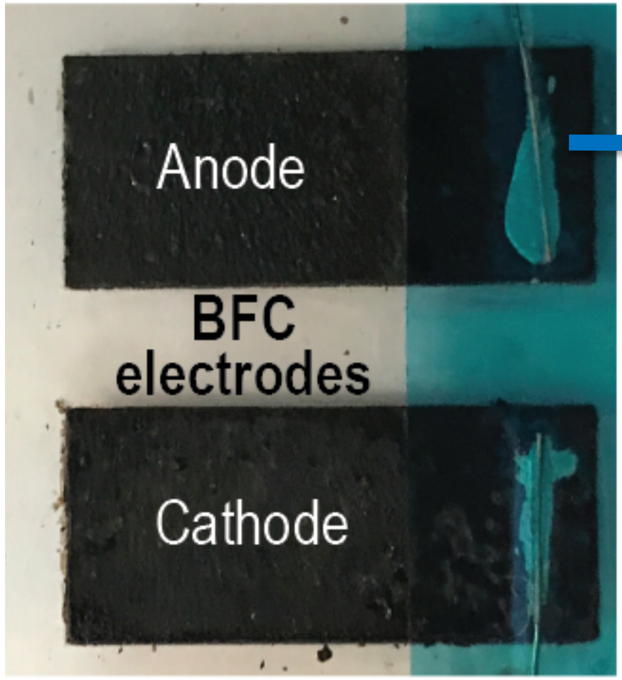
BFC Material Composition

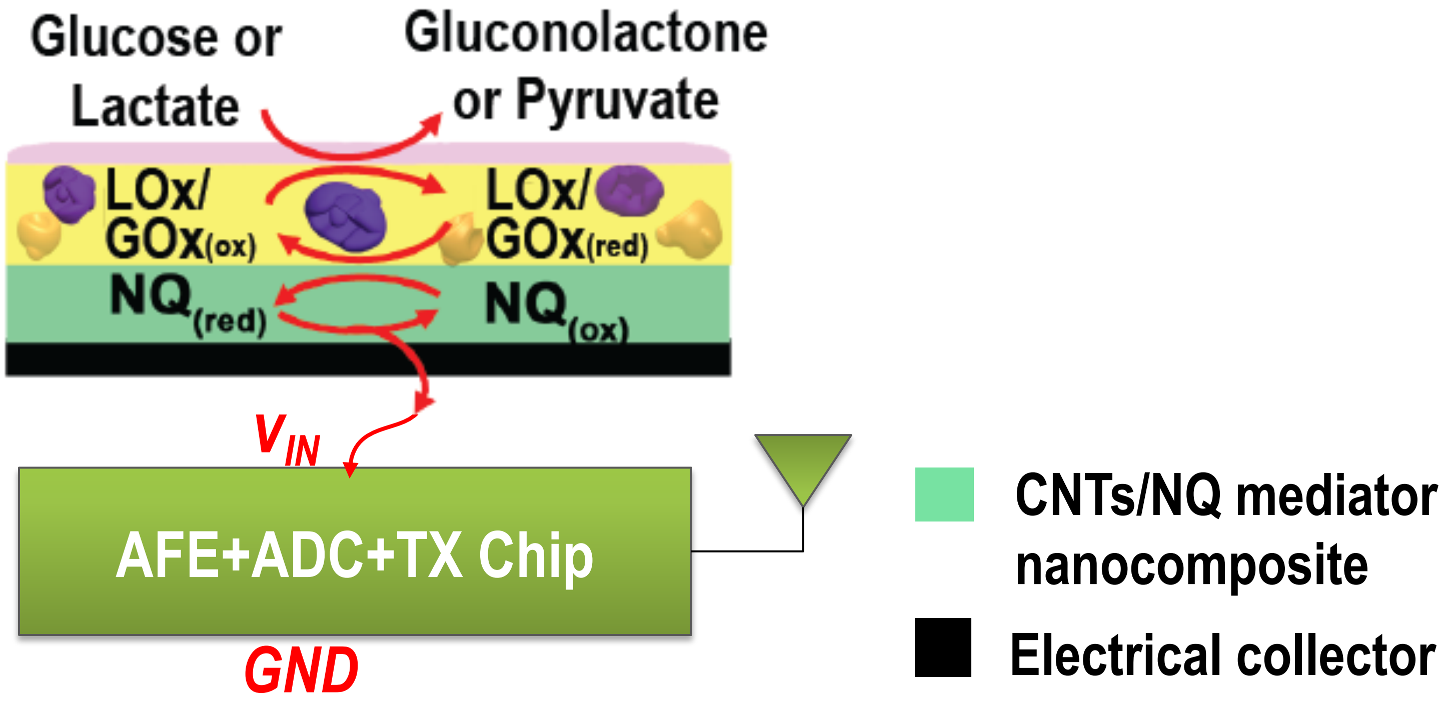




- Custom-fabricated lactate and glucose biofuel cells (BFCs)

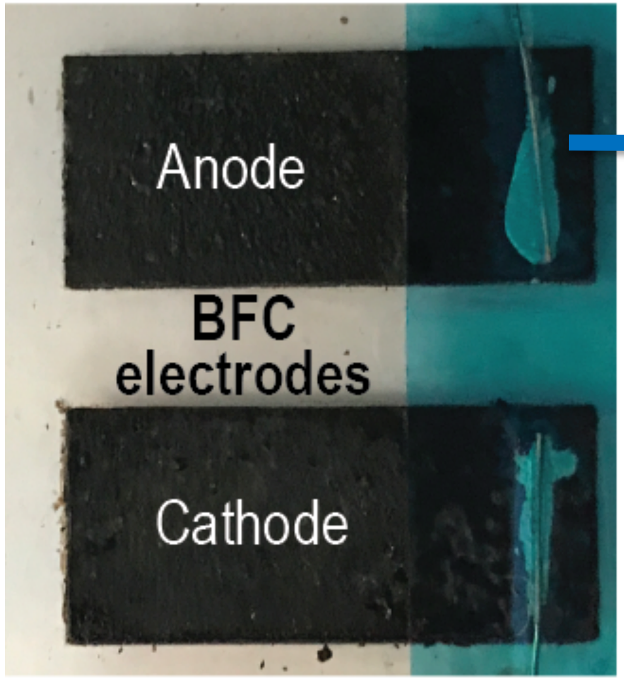
BFC Material Composition

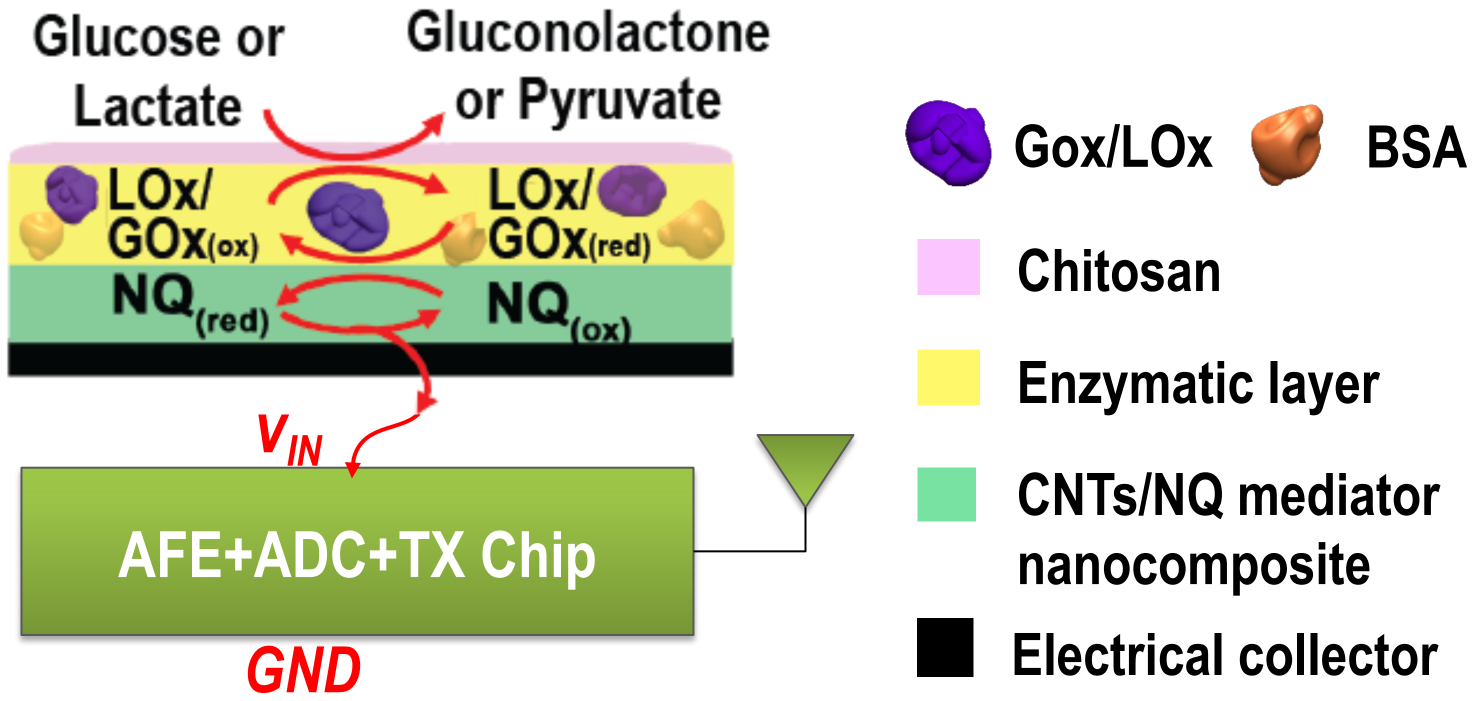




- BFC anodes material composition

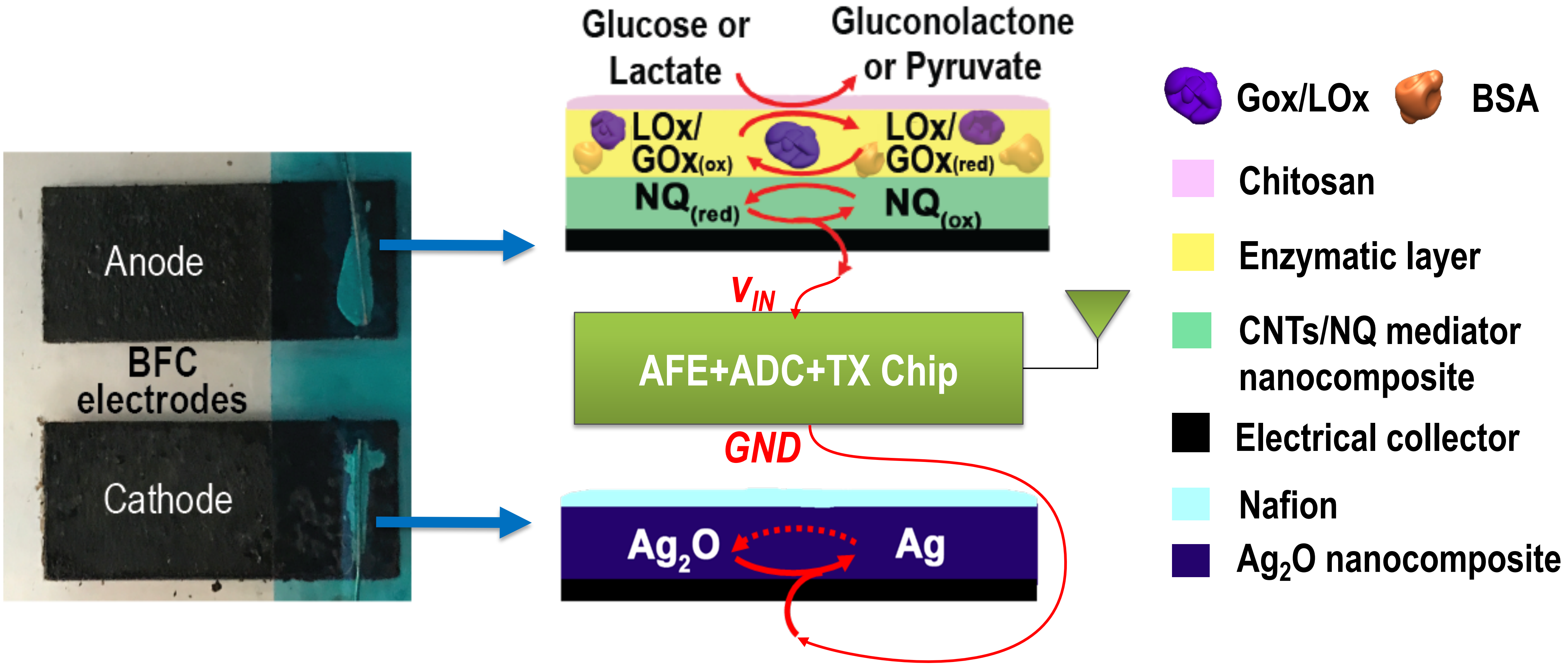
BFC Material Composition





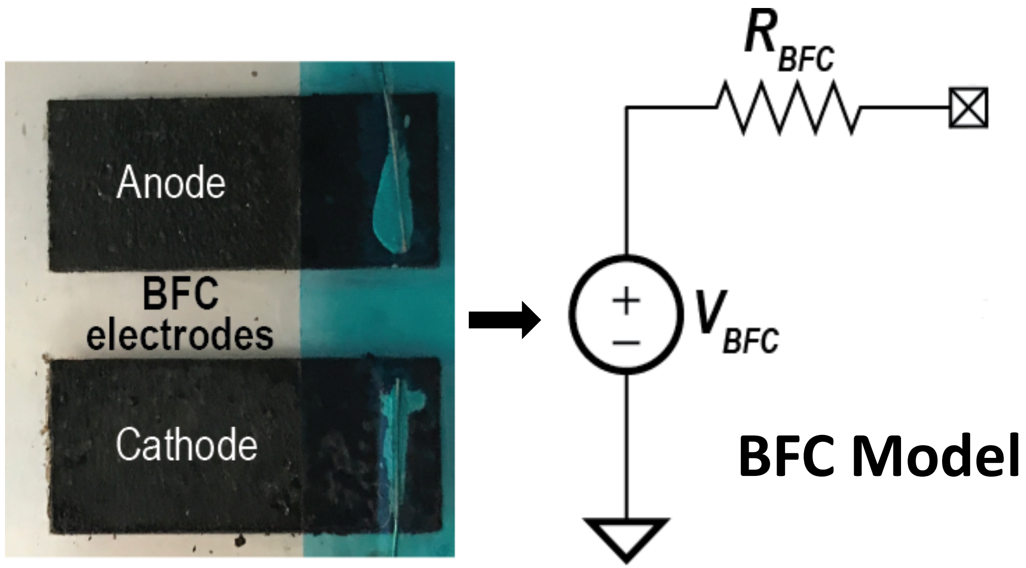
- Enzymatic cocktail consisting of lactate or glucose oxidase

BFC Material Composition



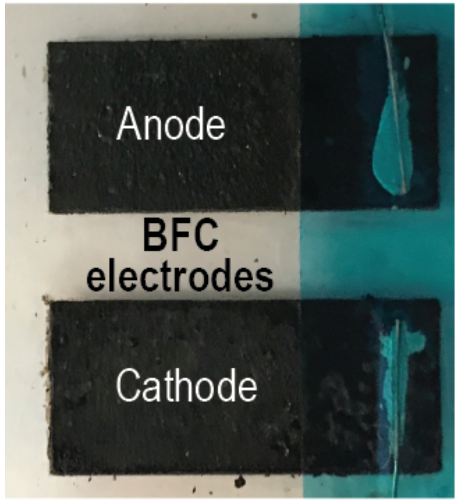
- BFC cathode material composition

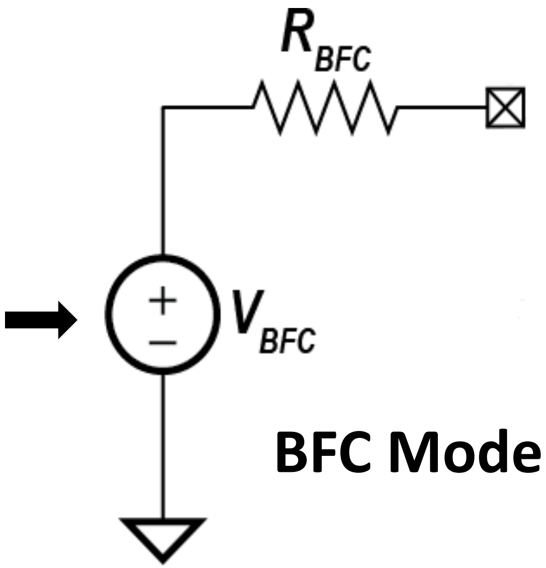
Biosensing System Architecture



- Steady-state BFC model

Biosensing System Architecture



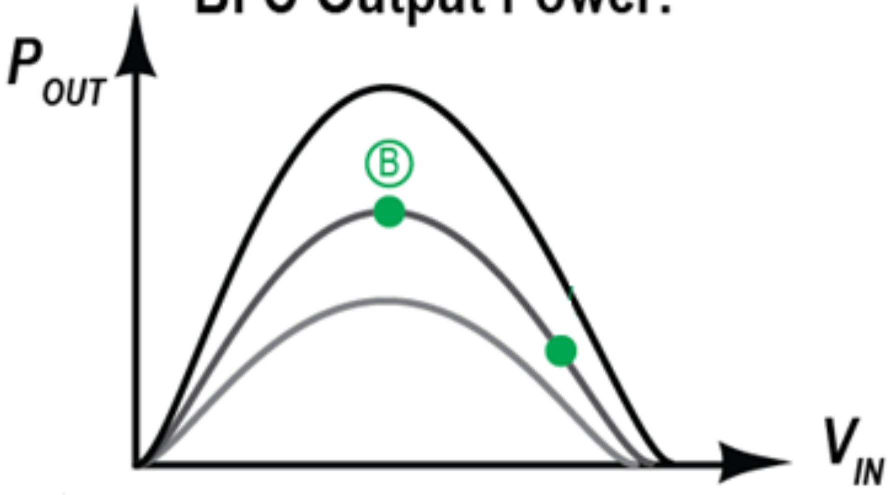


BFC Model

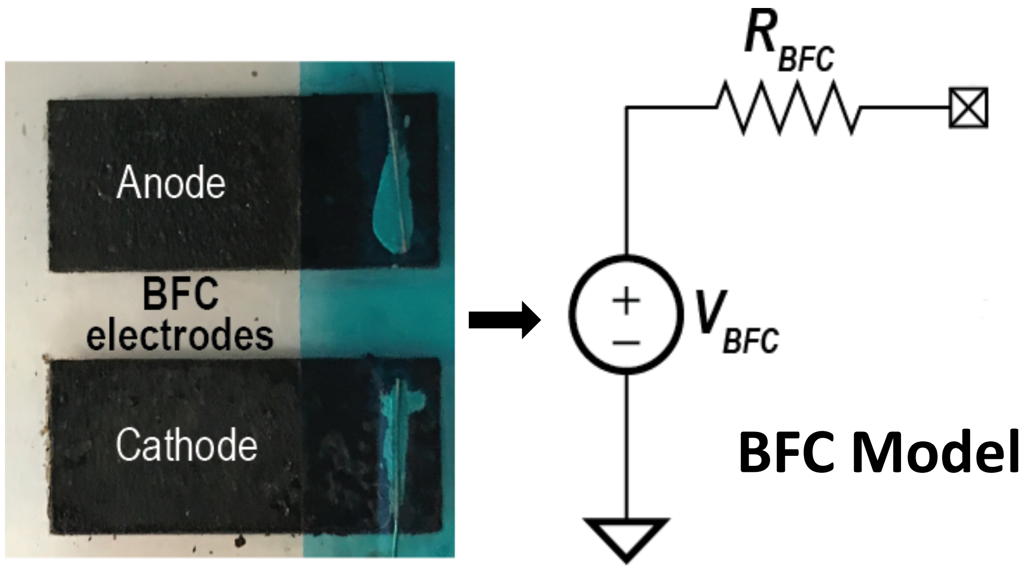
- Linear correlation of maximum power point (MPP) of the BFC (point B) with fuel concentration

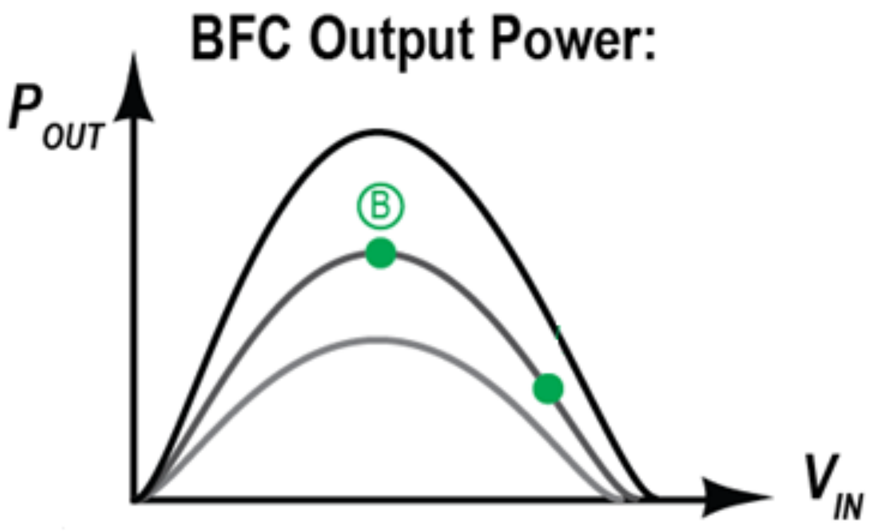
How to measure MPP?

BFC Output Power:



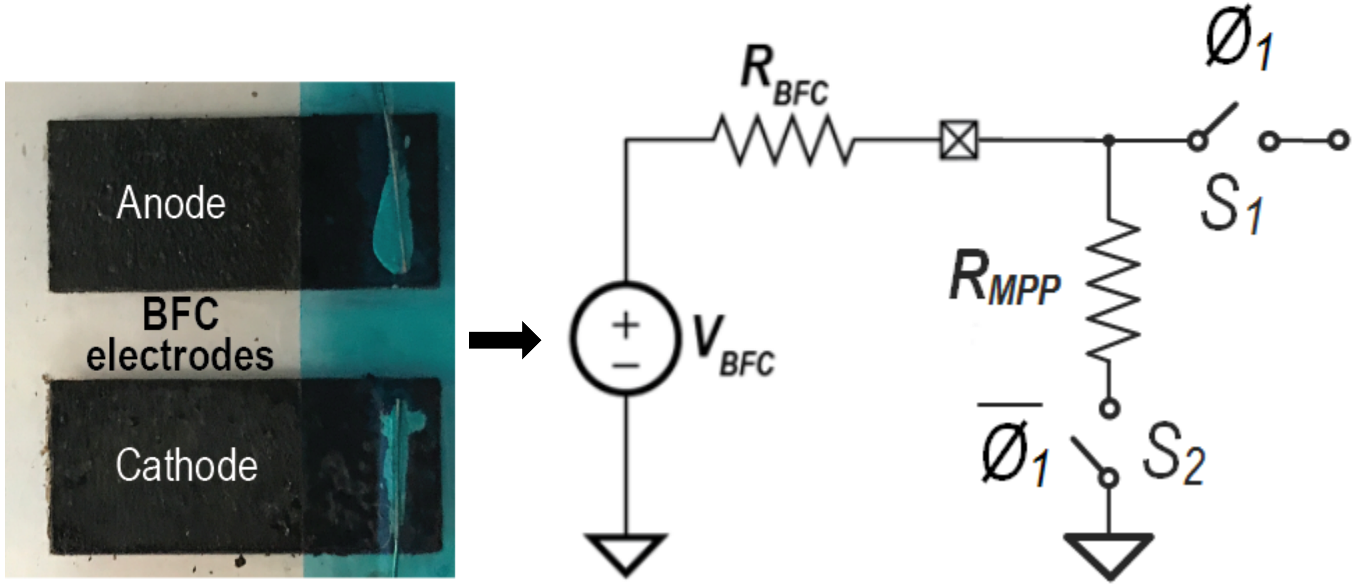
Biosensing System Architecture

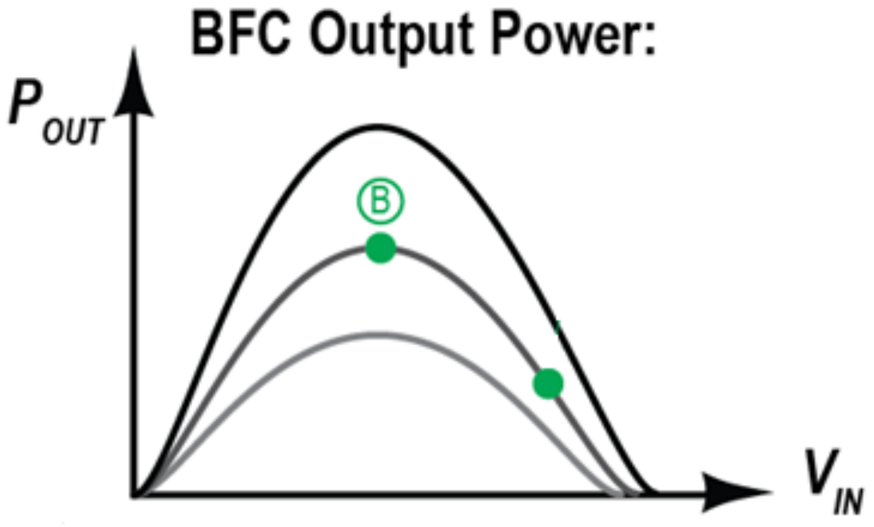




- **To measure maximum power point (MPP)**
  - DC-DC converter for MPP tracking
    → Bulky inductors, large power

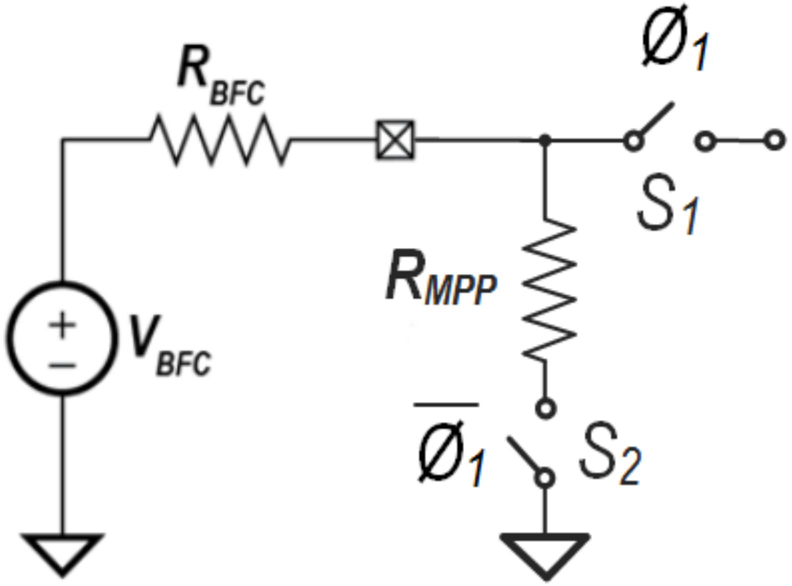
Biosensing System Architecture





- **To measure maximum power point (MPP)**
  - DC-DC converter for MPP tracking
    → Bulky inductors, large power
  - Always presenting a matched load
    → Limits longevity
  - Periodically presenting a matched load (here with a 1% duty ratio)

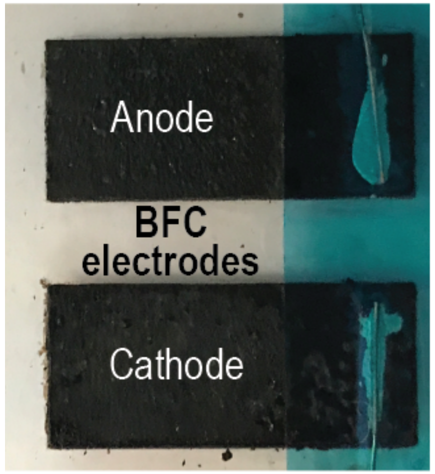
Biosensing System Architecture

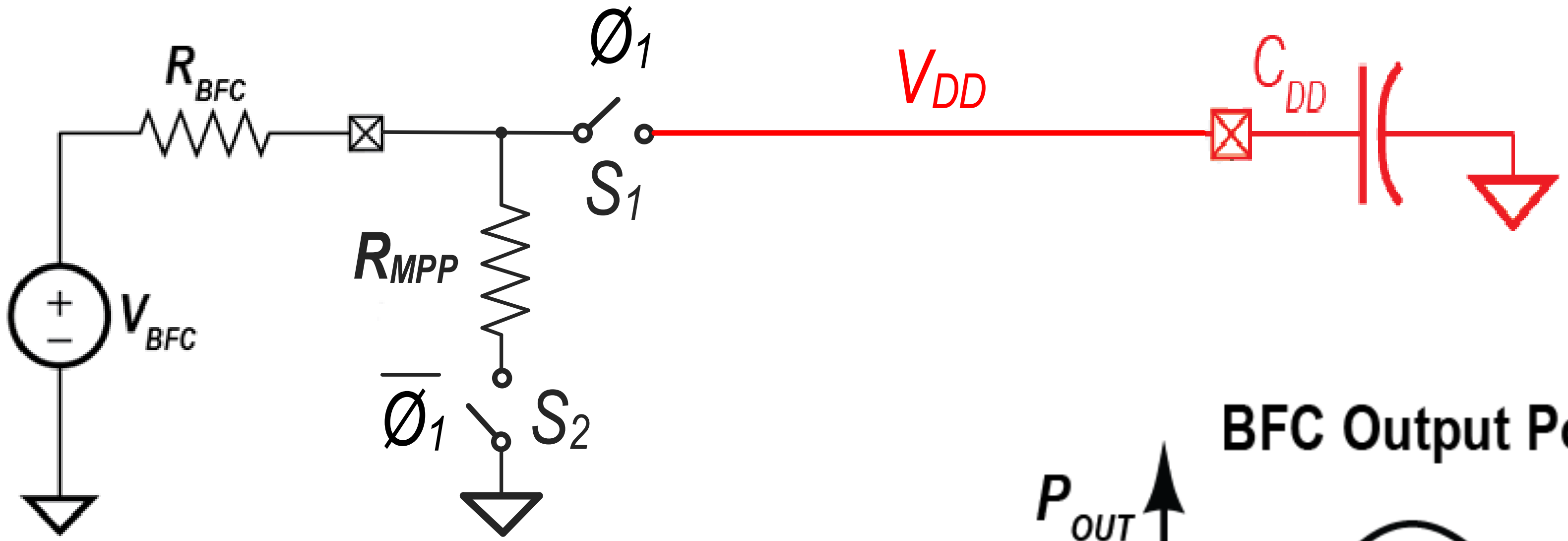


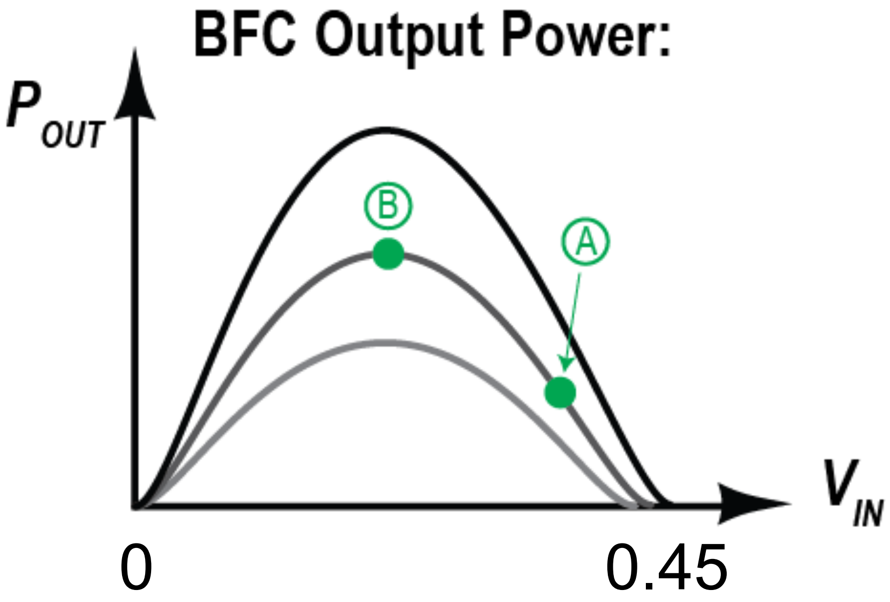
- Matched load R_{MPP} at only 1% duty ratio in this work

→ *To avoid fuel depletion at the maximum possible rate*

Biosensing System Architecture



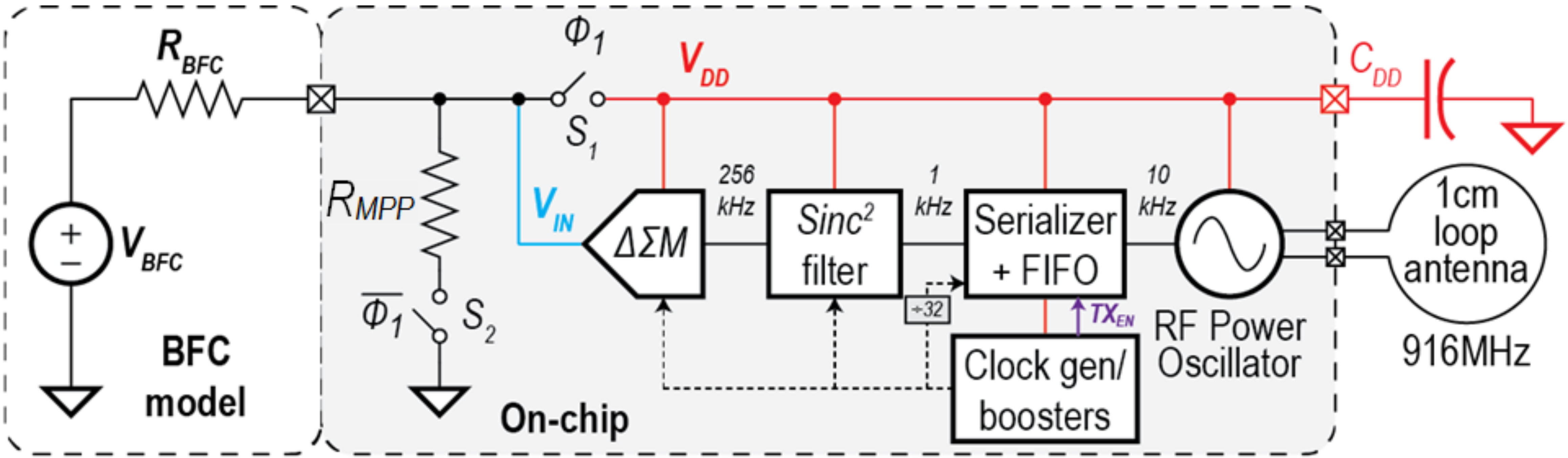


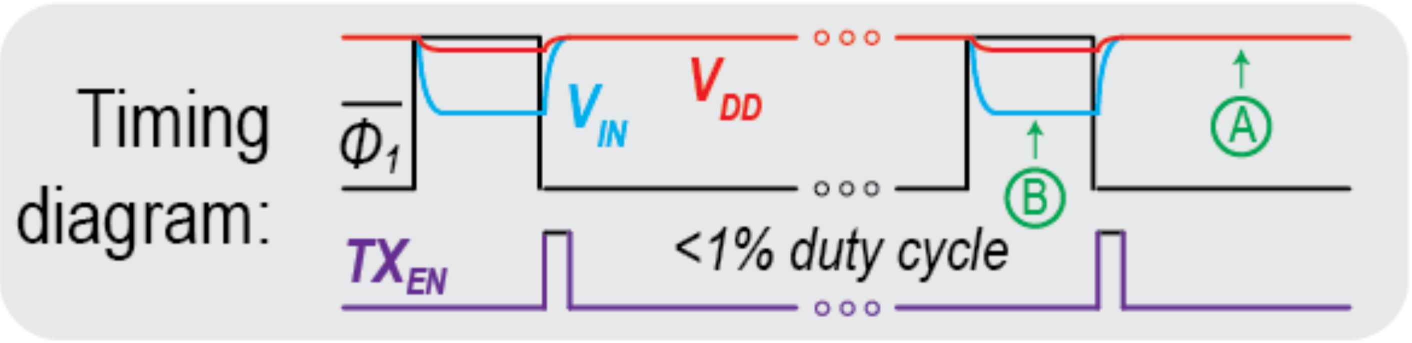


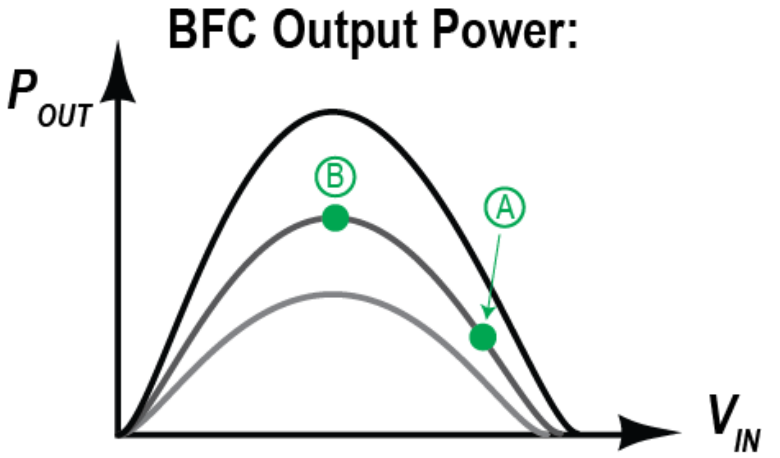
- **To minimize the rate of fuel consumption**
  - *Average power is kept much less than the BFC's MPP* (point B)
  - V_{DD} *near the open-circuit* (point A)
- **The BFC open-circuit is relatively large**

→ *We need no DC-DC converter*

Biosensing System Architecture



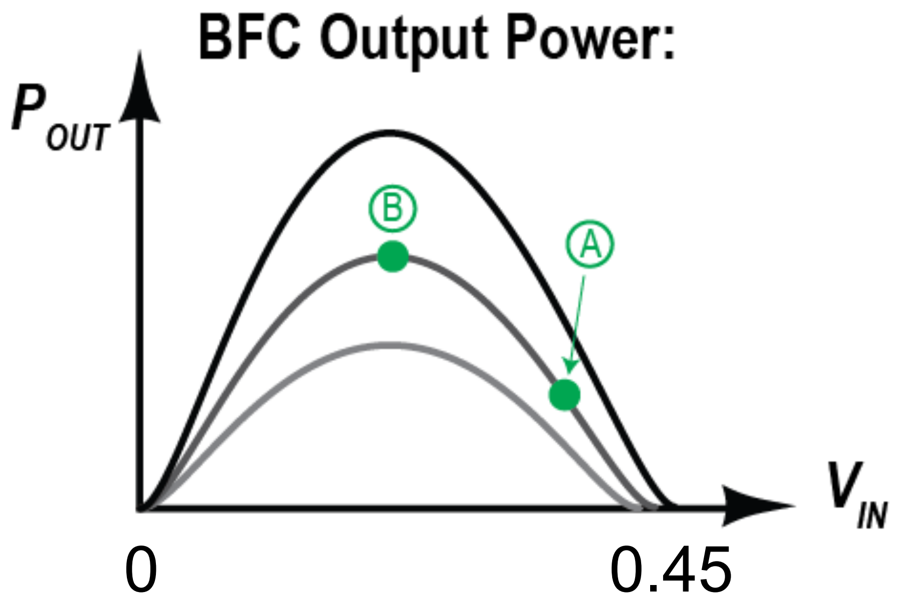




Circuit Design Requirements

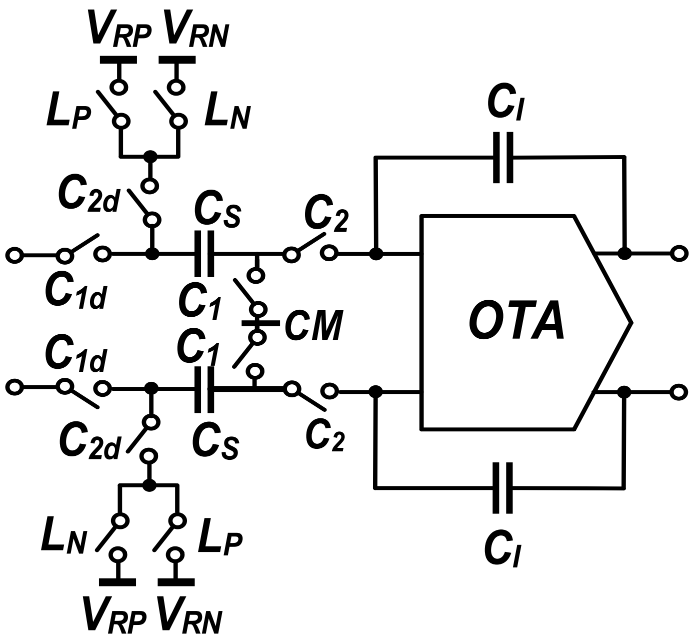
Circuit Design Limitations:

- BFC's open circuit voltage < 0.45V
  - *Complete integrated wireless biosensor must operate at 0.3-0.4V*
- Limited underlying fuel energy
  - *Low energy consumption*

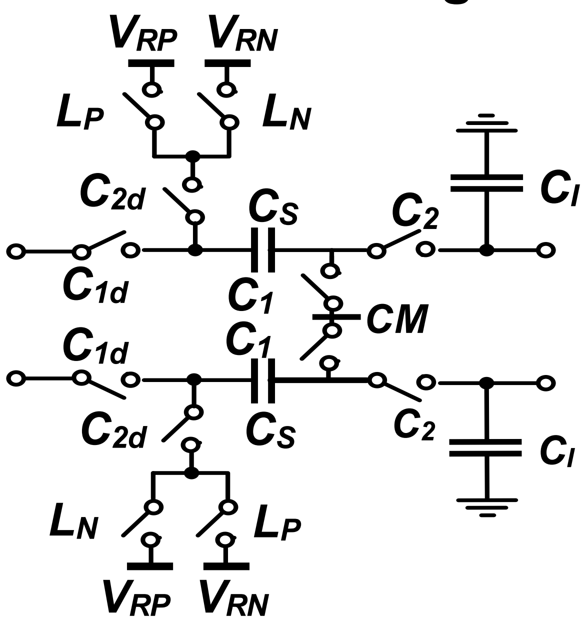


ΔΣ Modulator Architecture

SC active Integrator



SC Passive Integrator

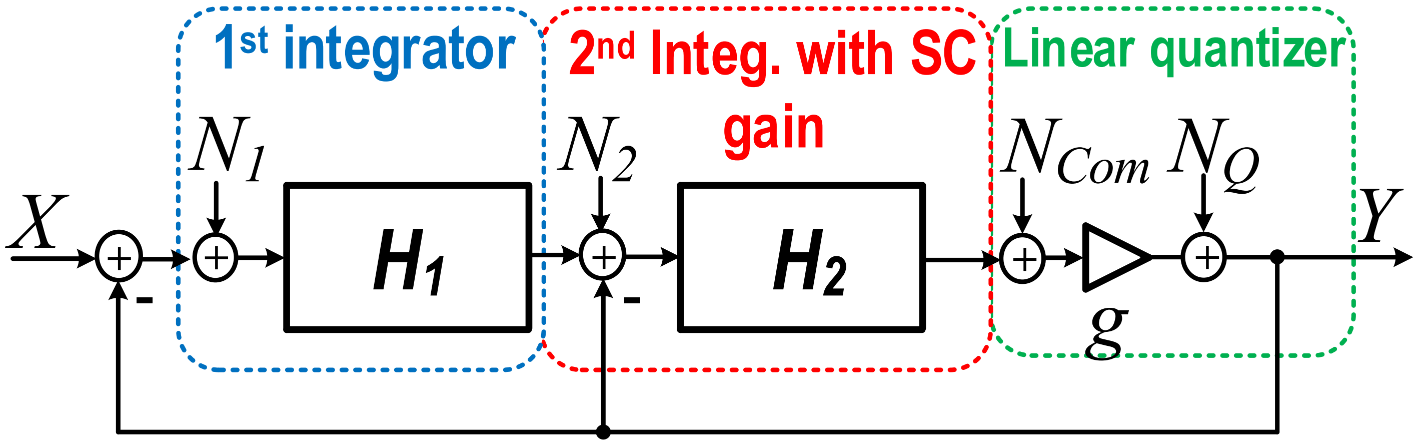


- × 1/f noise
- × Difficult to scale down V_{DD} to 0.3V
- × High power to attain large gain/low noise
- × OTA output swing V_{DD}-2V_{DSAT}~0.1V
- ✓ Lower area, C_I = 5pF

- ✓ 1/f noise free
- ✓ Easy to scale down V_{DD}
- ✓ Energy-efficient
- × Leaky integrator with no gain
- × Larger area, C_I = 30pF

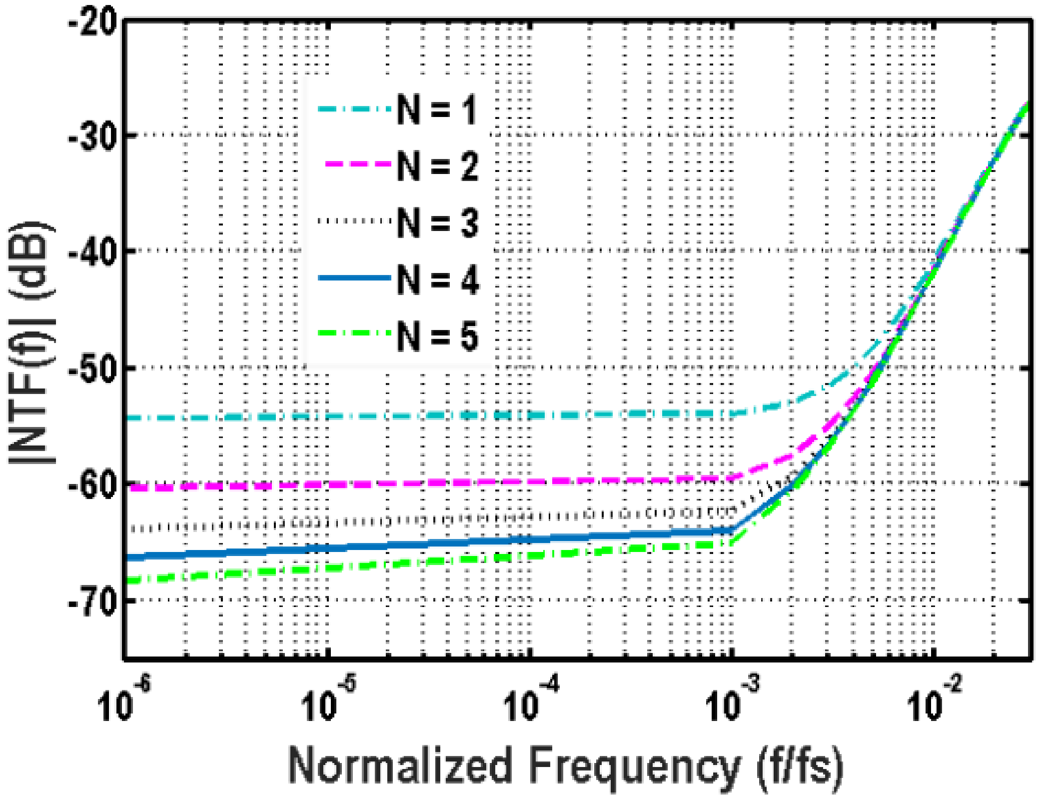
ΔΣ Modulator Architecture

- 2^{nd}-order single-loop feedback architecture with 1-bit quantizer
- Energy-efficient passive filters as alternative to power-hungry active ones



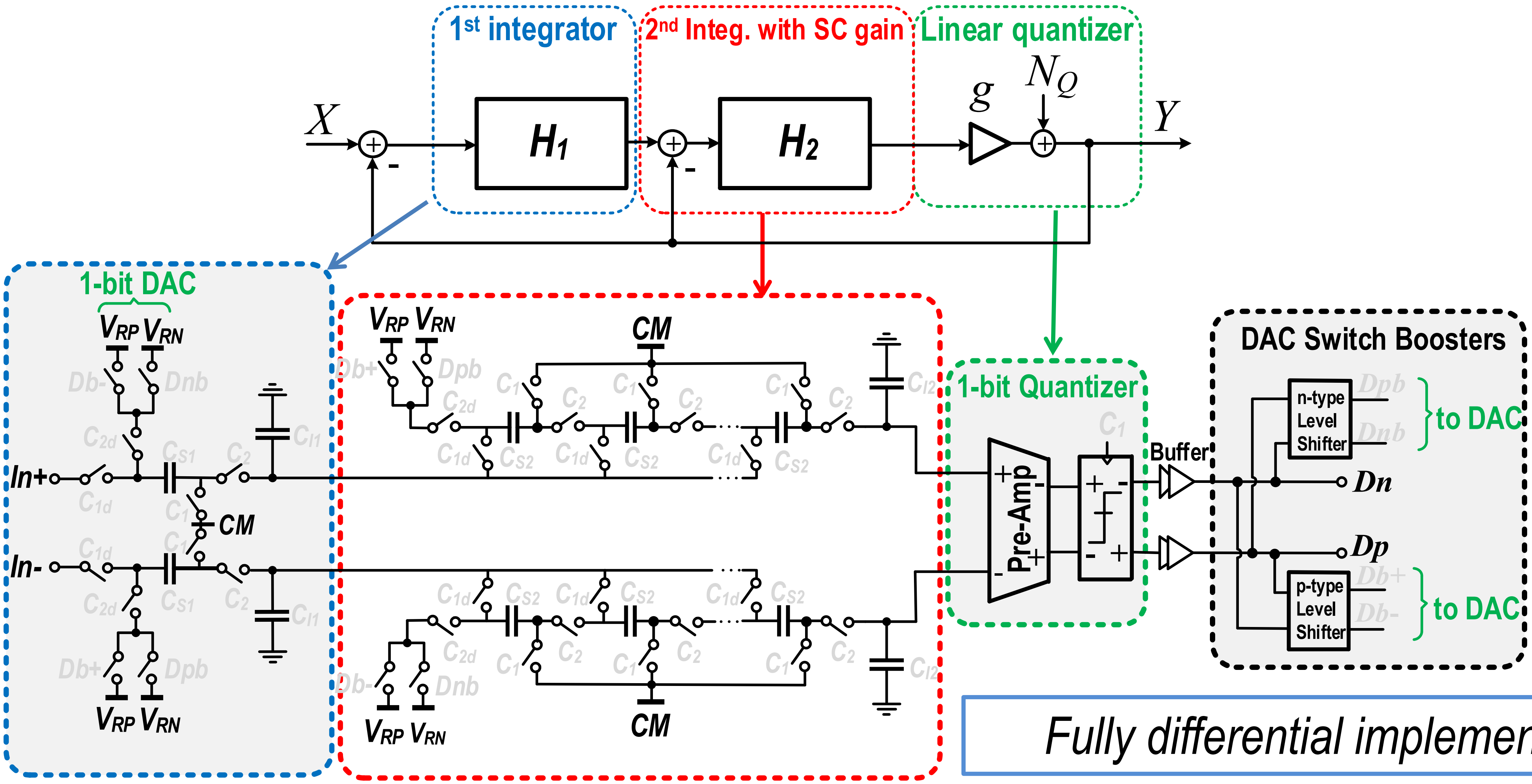
$$Y \approx X + N_1 + \frac{N_2}{H_1} + \frac{N_{Com}}{H_1 H_2} + \frac{N_Q}{g H_1 H_2}$$

$$NTF = \frac{Y}{N_Q} = \frac{1}{g H_1 H_2}$$



Impact of passive gain *N* on |NTF|

ΔΣM Circuit

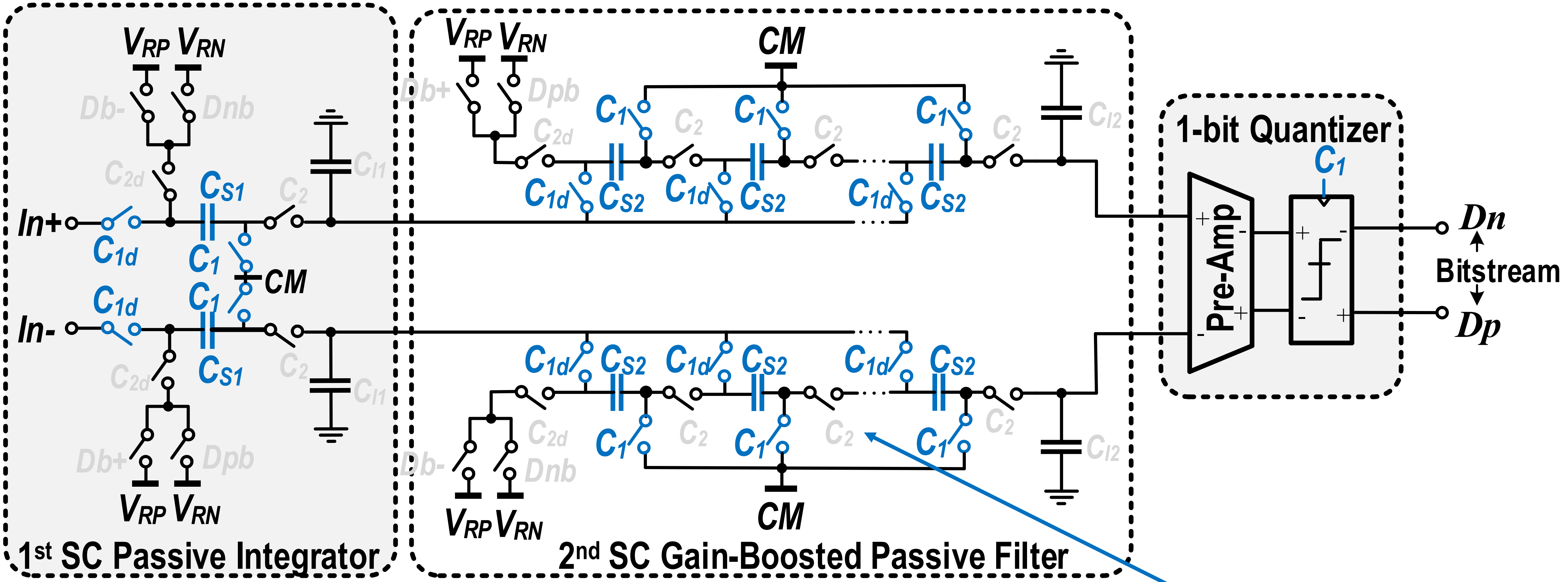


SC passive filter

SC gain-boosting passive filter

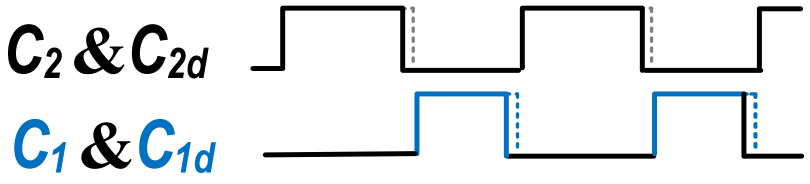
Fully differential implementation

ΔΣM Circuit

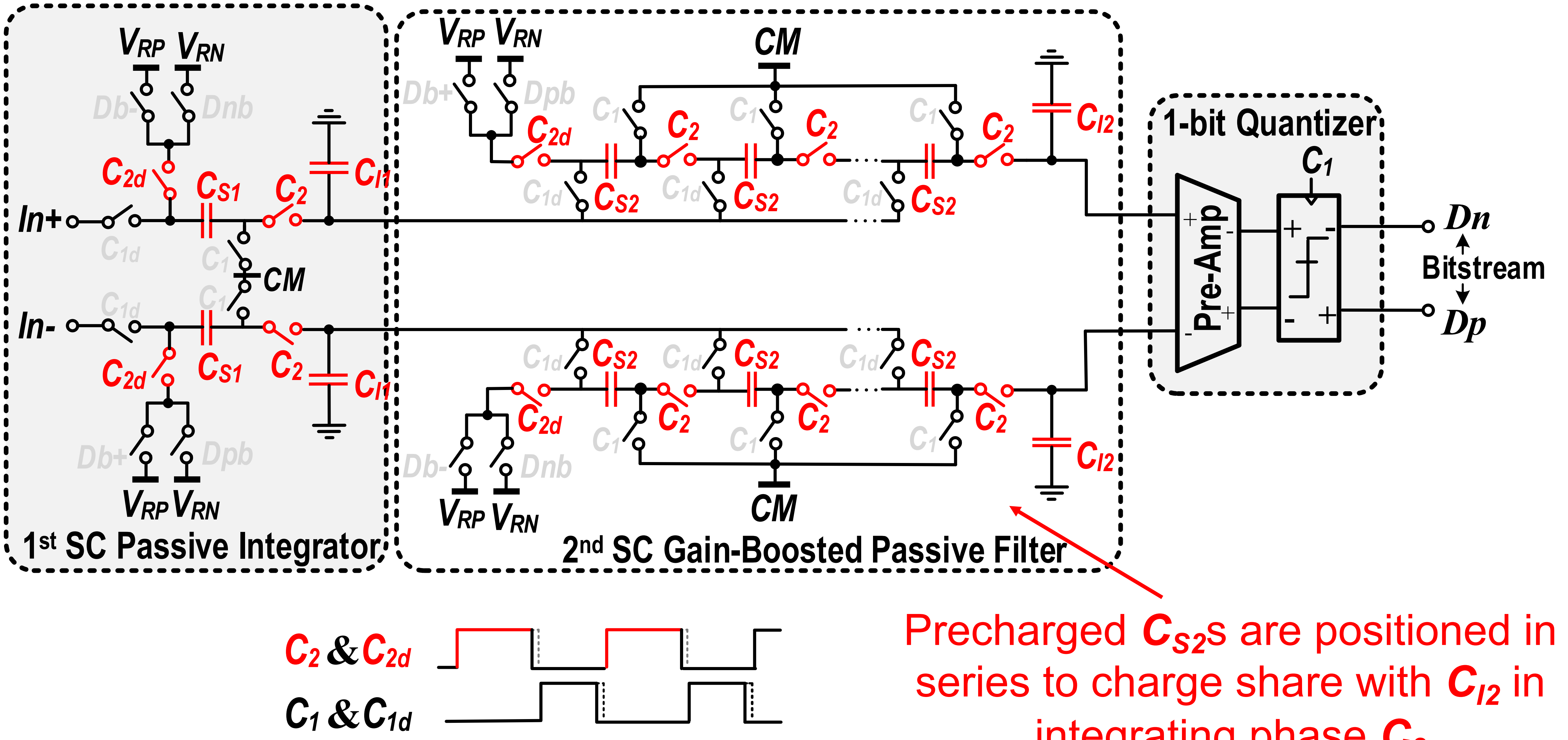


Parallel sampling onto C_{S2}s in sampling phase C_1

- **Charge redistribution gain-boosting scheme**

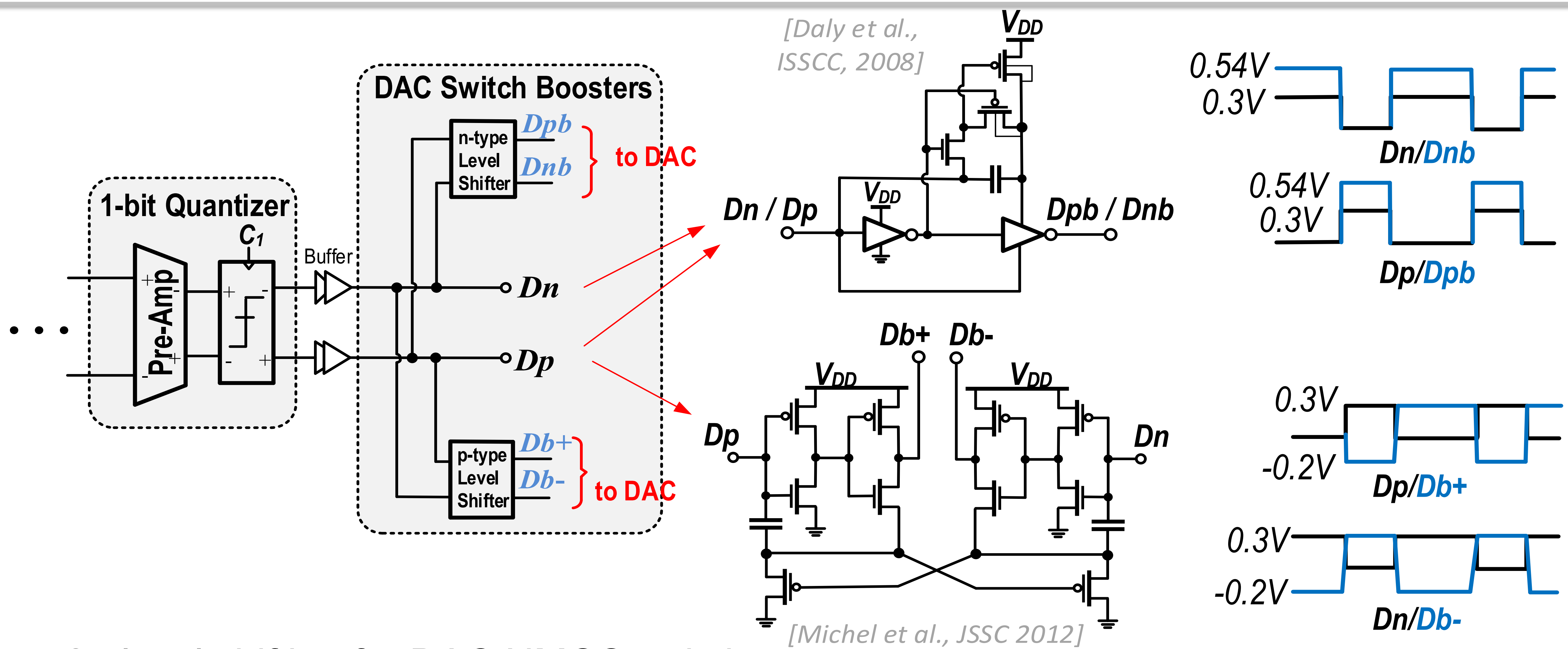


ΔΣM Circuit



Precharged C_{S2}s are positioned in series to charge share with C_{I2} in integrating phase C_2

0.3V ΔΣM Circuit Design



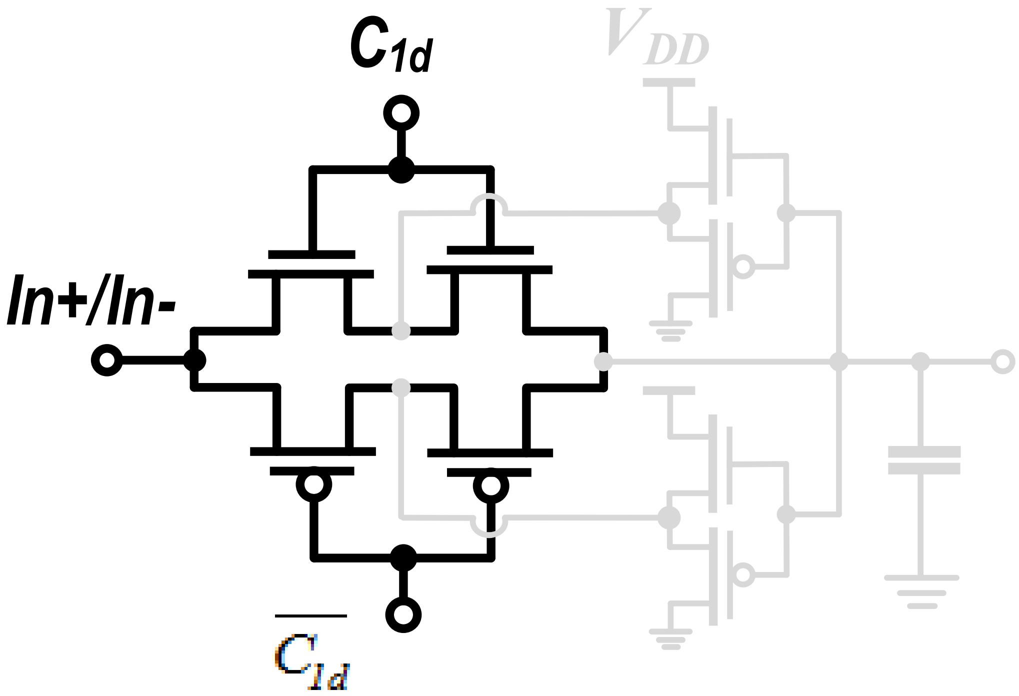
- 2× level shifting for DAC NMOS switches
- -200mV charge pump level shifter for DAC PMOS switches

0.3V ΔΣM Circuit Design

Sampling switch

To increase $g_{ds,ON}/I_{OFF}$

- *Cascading*
- Feedback amplifier
- 3× clock boosting for gate of NMOS switch
- -200mV charge pump level shifter for gate of PMOS switch



0.3V ΔΣM Circuit Design

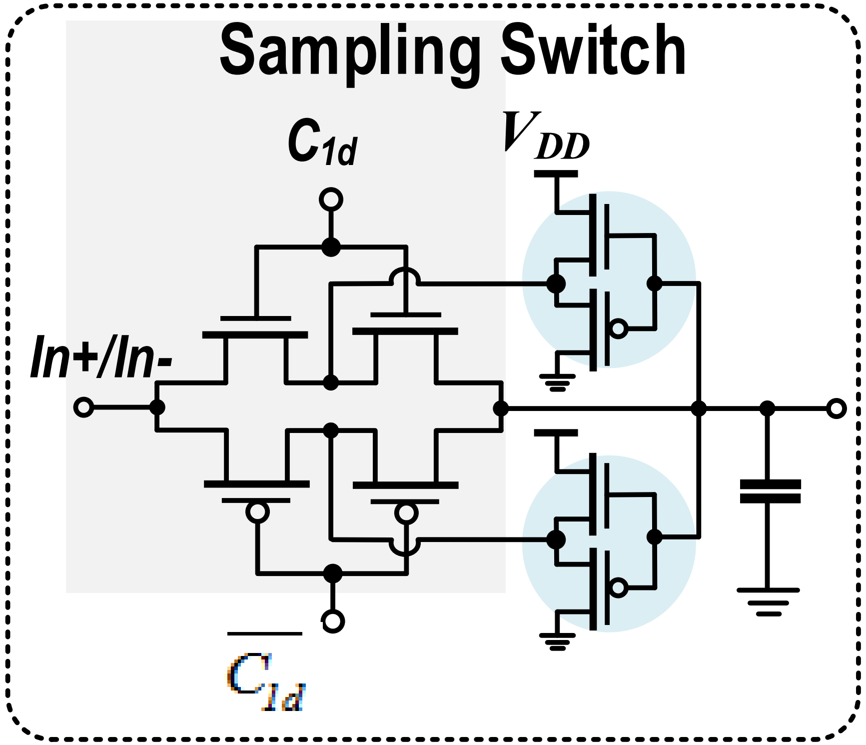
Sampling switch

To increase $g_{ds,ON}/I_{OFF}$

- Cascading
- Feedback amplifier:

PMOS source follower with self-biased NMOS

- 3× clock boosting for gate of NMOS switch
- -200mV charge pump level shifter for gate of PMOS switch



0.3V ΔΣM Circuit Design

Sampling switch

To increase $g_{ds,ON}/I_{OFF}$

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- *3× clock boosting for gate of NMOS switch*
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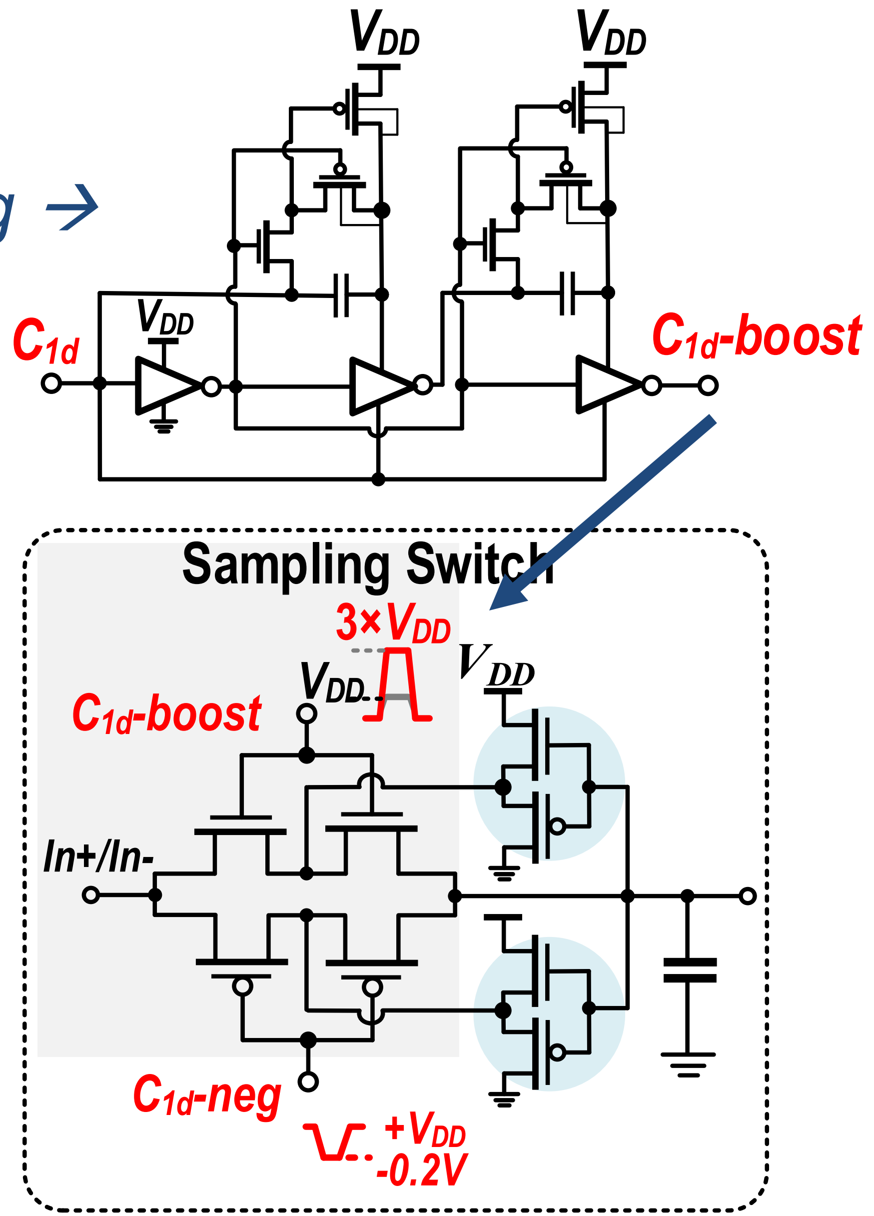
3× Clock Boosting →



0.3V ΔΣM Circuit Design

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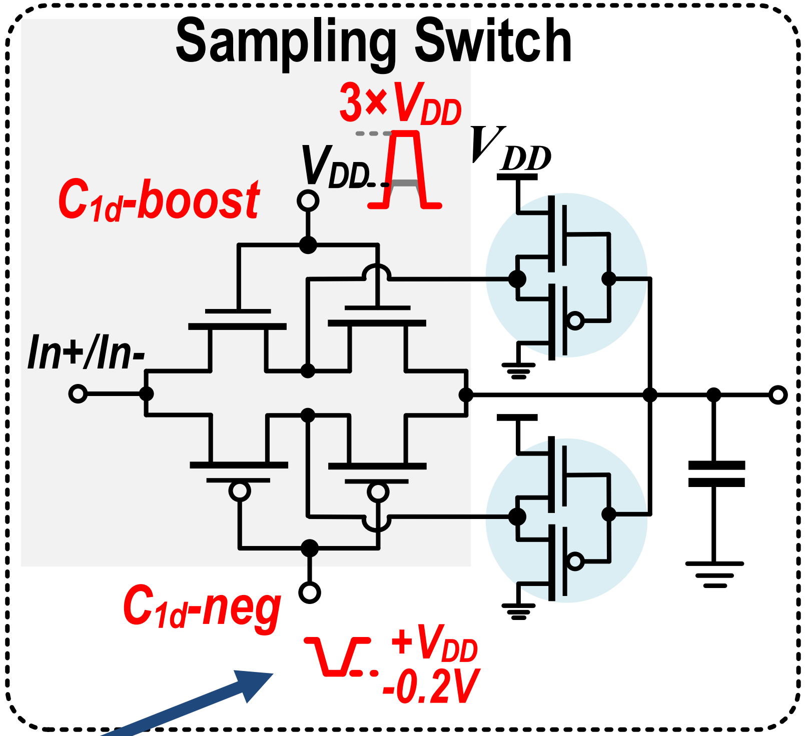
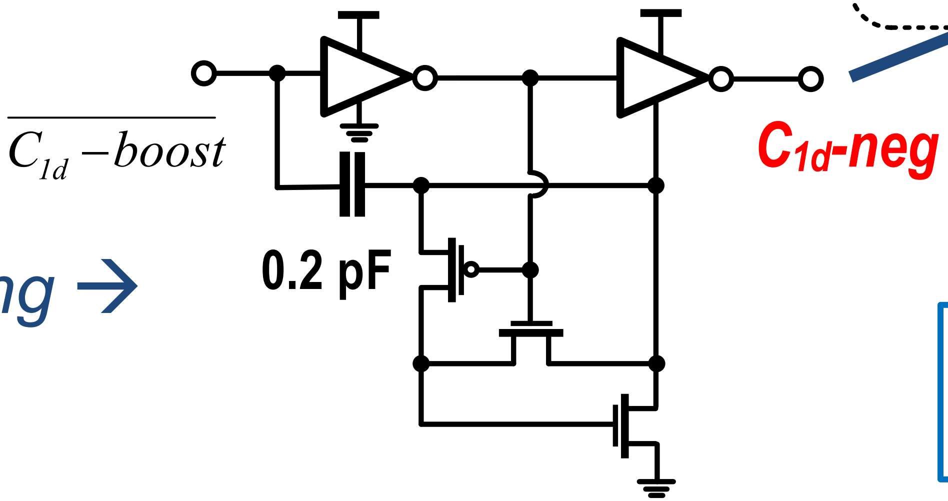


Negative Level Shifting →

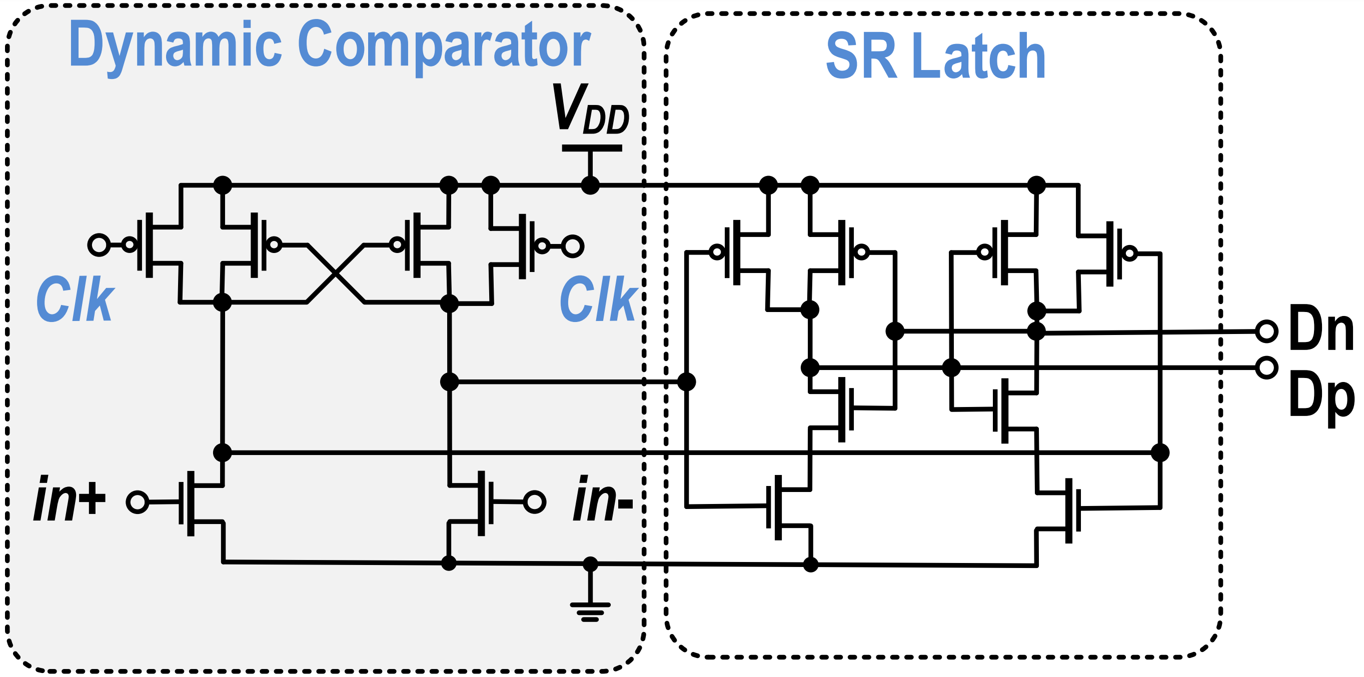


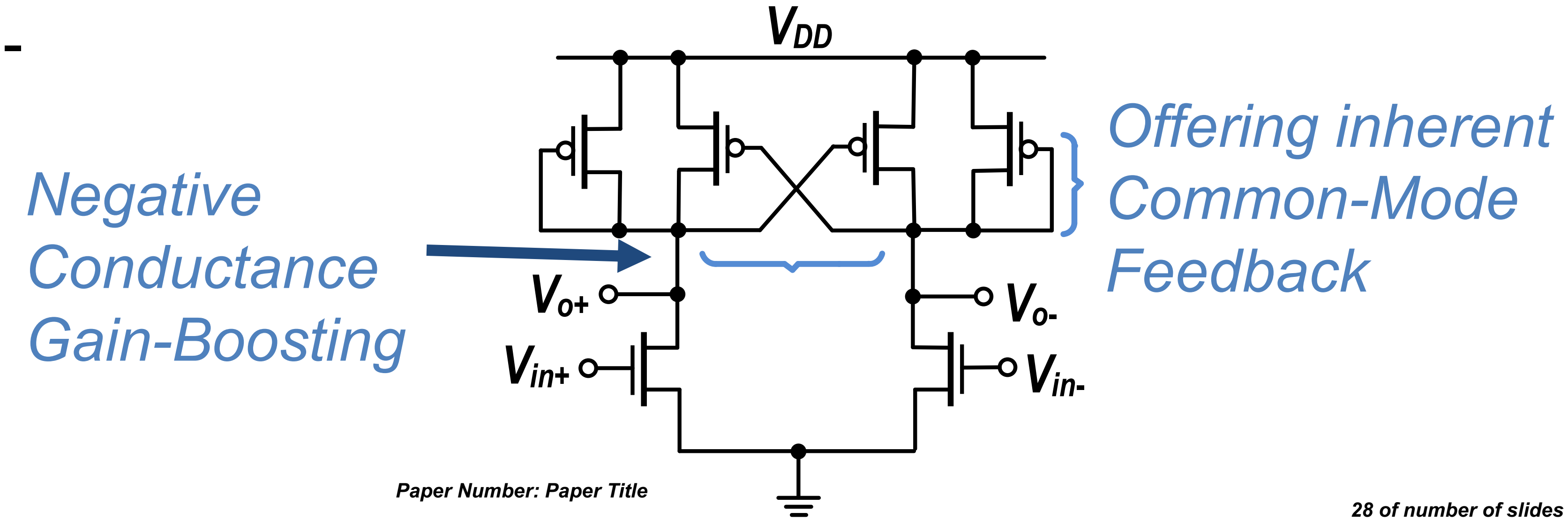
→ *Increases SNDR by 3dB*

0.3V ΔΣM Circuit Design

0.3V Single-Bit Quantizer:

- **Dynamic comparator**
- **Preamplifier**
  - Low-V_{th} transistors
  - Stacking only two transistors
  - Positive feedback gain-boosting

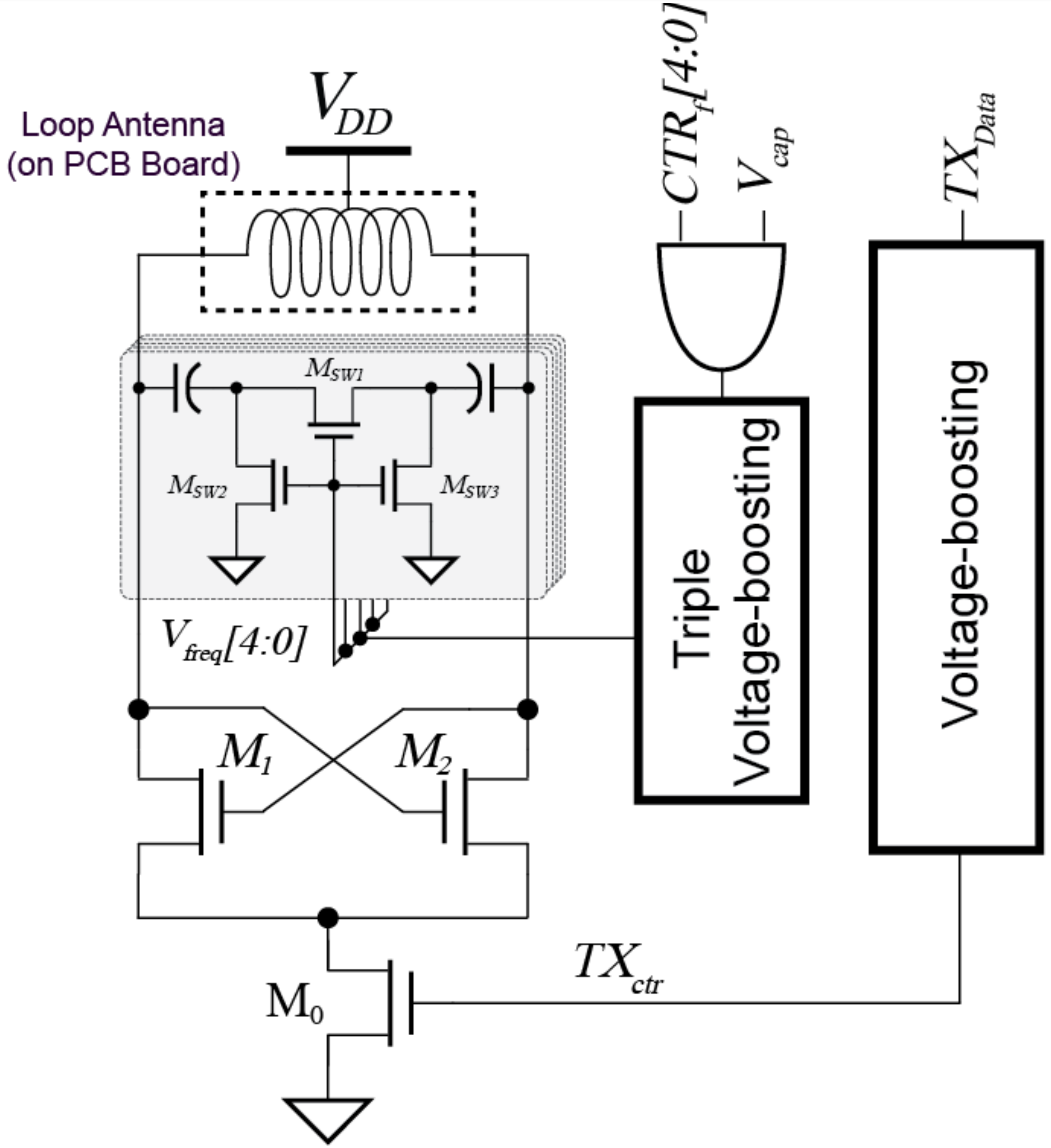




TX Design

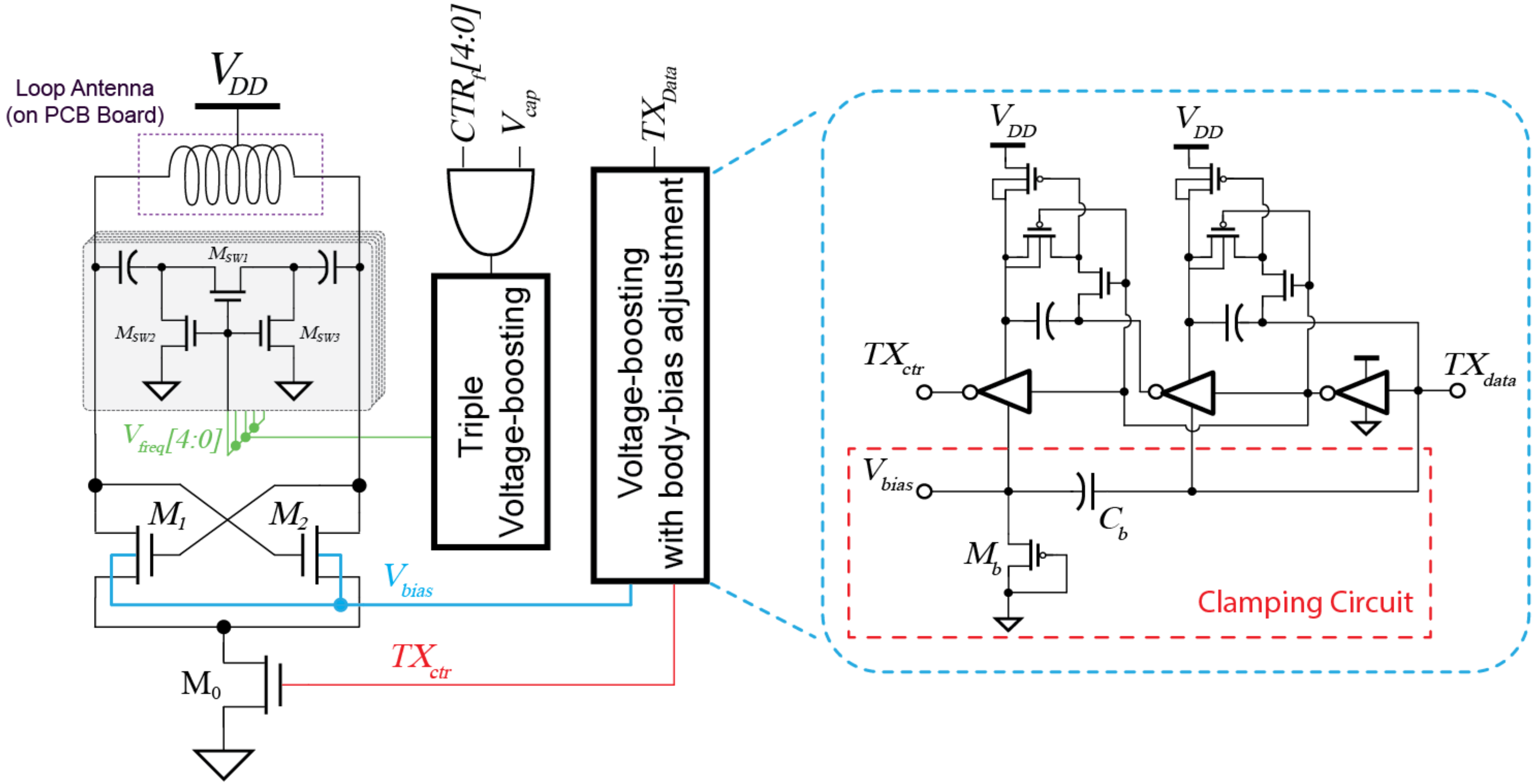
- **Direct-RF power oscillator (RFPO)**
  - Inherent impedance matching to antenna
  - Low leakage power during inactive phase
  - OOK-modulation

- **0.3-0.4V low supply voltage**
  - Limits the efficiency, I_{ON}/I_{OFF} ratio and start-up time
  - Boost the power supply
  - Large inductors or capacitors



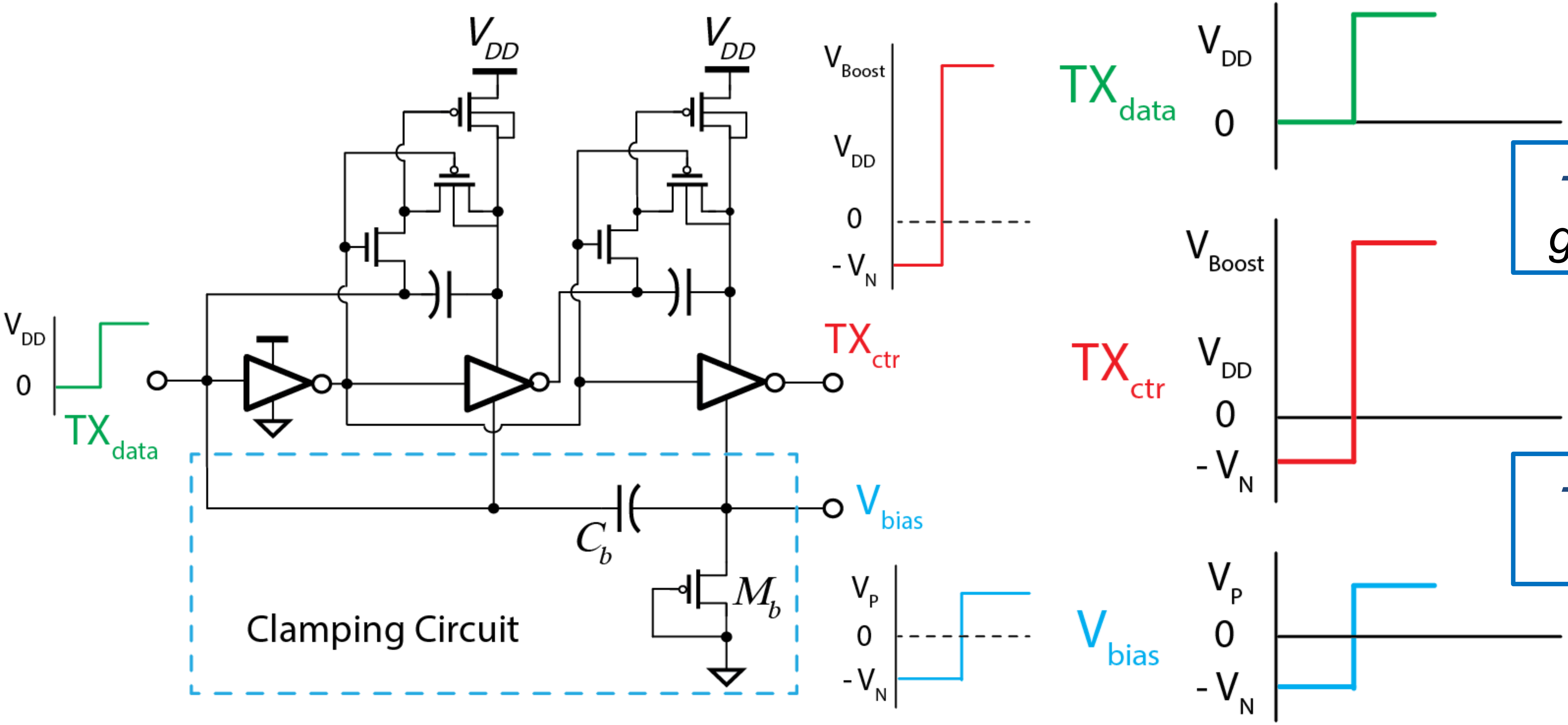
TX Design

- TX control circuit for improving I_{ON}/I_{OFF} ratio of transistors and start-up time



TX Design

- When TX_{data} = '1', TX_{ctr} is boosted 3× and V_{bias} is set to ~V_{th}



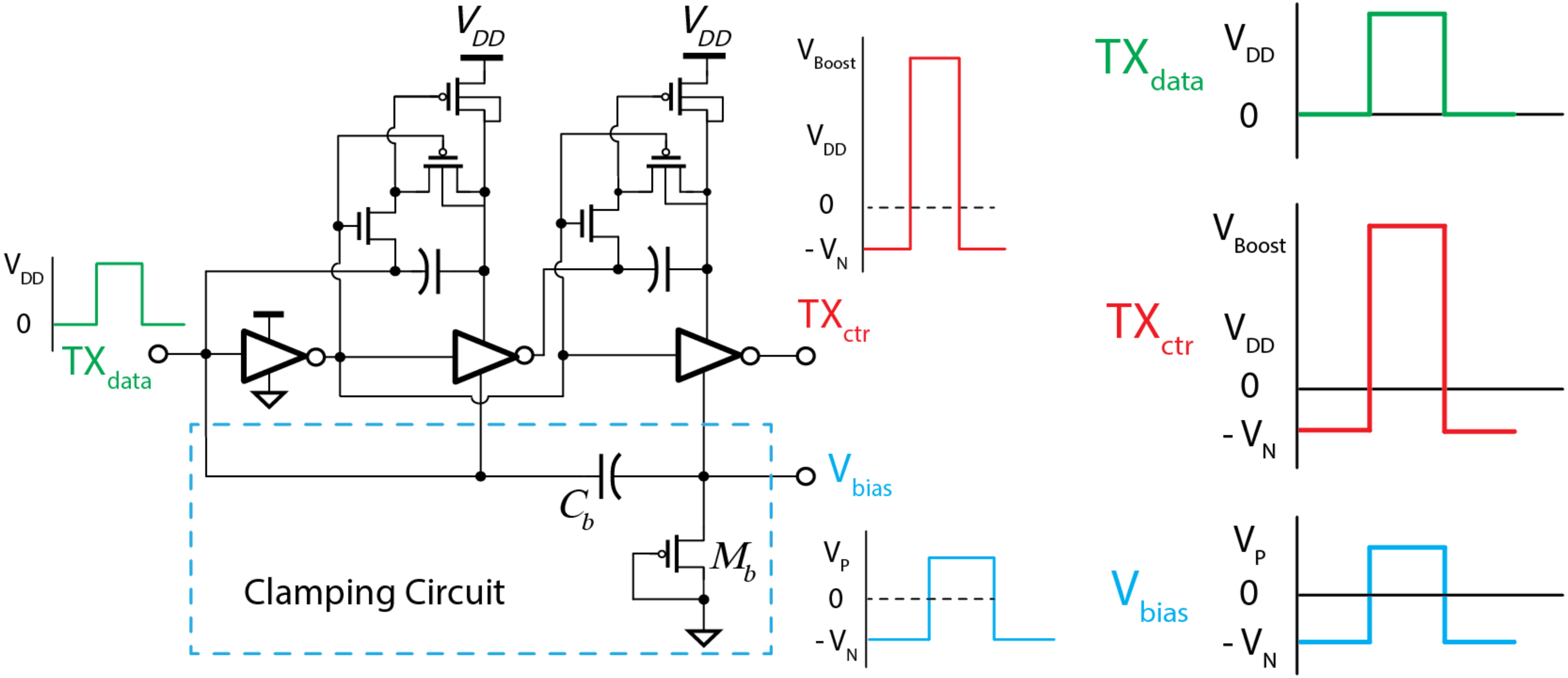
→ *Increases $g_{ds,ON}$ by 94%*

→ *Increases g_m by 30%*

→ *Improves start-up time and power-efficiency*

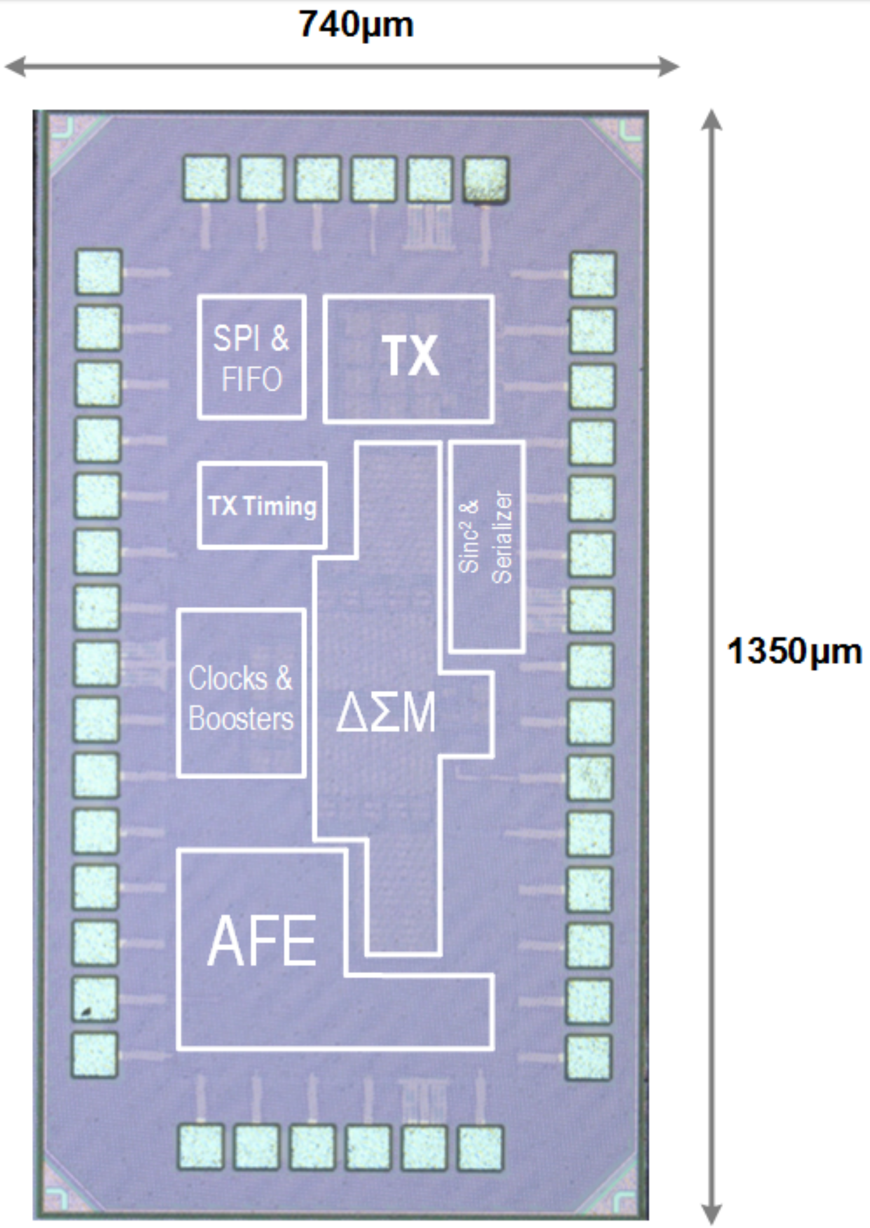
TX Design

- When TX_{data} = 0, the V_{bias} is set to ~ $-V_{th}$



→ *Helps reduce <u>off-leakage</u> up-to 92% during TX inactive phase*

Die Micrograph



TSMC 65nm LP CMOS

1 mm^2 with pads

On-chip ΔΣ ADC clocks

Power supply: 0.3-0.4V

Power break-down @ 0.3V:

TX active power: 30.1µW

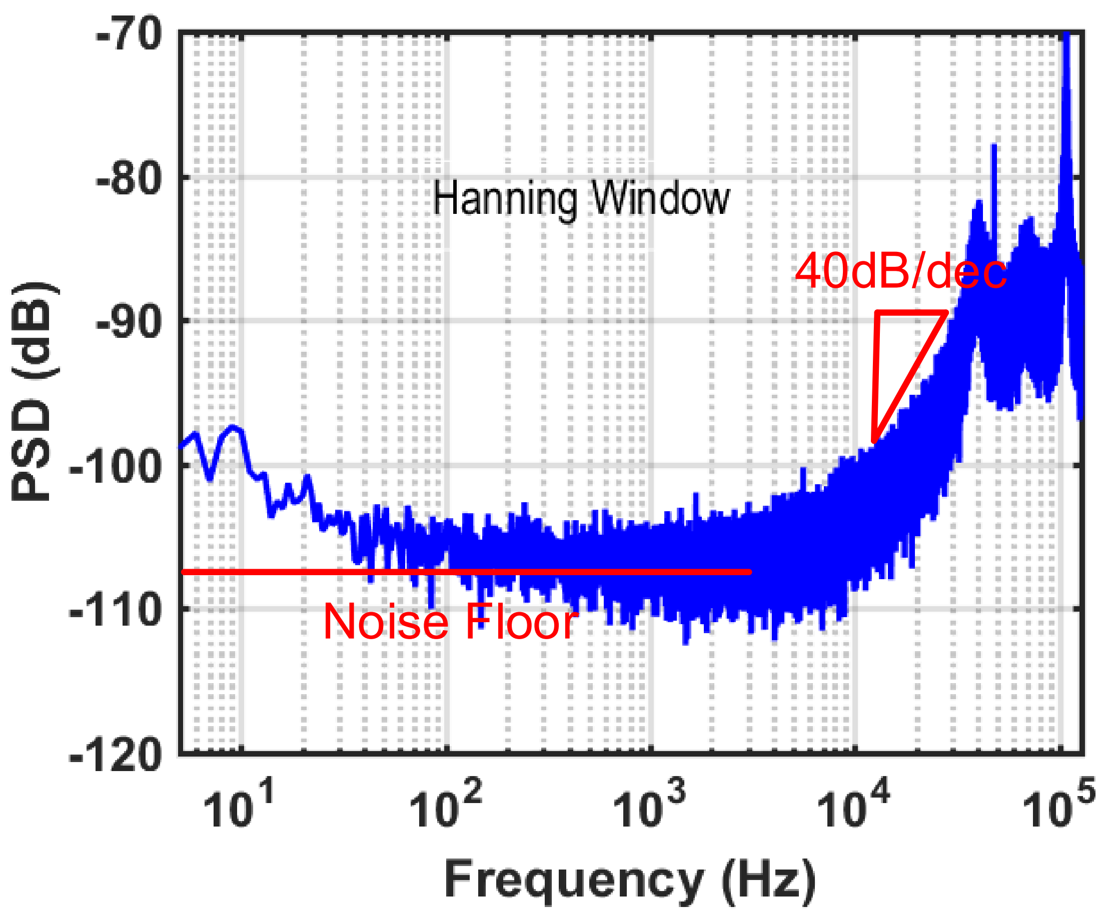
TX standby power: 2.88nW

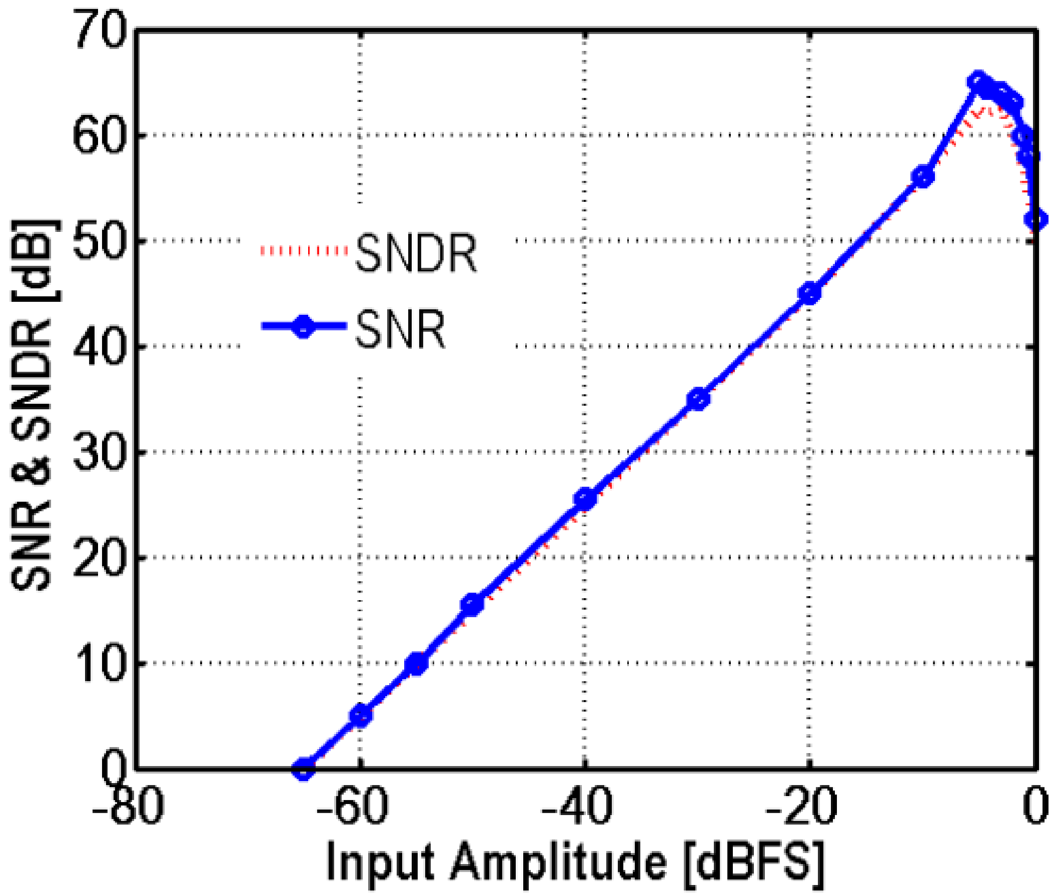
ΔΣ ADC active power: 180nW

ΔΣ ADC standby power 2nW

In-Vitro Experimental Results

PSD of ΔΣ Modulator



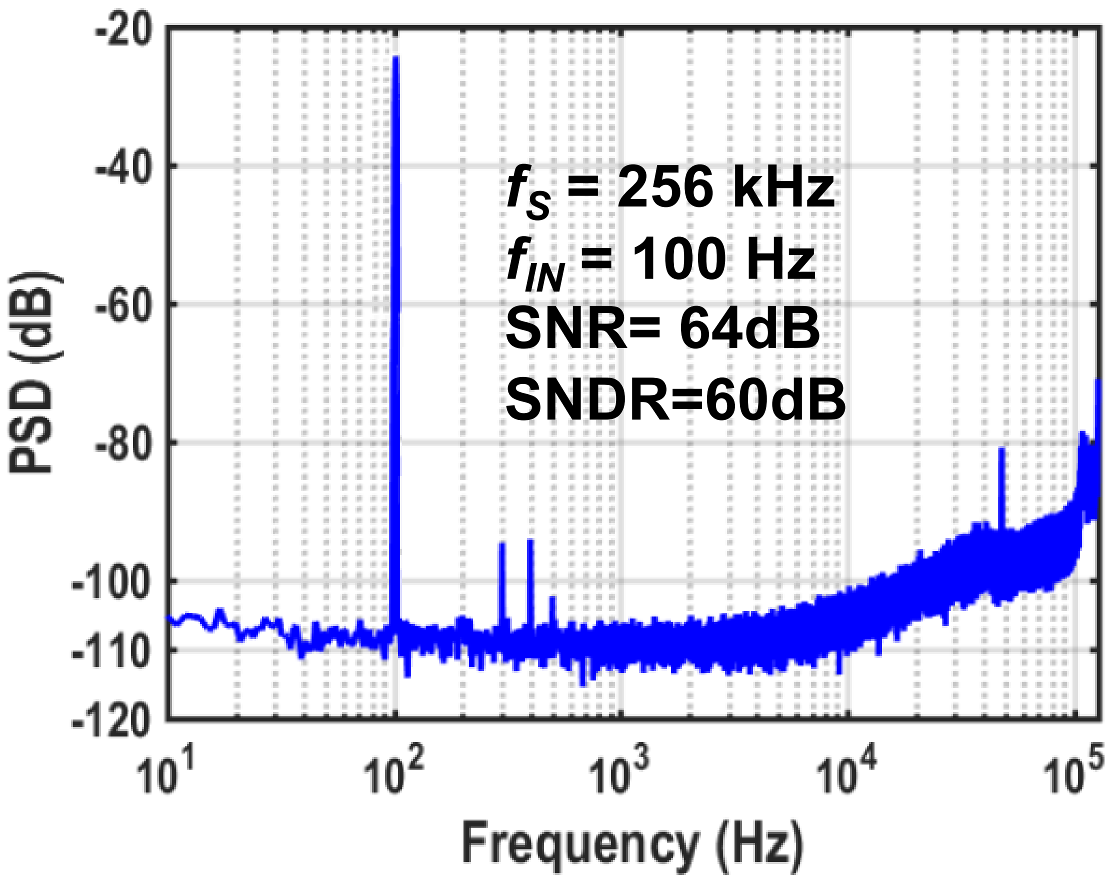


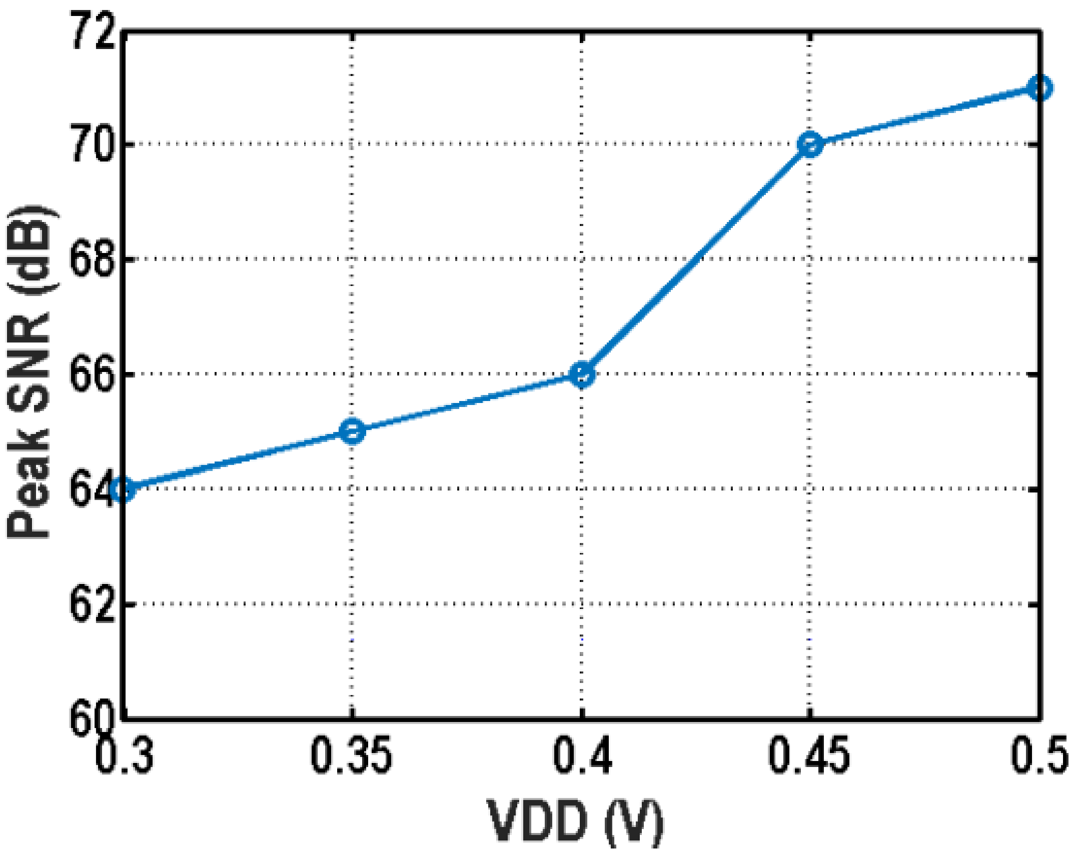
2^{nd}-order noise-shaping

Noise floor: -105dB

SNR = 64dB / SNDR = 60dB

PSD of ΔΣ Modulator





V_{DD} = 0.3V

- Sampled at 256kHz clock

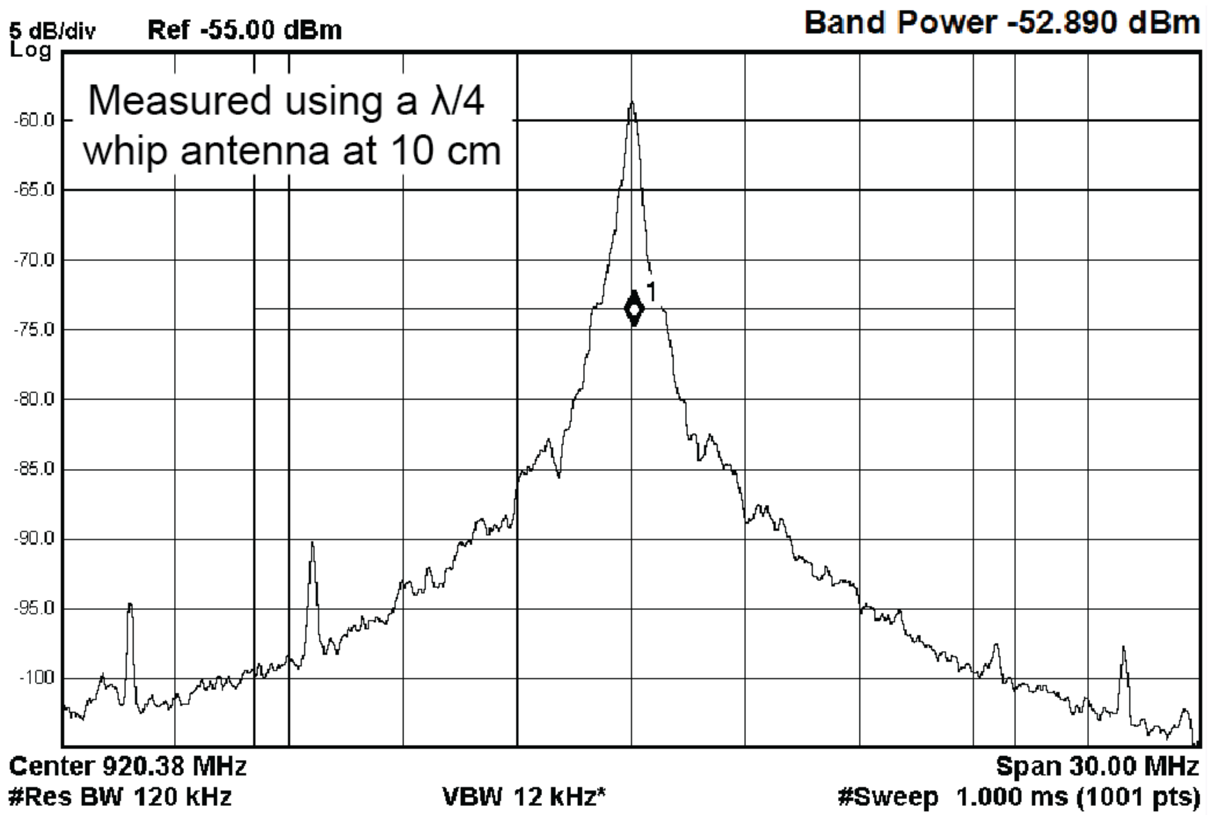
- ADC is robust to supply variation

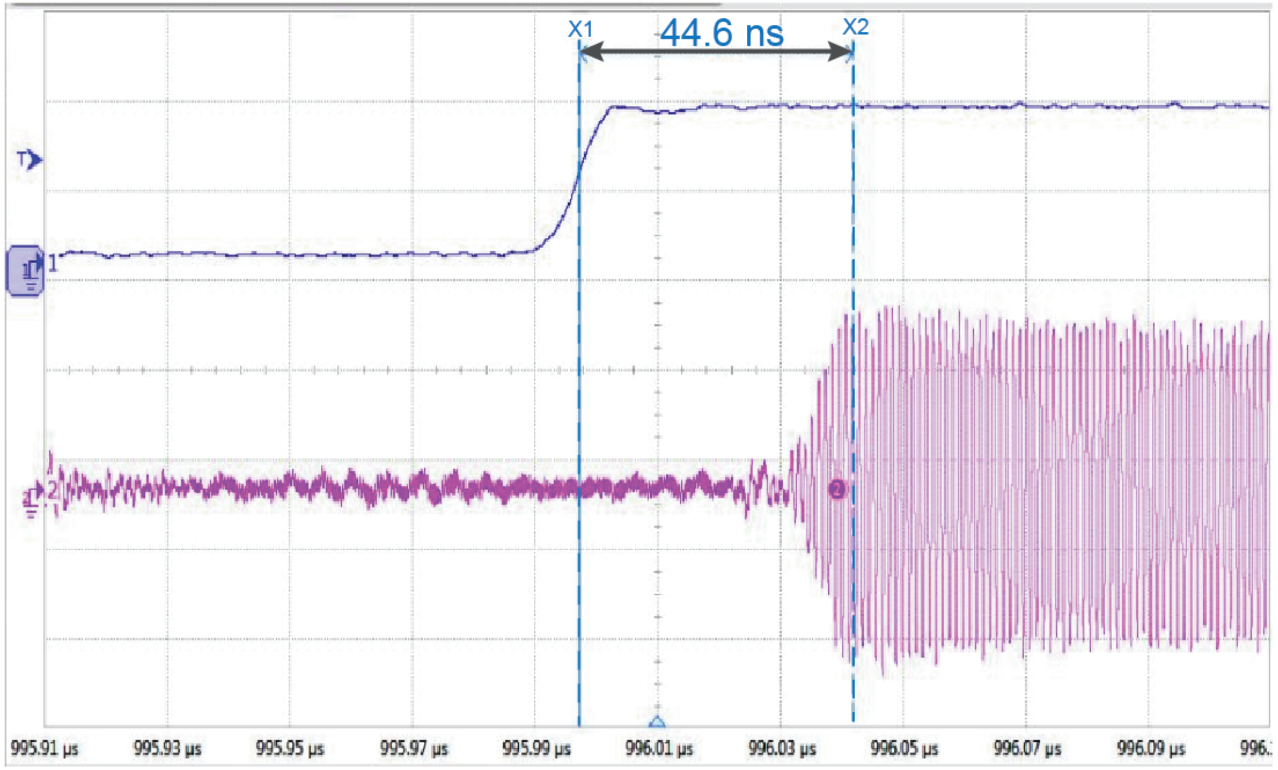
SNR = 71dB @ 0.5V

SNDR = 65.5dB @ 0.5V

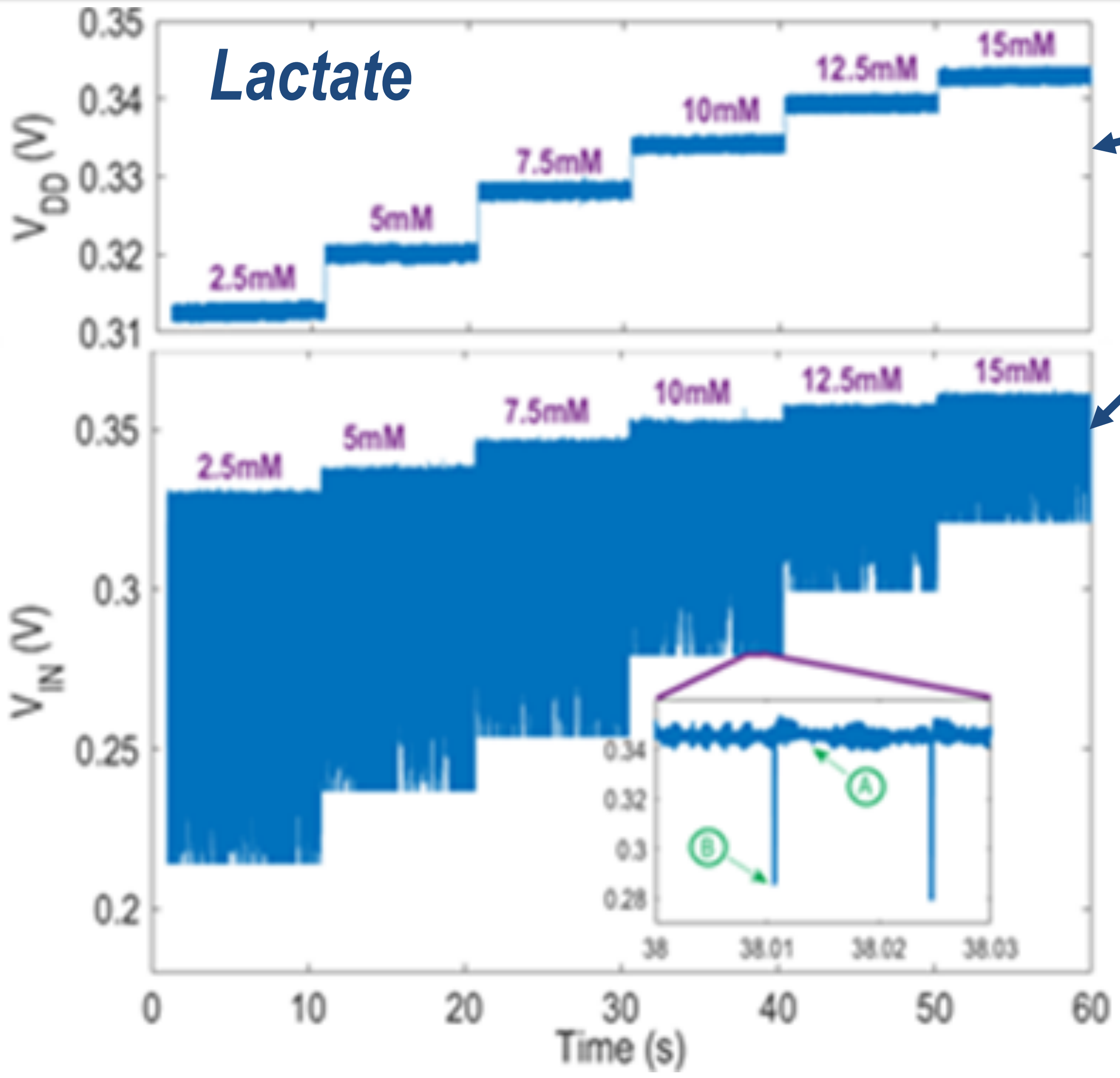
TX Performance

- Operating at 1Mbps, the TX output power > -53dBm at 10cm with V_{DD} =0.3V
- Consumes 30pJ/bit at 0.3V
- Start-up time < 44.6ns



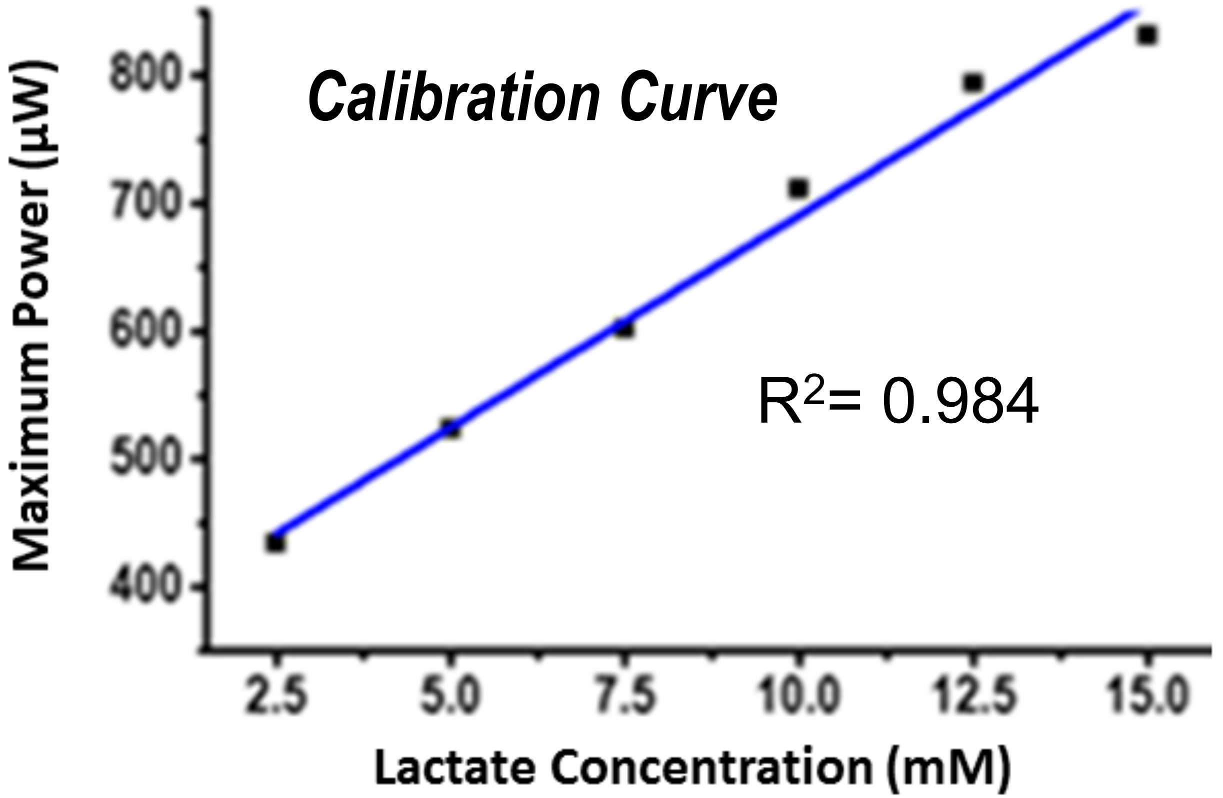


In-Vitro Experiments (Lactate)



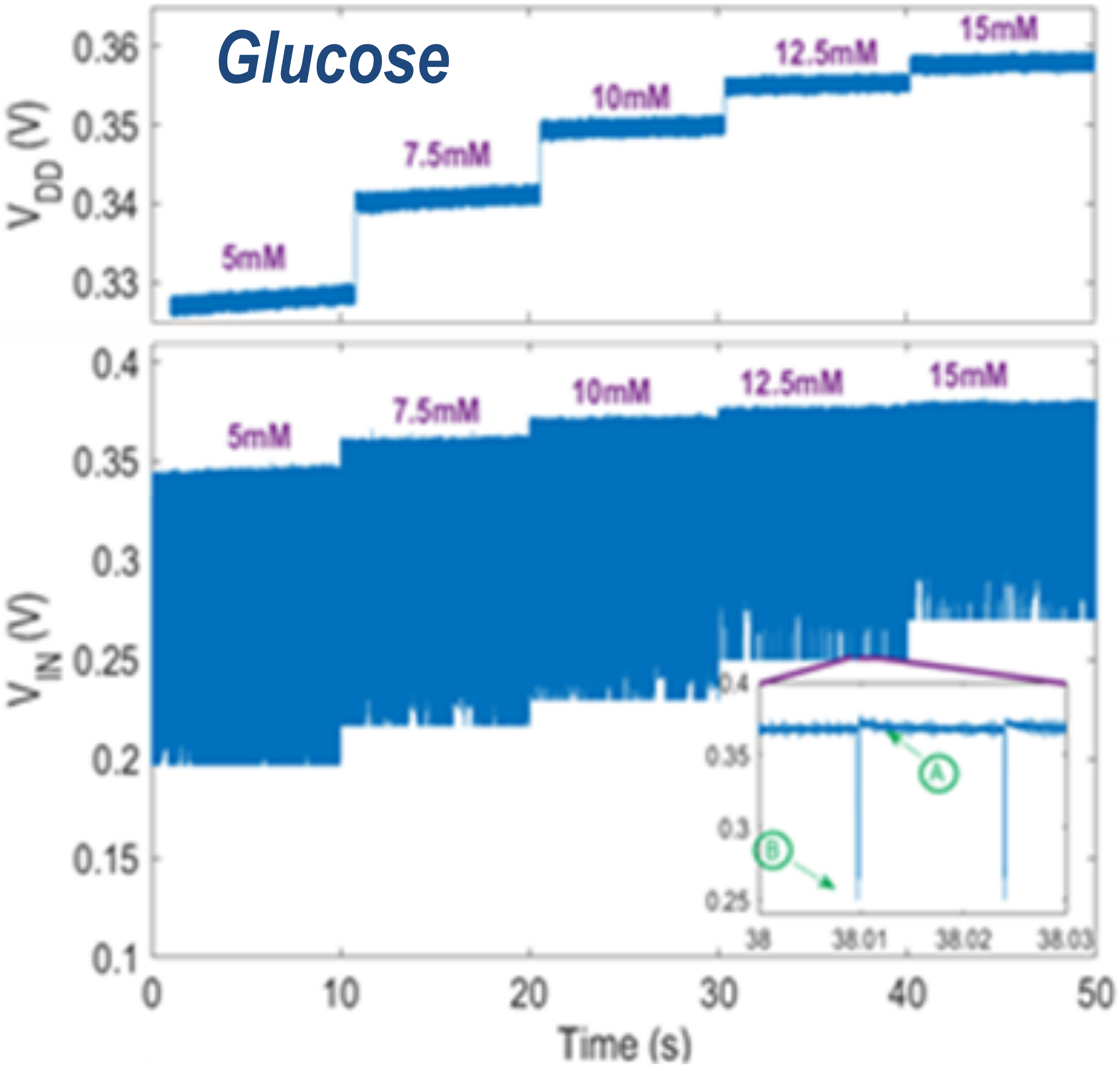
Dynamic V_{DD} variation

BFC output power



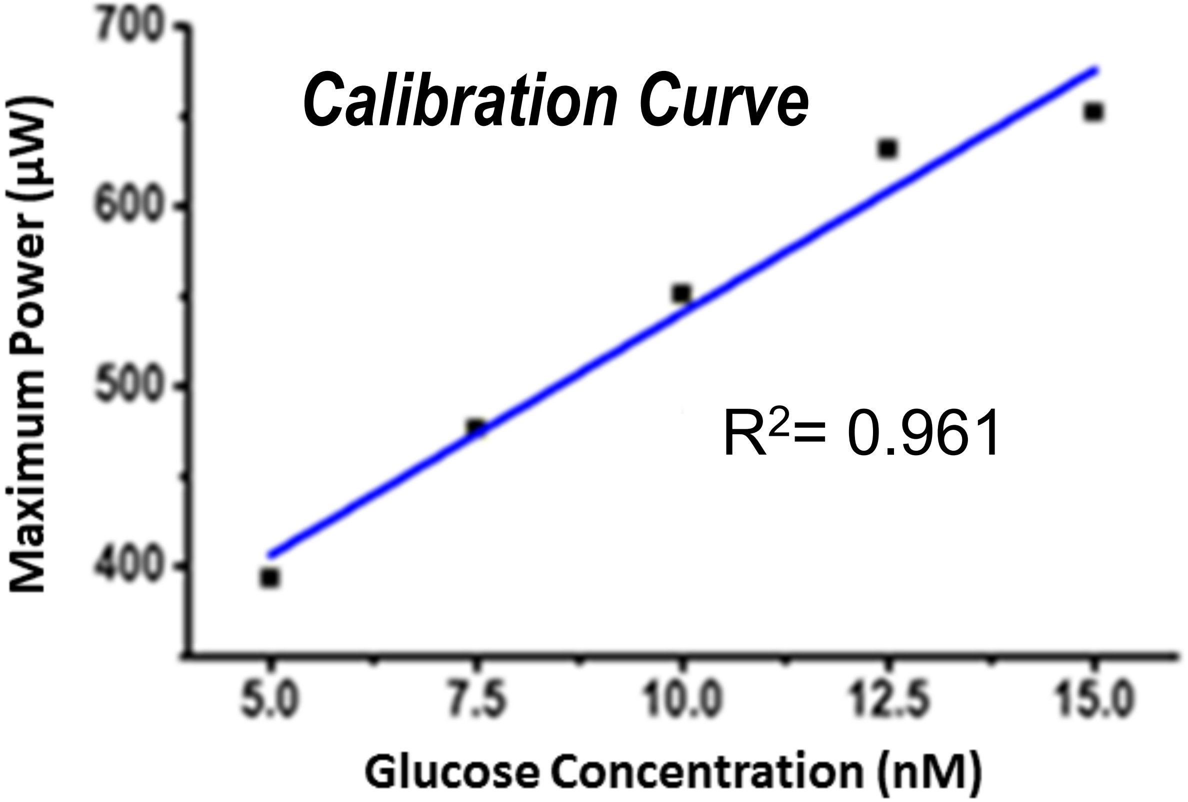
- Physiologic ranges in human perspiratio

In-Vitro Experiments (Glucose)



Dynamic V_{DD} variation

BFC output power



- Physiologic ranges in human perspiration

Conclusions

- **Demonstration of an integrated self-powered biochemical sensing system with digital wireless readout**
- **At 1% duty-cycle, the ADC and TX consume an average of 1.15μW**
- **Passive ΔΣ ADC and RF power oscillator circuits enabled 0.3V Biosensor**
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Thank you for listening!