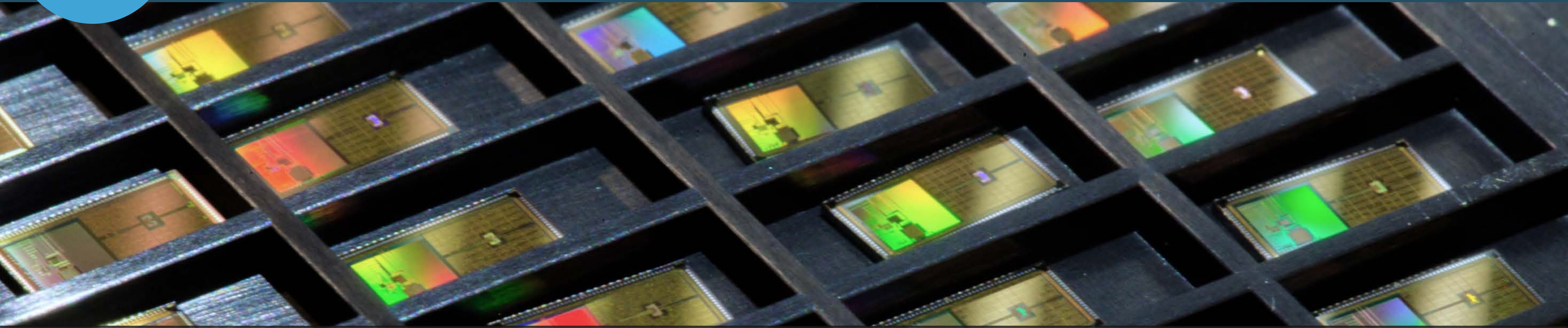
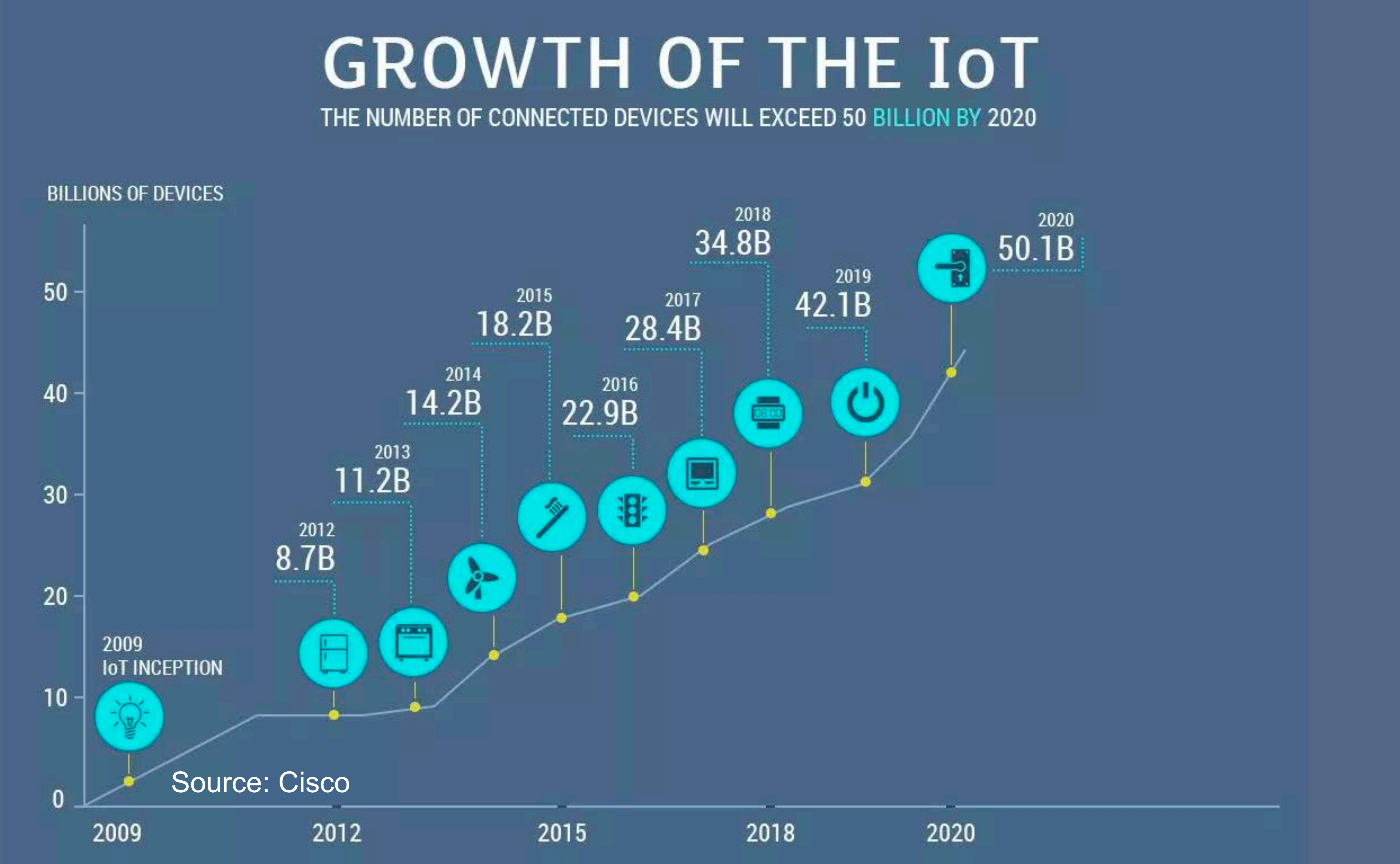
UC San Diego
Jacobs School of Engineering

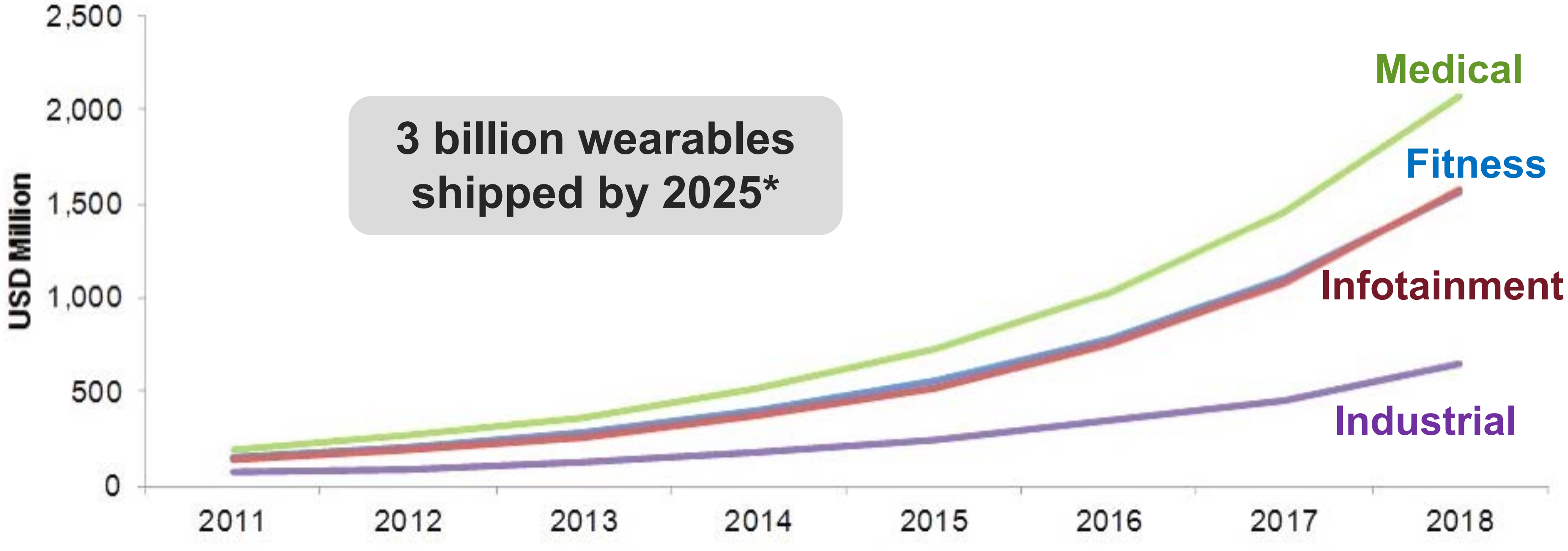


Ultra-Low-Power Integrated Circuits and Physiochemical Sensors for Next-Generation “Unawearables”

Patrick Mercier
University of California, San Diego


GROWTH OF THE IoT
THE NUMBER OF CONNECTED DEVICES WILL EXCEED 50 BILLION BY 2020
BILLIONS OF DEVICES
50
40
30
20
10
0
2009
IoT INCEPTION
2012
8.7B
2013
11.2B
2014
14.2B
2015
18.2B
2016
22.9B
2017
28.4B
2018
34.8B
2019
42.1B
2020
50.1B
2009
2012
2015
2018
2020
Source: Cisco

Wearables:
an exciting high-growth market



*IDTechEx 2015 Report

Source: Transparency Market Research

Why aren't we there now?

Size & Usability:

Need to develop sensors that are small & seamlessly integrated into daily life

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Battery Life:

Need ultra-low-power and/or energy harvesting to minimize re-charging

---

Utility:

Need to develop sensors that are actually useful

Mission:

Address these issues through innovative transdisciplinary research

Wearables Roadmap

MARKET SIZE

PHASE I
Devices on the wrist

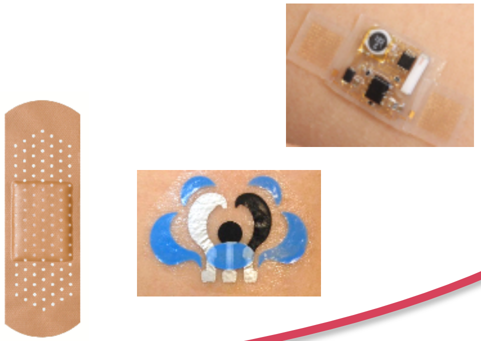
- \+ Well-understood use case
- \+ Room for a battery

- – Limited sensing opportunities
- – Maintenance burden

PHASE II
Patches

- \+ Many sensing modalities

- – Requires daily user interaction
- – Not convenient



PHASE III
Unawearables

Applications:
Health & Fitness
Entertainment
Medical

- \+ Built directly into already used objects/textiles
- \+ Many sensing modalities
- \+ Automatic wireless comms, energy harvesting

Research challenges: new biosensors, ultra-low-power bioelectronics, energy harvesting, soft integration

2018 2020 2022

Why aren't we there now?

Size & Usability:

Need to develop sensors that are small & seamlessly integrated into daily life

Battery Life:

Need ultra-low-power and/or energy harvesting to minimize re-charging

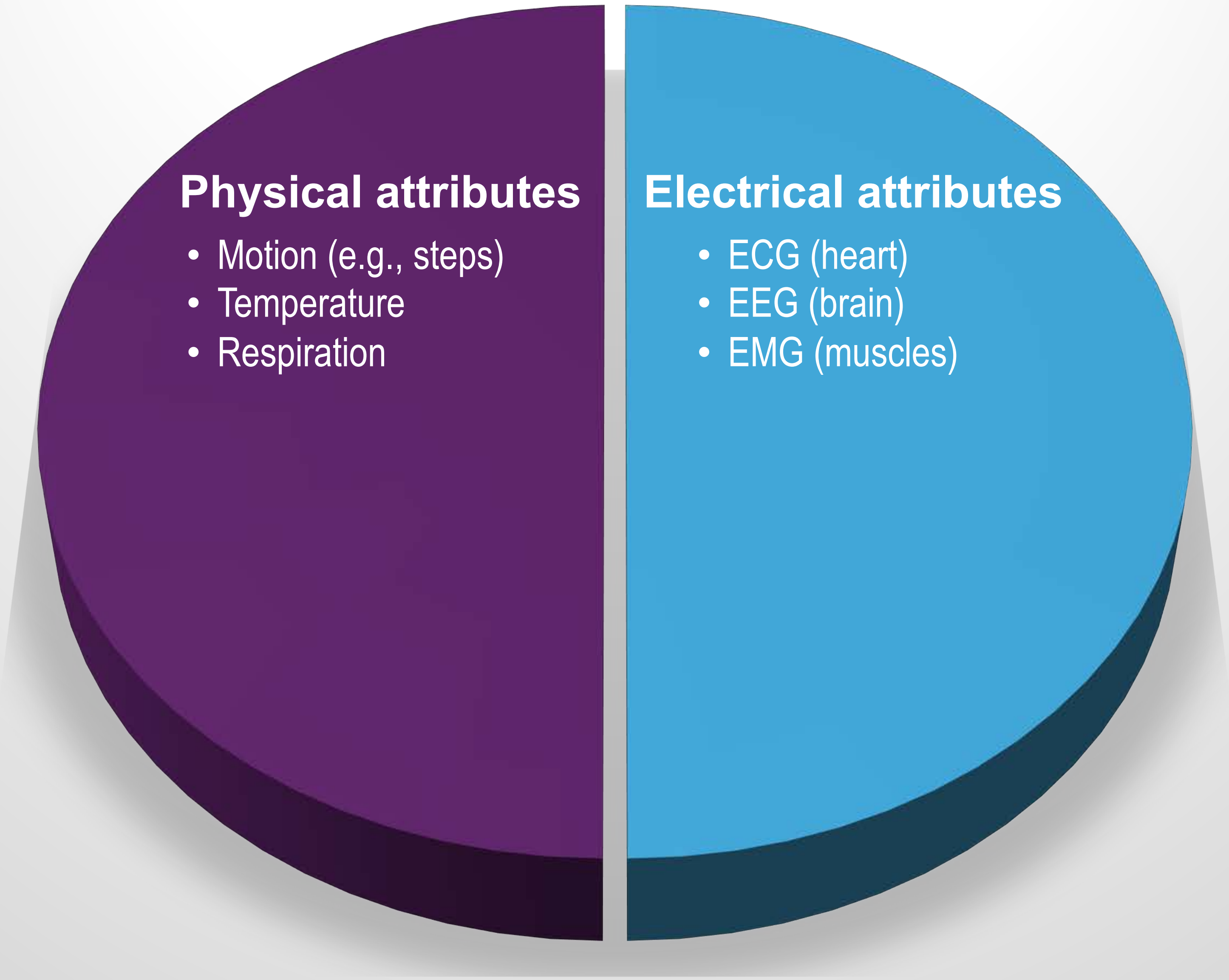
Utility:

Need to develop sensors that are actually useful

Mission:

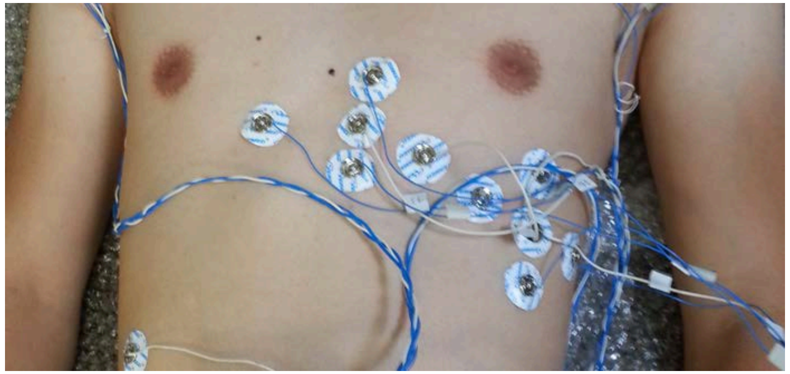
Address these issues through innovative transdisciplinary research

Wearable sensing opportunities

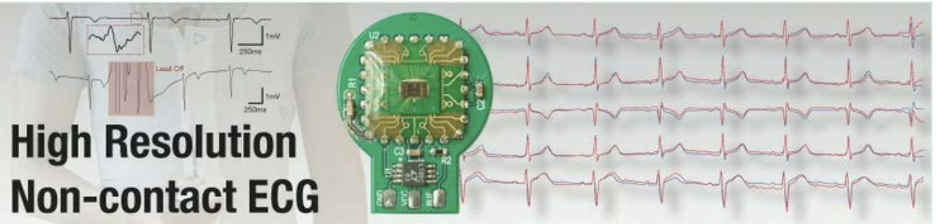


Electrophysiology today

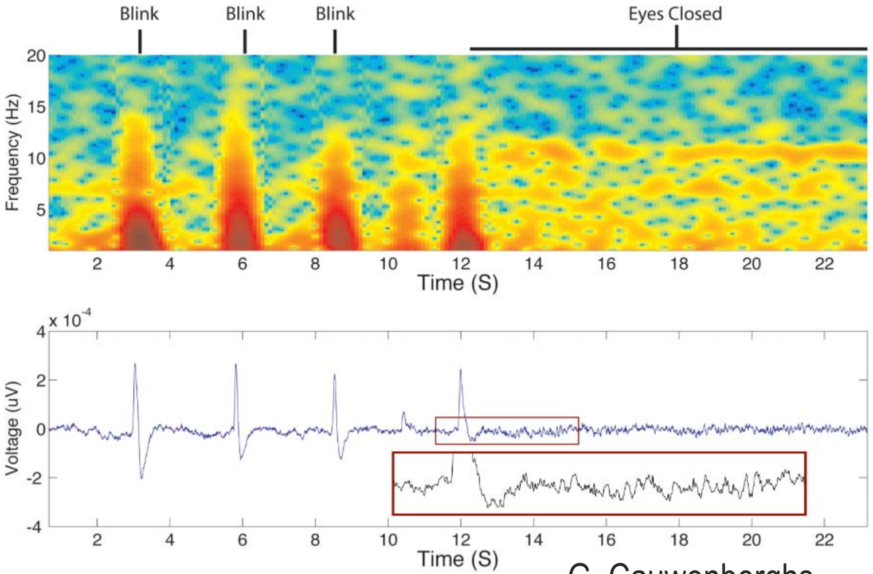
Wet electrodes:
- Inconvenient
- Irritating
- Good performance



Non-contact electrodes:
- Very convenient (can integrate into textiles)
- Opportunities for large number of channels
- Severe motion artifacts



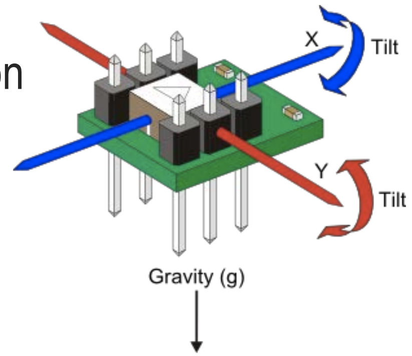
Cognionics



G. Cauwenberghs

Hardware + software co-design for motion artifact reduction

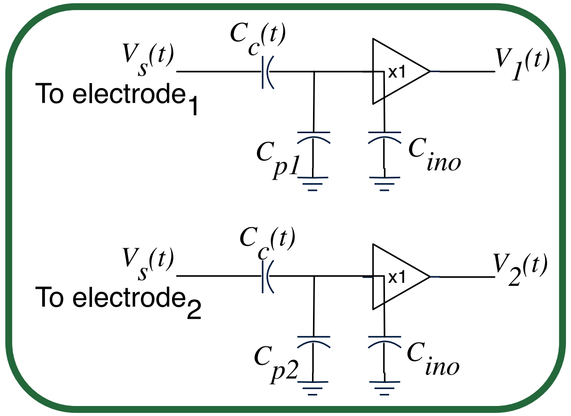
Naïve solution:
Measure electrode motion via accelerometer

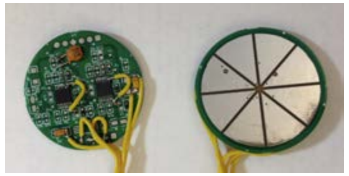


Problem: measures absolute motion; not motion w.r.t. body

Proposed solution:

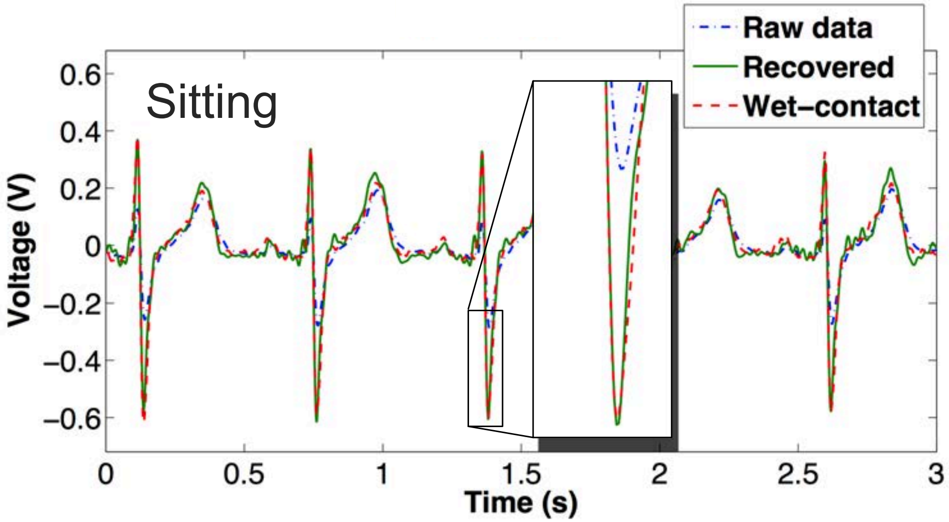
Dynamically measure change in electrode impedance via a dual-channel electrode

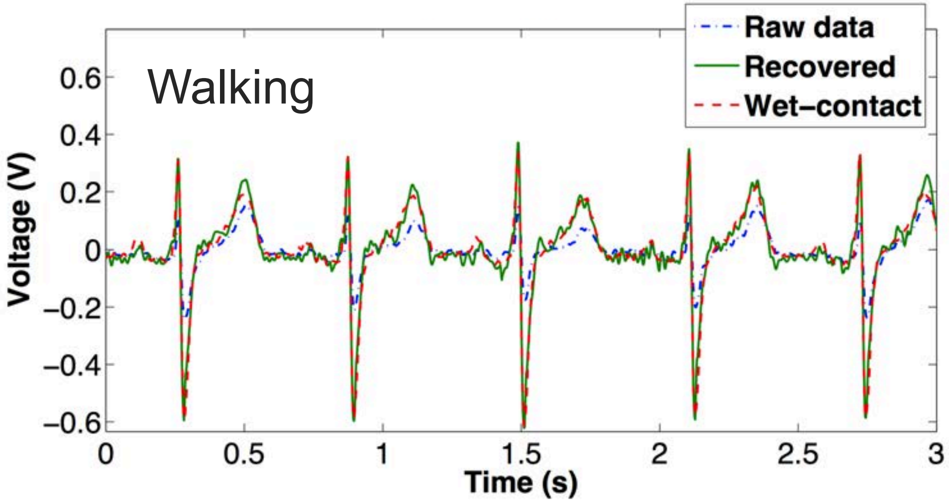




$$\begin{cases} V_1(t) = \frac{V_s(t)C_C}{C_C+C_{p1}} \\ V_2(t) = \frac{V_s(t)C_C}{C_C+C_{p2}} \end{cases}$$

Experimental results:

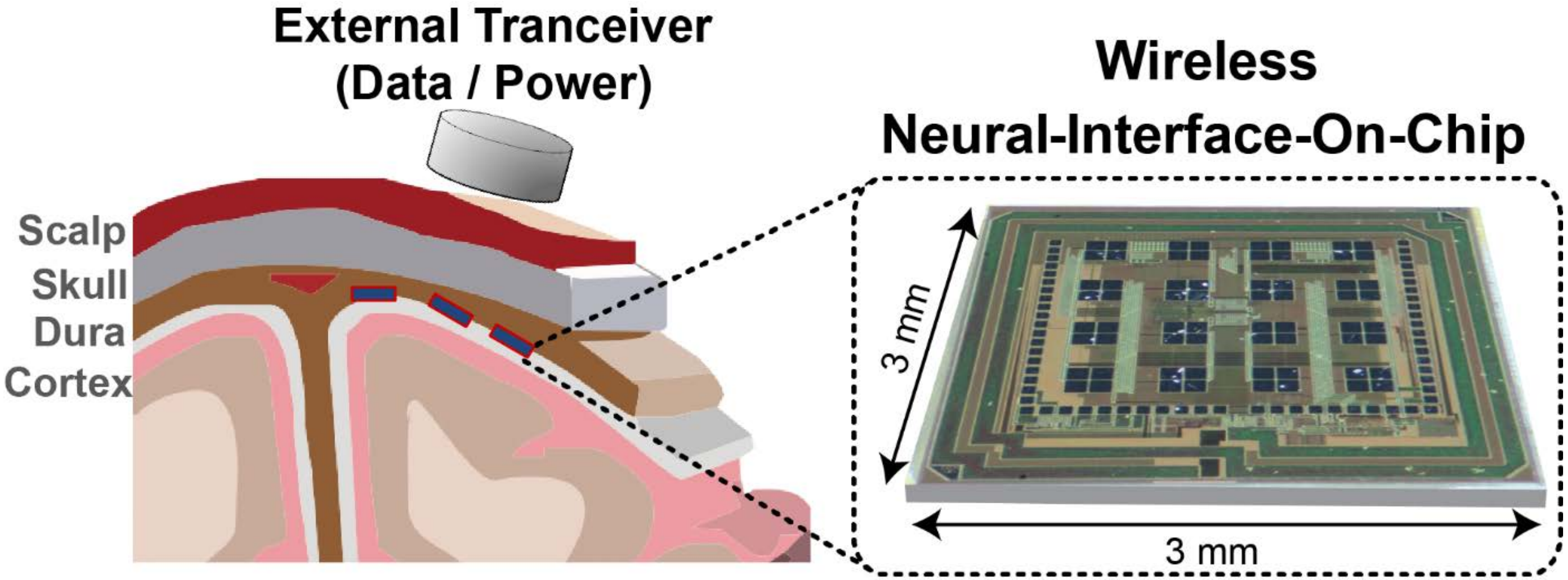


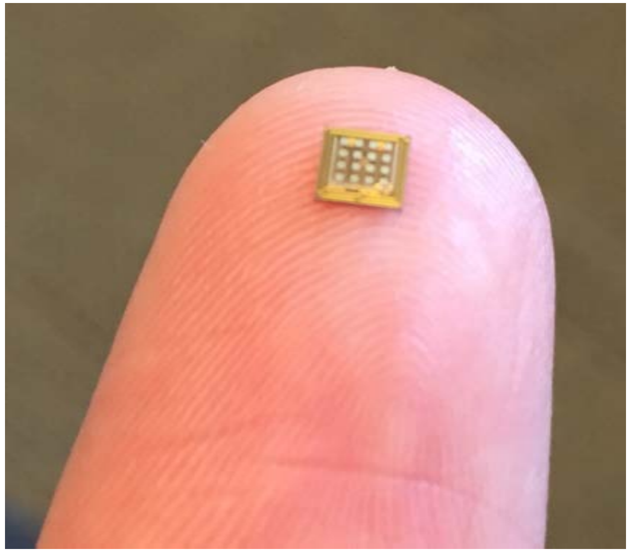


Up to 76% reduction of artifacts

Lin et al., BioCAS 2015

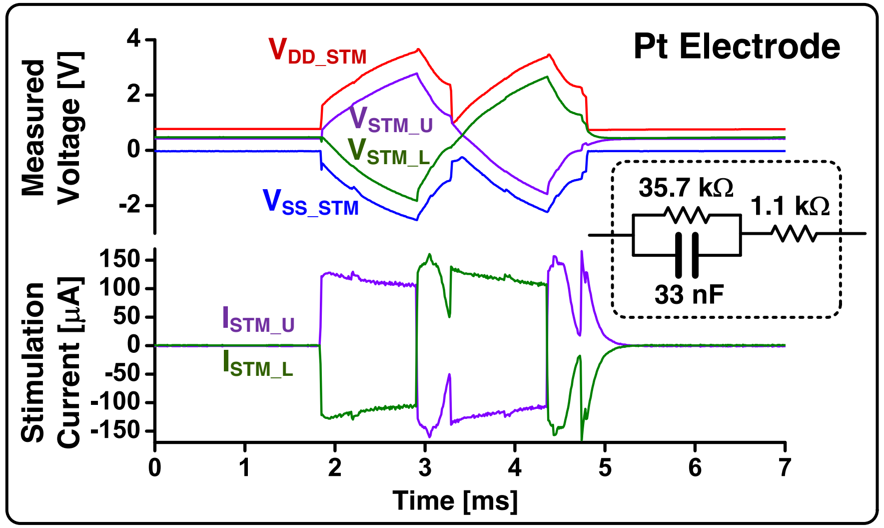
Fully-on-chip Wireless Neural Interfacing Devices





ADVANTAGES:

- Fully-integrated: no wires, batteries, or any other external components
- Fully encapsulated with biocompatible material: no adverse reactions with the brain
- Microchip integration means upwards of 100s of channels per chip
- Completely modular design
- Possible to place *many* chips in the brain for large-scale recording/stimulation

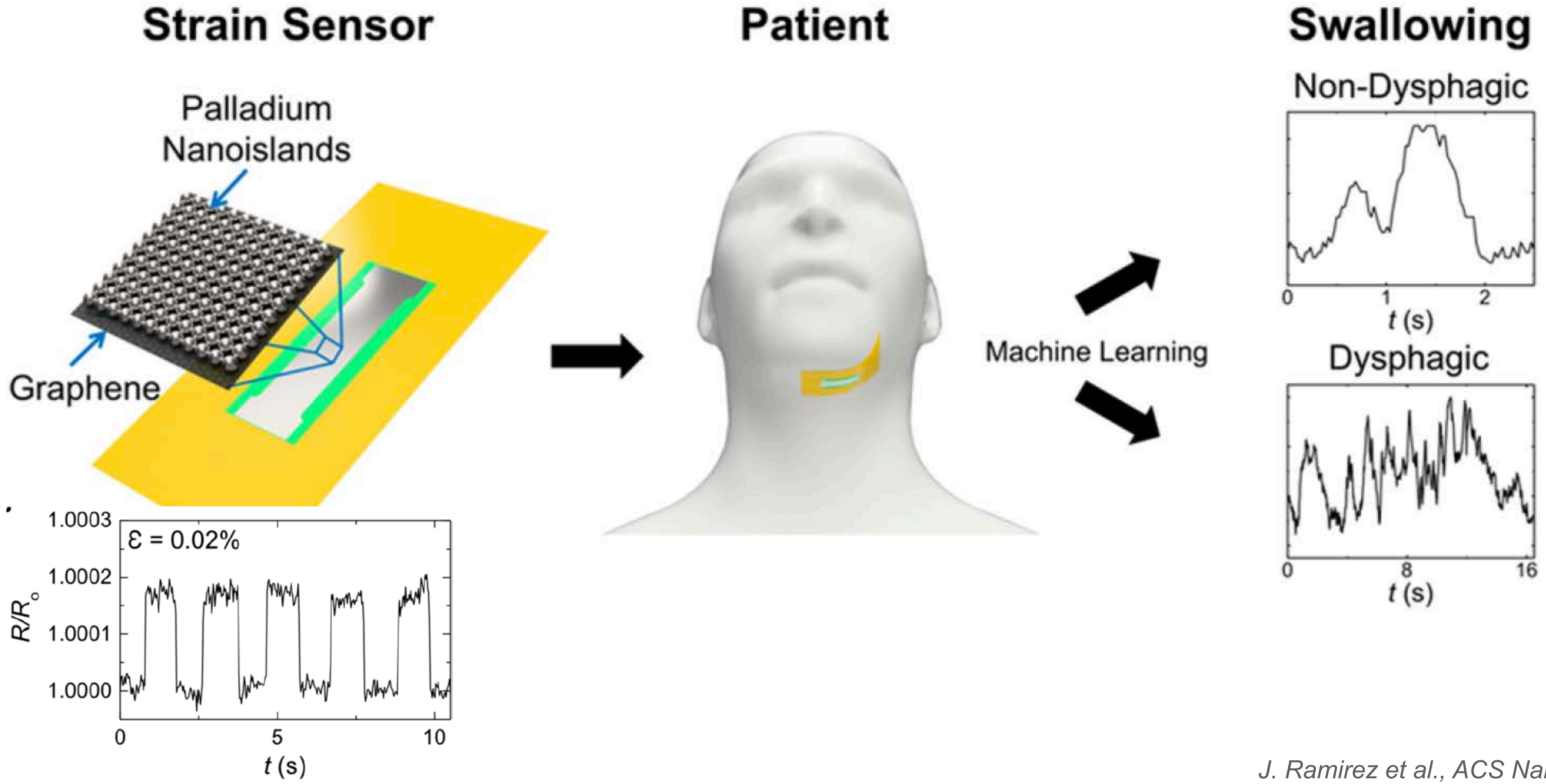


Adiabatic current stimulator:

- 6x more efficient than conventional approaches
- >2x more efficient than prior work that use large off-chip inductors

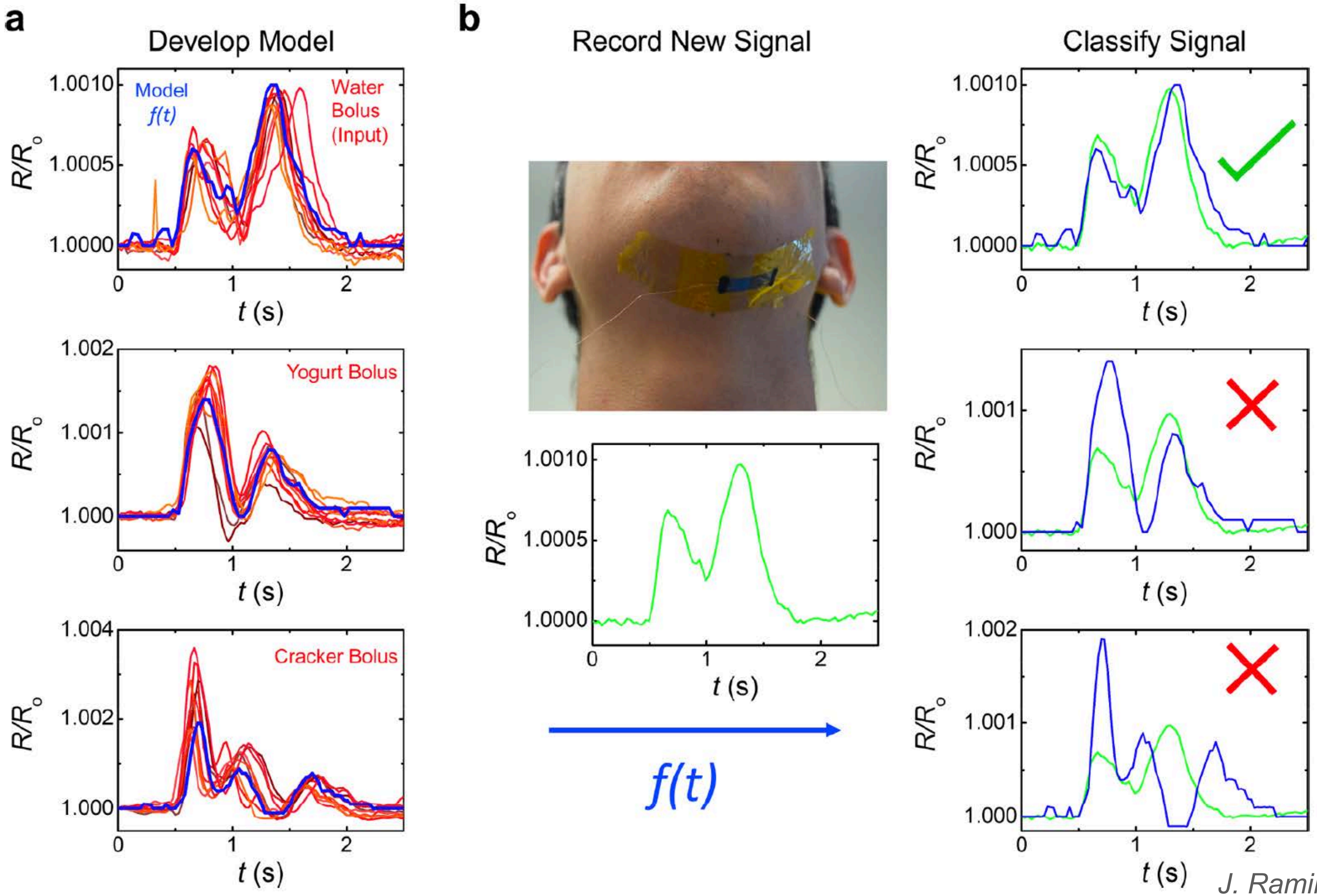
S. Ha et al., VLSI'15 / TBioCAS'18

Strain sensing for detecting risk of fibrosis in head+neck cancer patients



J. Ramirez et al., ACS Nano, 2018

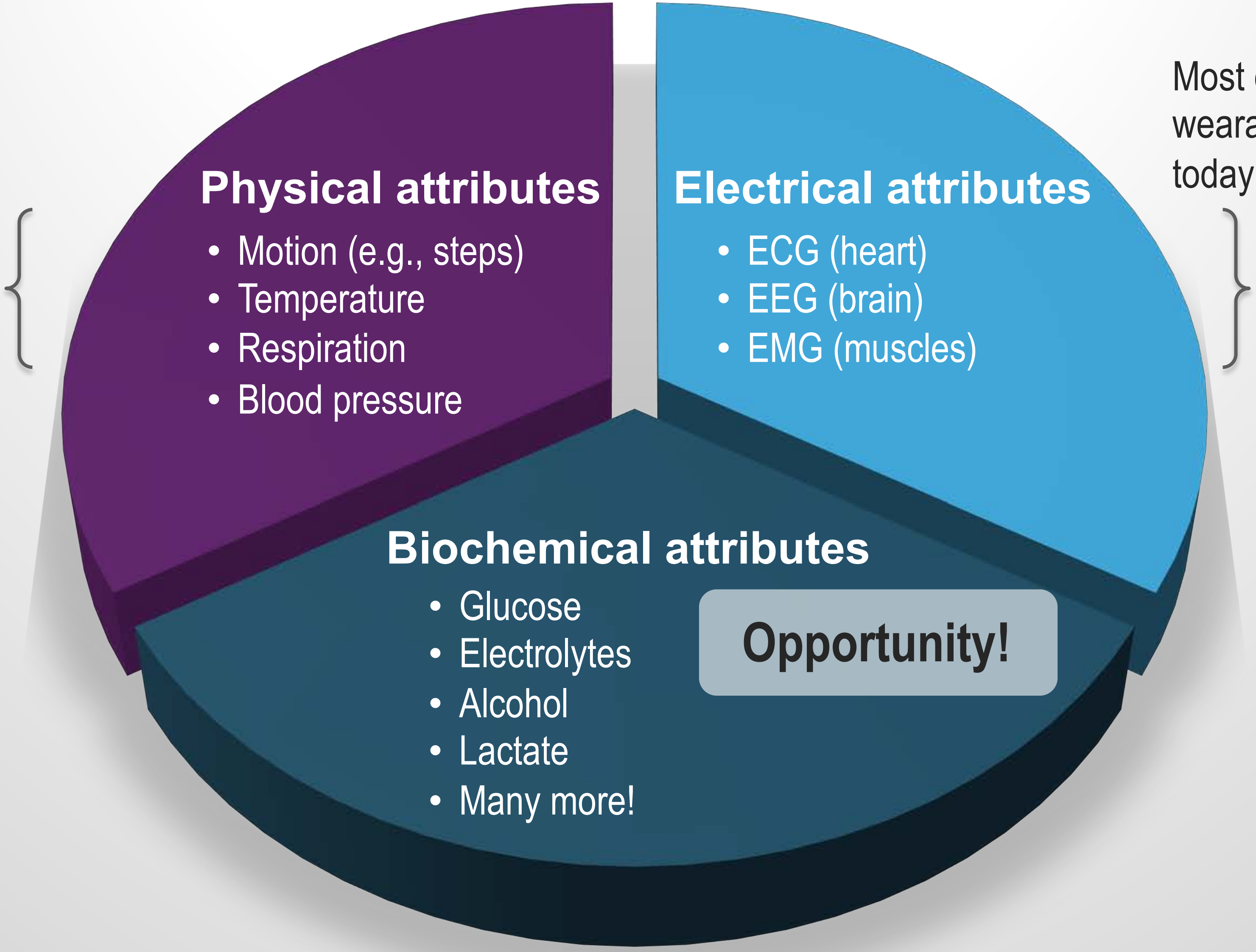
Machine learning for classification



84% accurate model

J. Ramirez et al., ACS Nano, 2018

Wearable sensing opportunities



Most of the wearables market today

Biochemical Sensing Today

Conventional lab testing

- Expensive, painful, time consuming/inconvenient
- Very infrequent spot measurements


Point-of-care devices

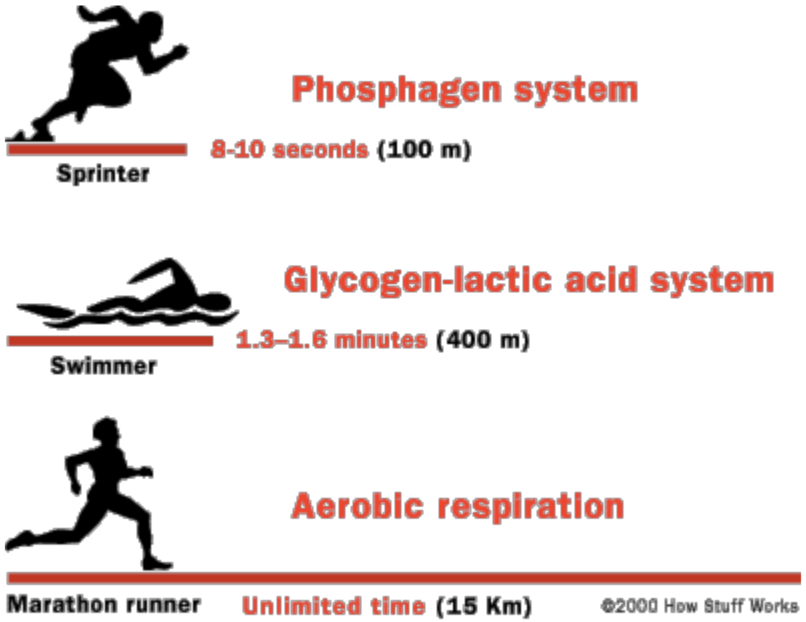
- Often still needs access to blood (invasive)
- Infrequent spot measurements (subsampling)



Research need: non-invasive, continuous measurement devices

Example: lactate monitoring for athletes

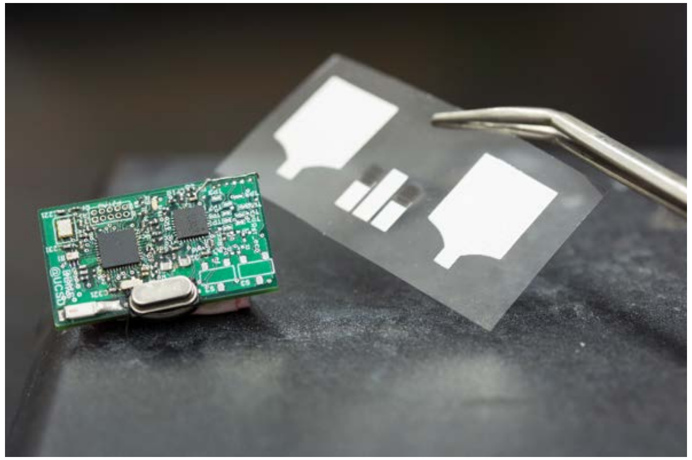
Staying below the "lactate threshold" important for endurance training

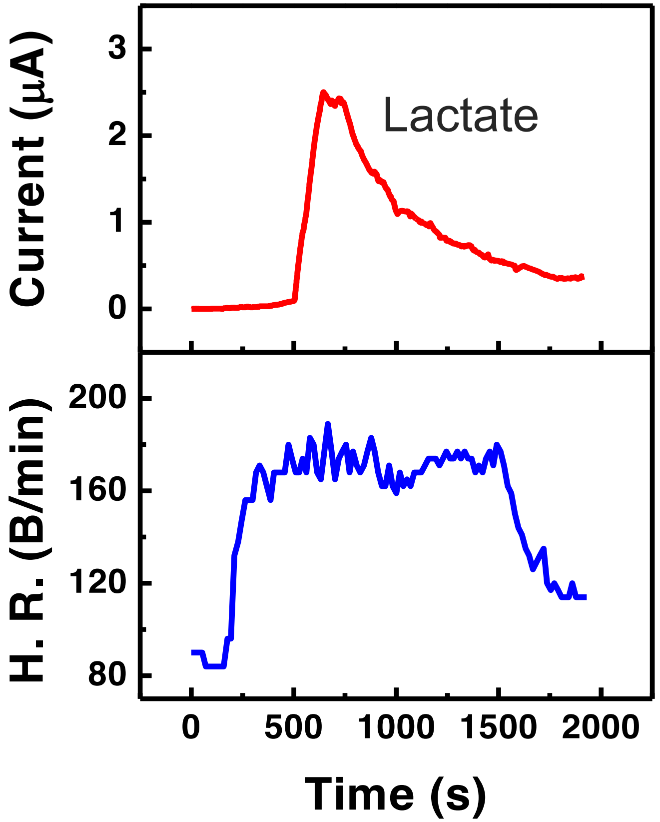


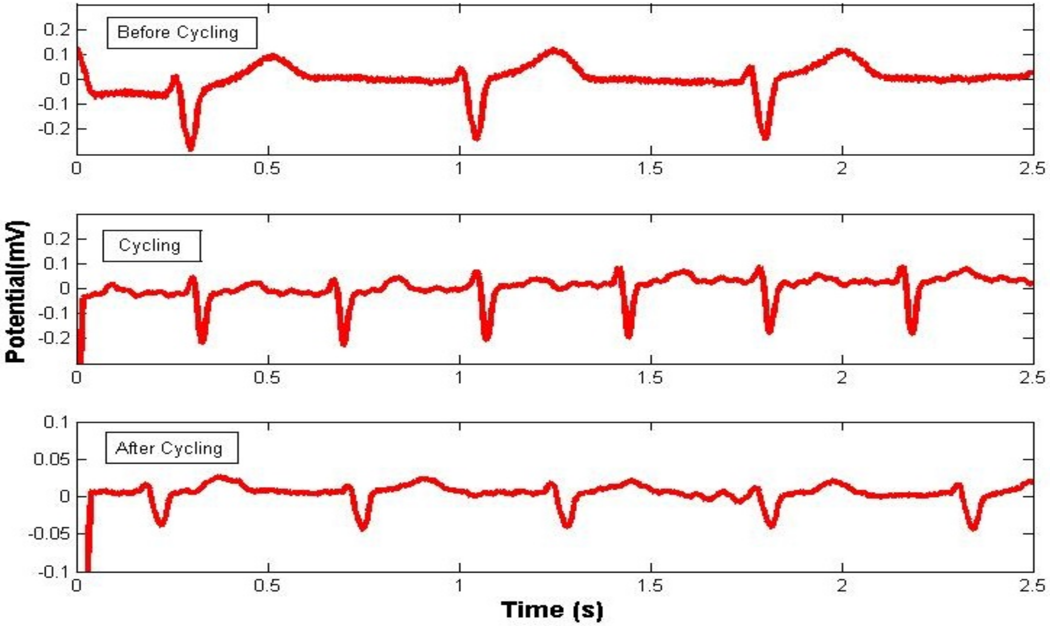
Current state-of-the-art testing method:

Non-invasive and/or continuous sensing is required

Hybrid physiochemical & electrophysiological sensing





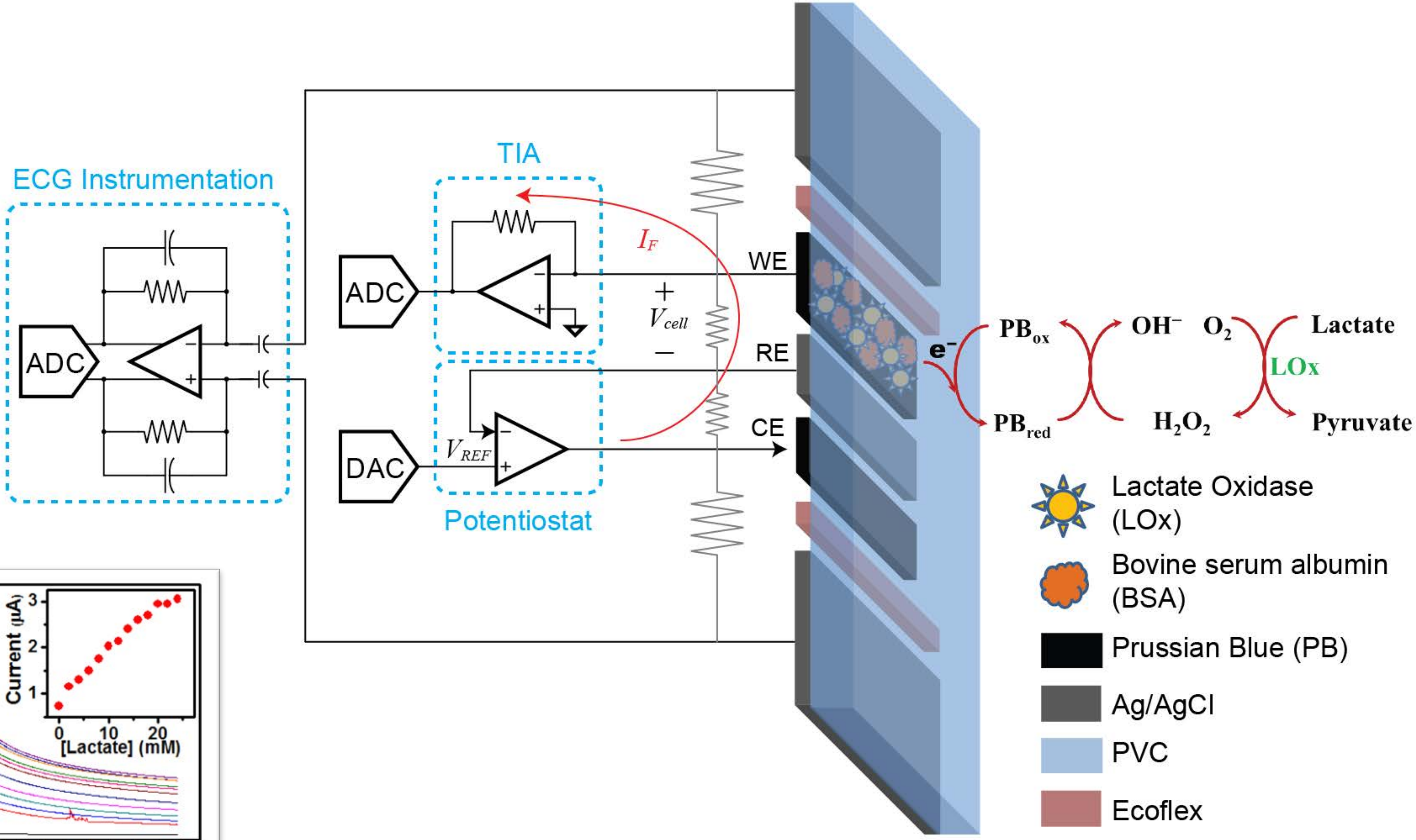


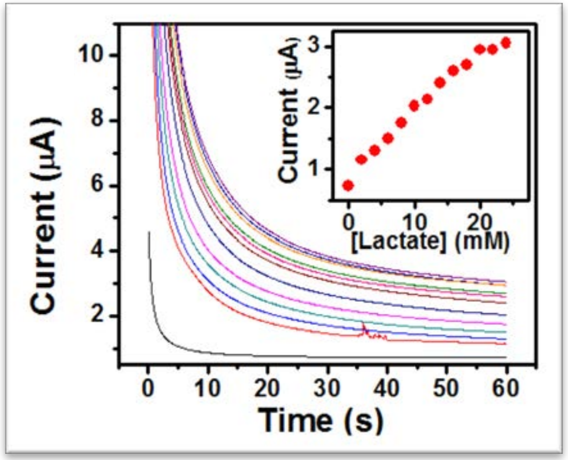
First demonstration of simultaneous chemical+electrophysiological sensing in a wearable patch

Opportunities for data analytics!

S. Imani et al., Nature Communications, 2016

Hybrid physiochemical/electrophysiological sensor operation

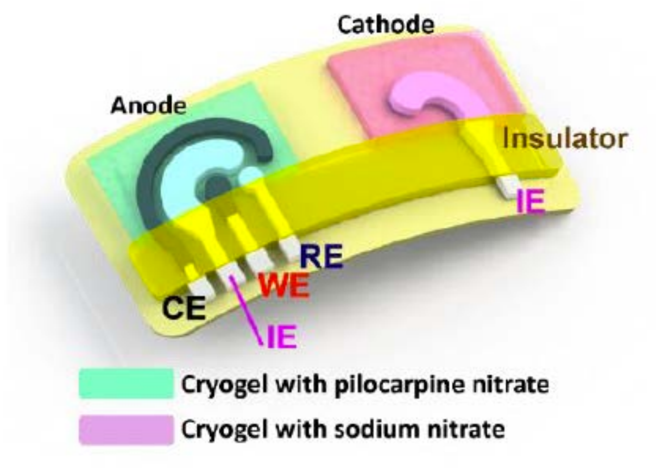


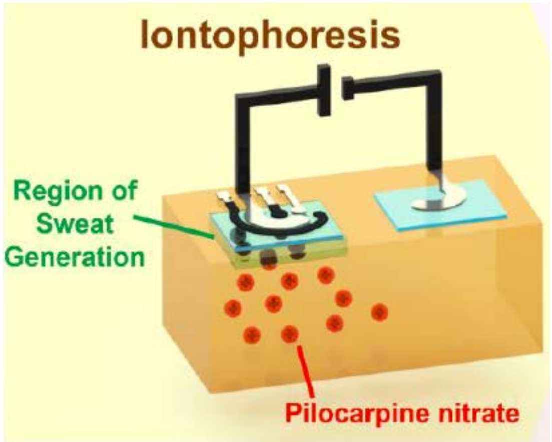


S. Imani et al., Nature Communications, 2016

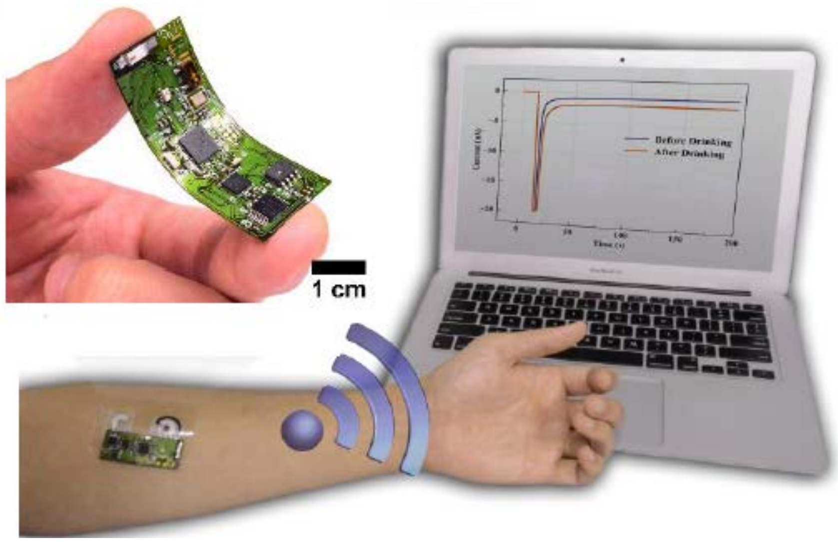
Non-invasive wearable alcohol sensor

Electrochemical analysis after iontophoresis:
To induce sweating → capture ethanol at the skin surface

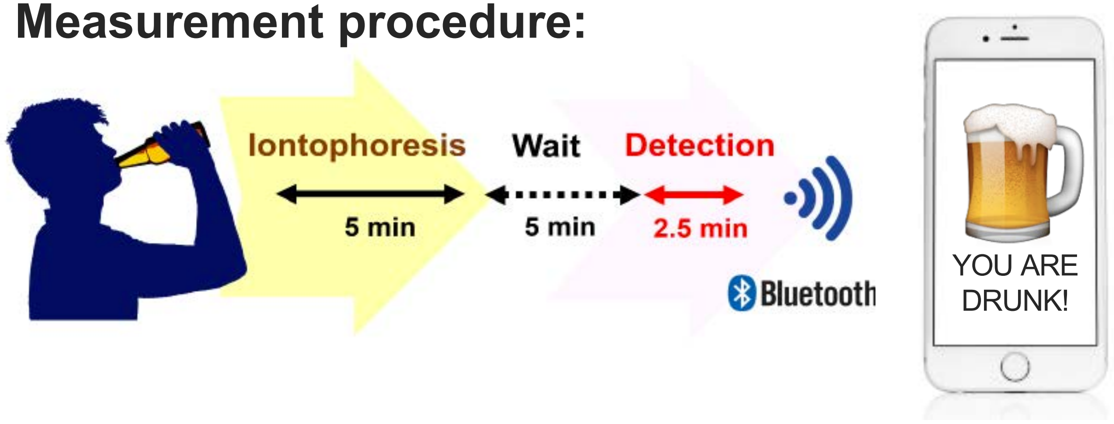


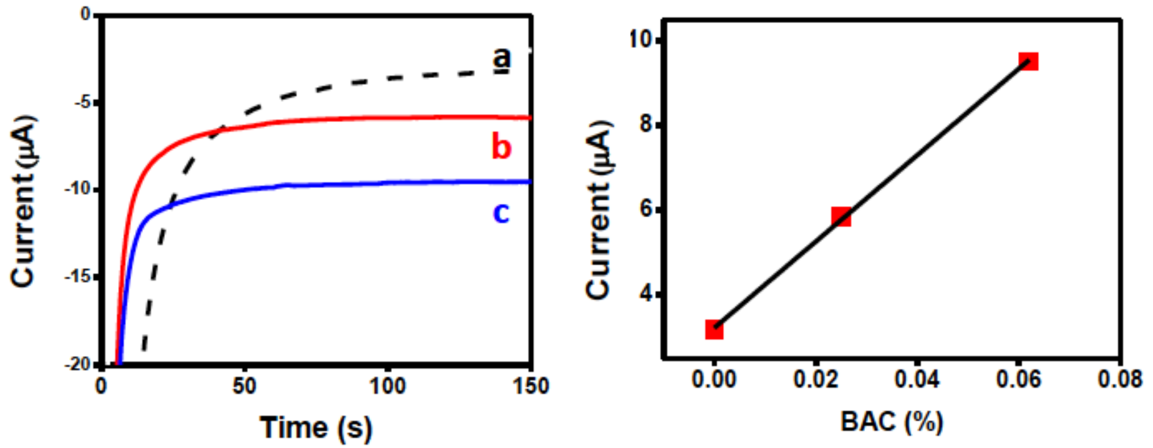


Epidermal prototype:



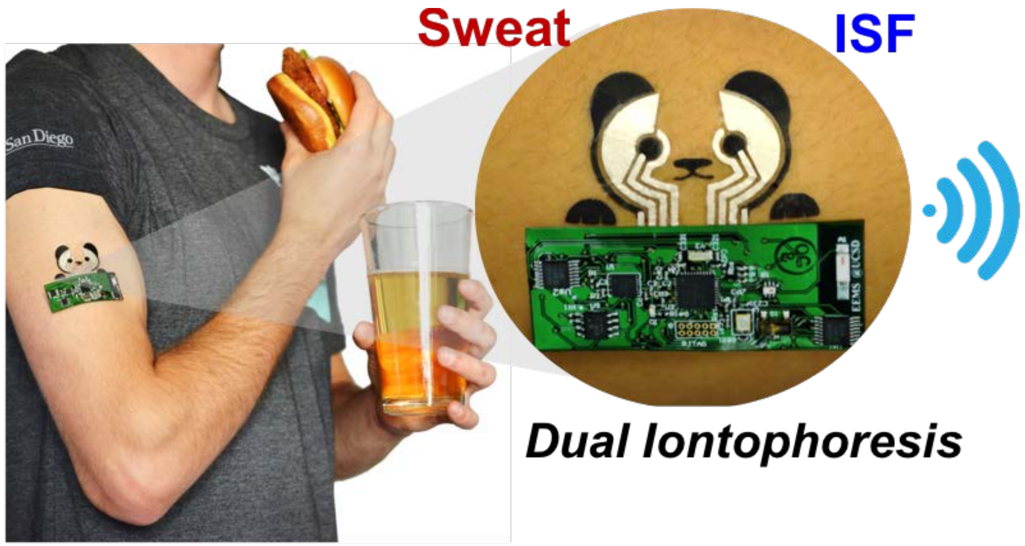
Measurement procedure:

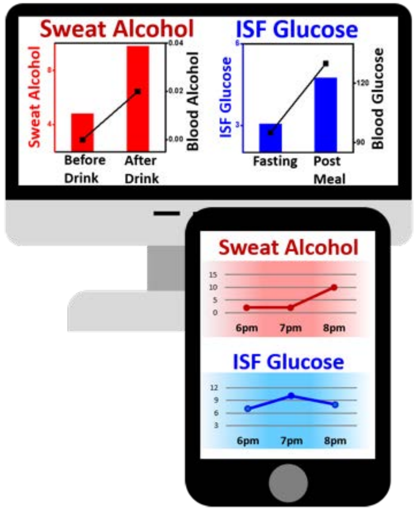




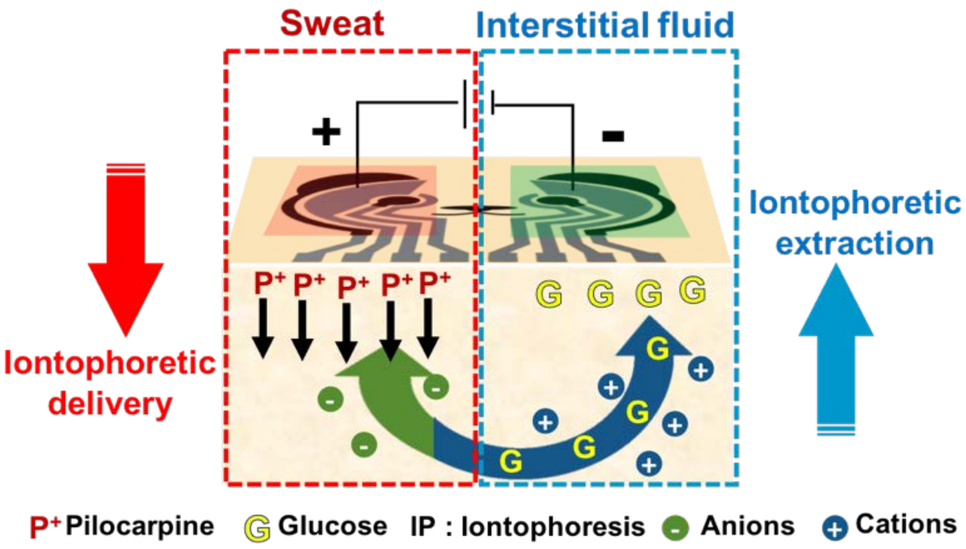
J. Kim et al., ACS Sensors, 2016

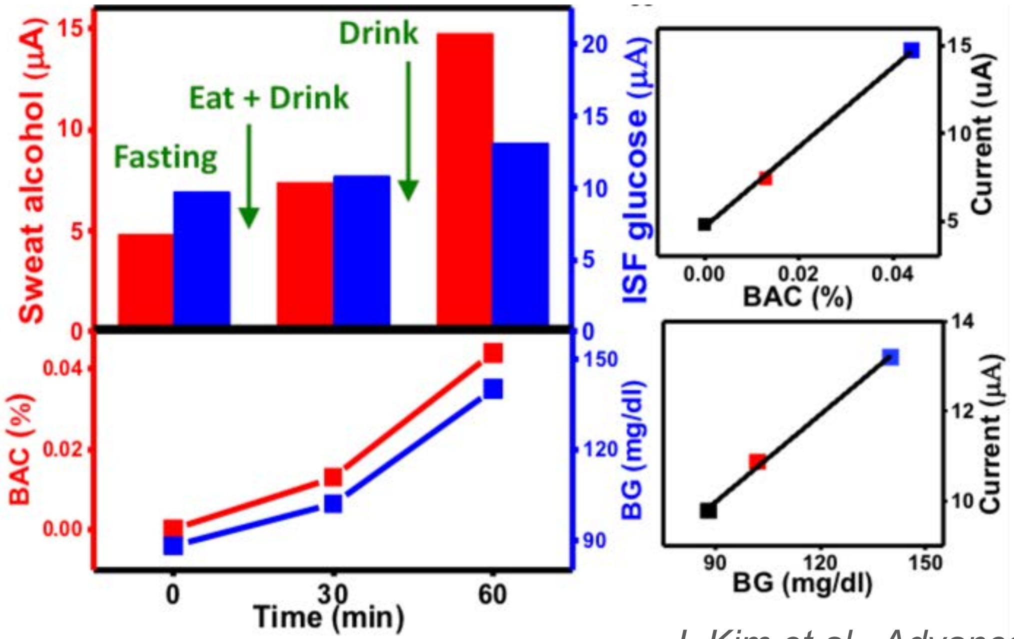
Non-invasive dual-fluid glucose/alcohol sensing





A wireless "glucohol" sensing platform



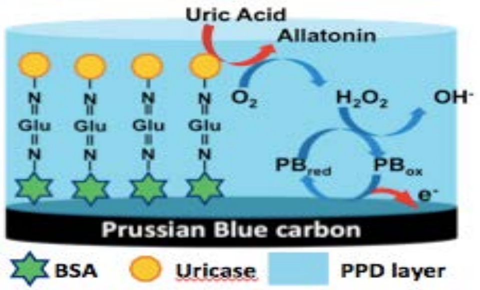


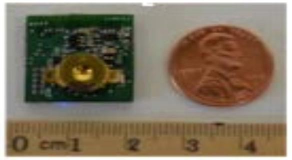
J. Kim et al., Advanced Science, 2018

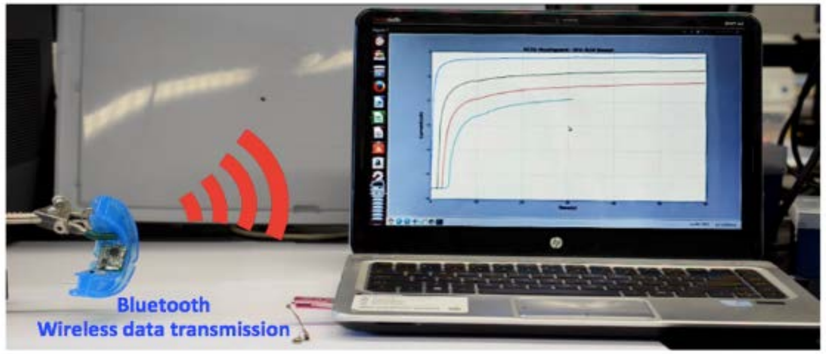
A wireless saliva sensor in a mouthguard

Health applications

Measure Uric Acid for Hyperuricemia





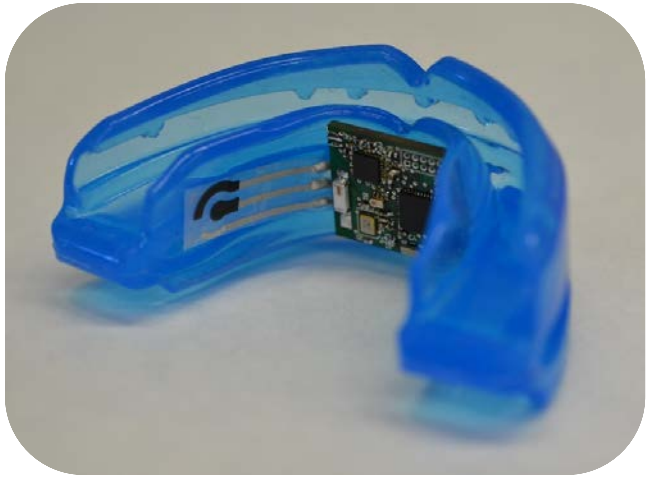


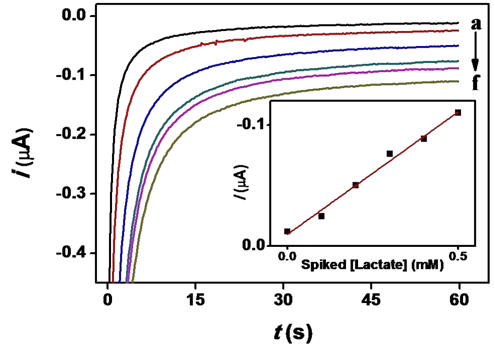
Startup company:

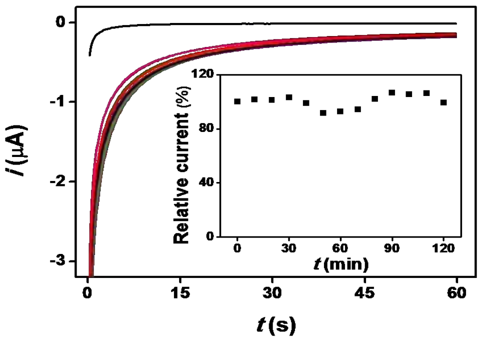
TRAQ

Fitness applications

Measure Lactate for Stress / Exertion







J. Kim et al., Biosensors & Bioelectronics, 2015

Why aren't we there now?

Size & Usability:

Need to develop sensors that are small & seamlessly integrated into daily life

Battery Life:

Need ultra-low-power and/or energy harvesting to minimize re-charging

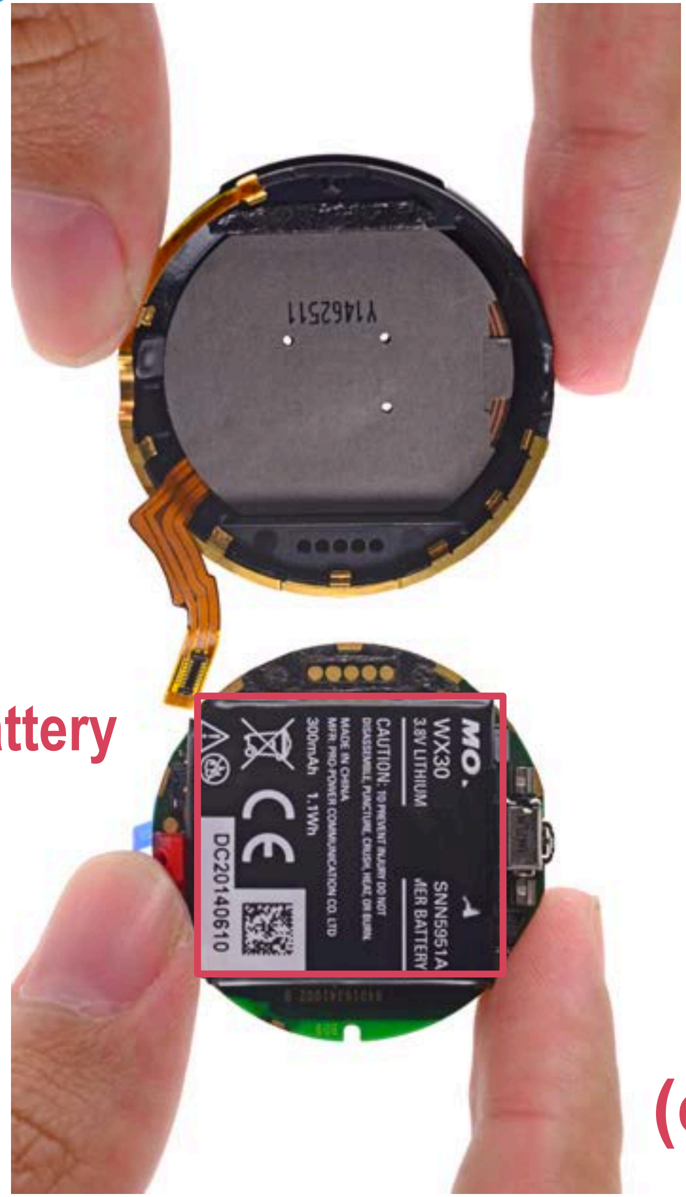
Utility:

Need to develop sensors that are actually useful

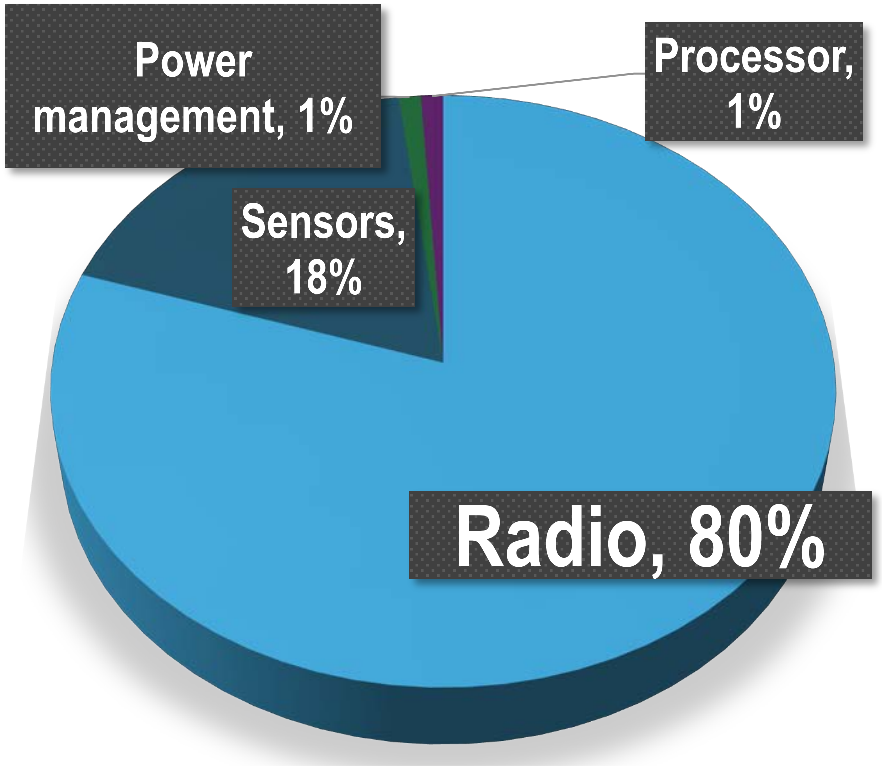
Mission:

Address these issues through innovative transdisciplinary research

Major limiter: battery size / battery life



Power breakdown:



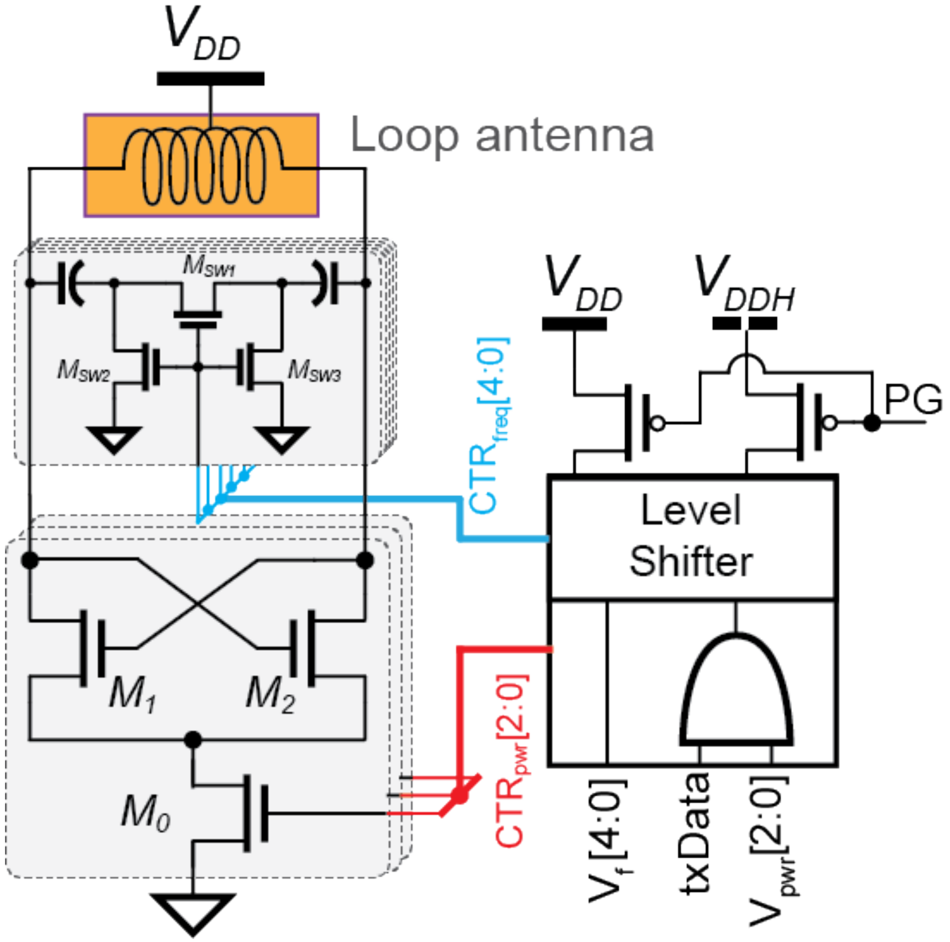
Research goal:

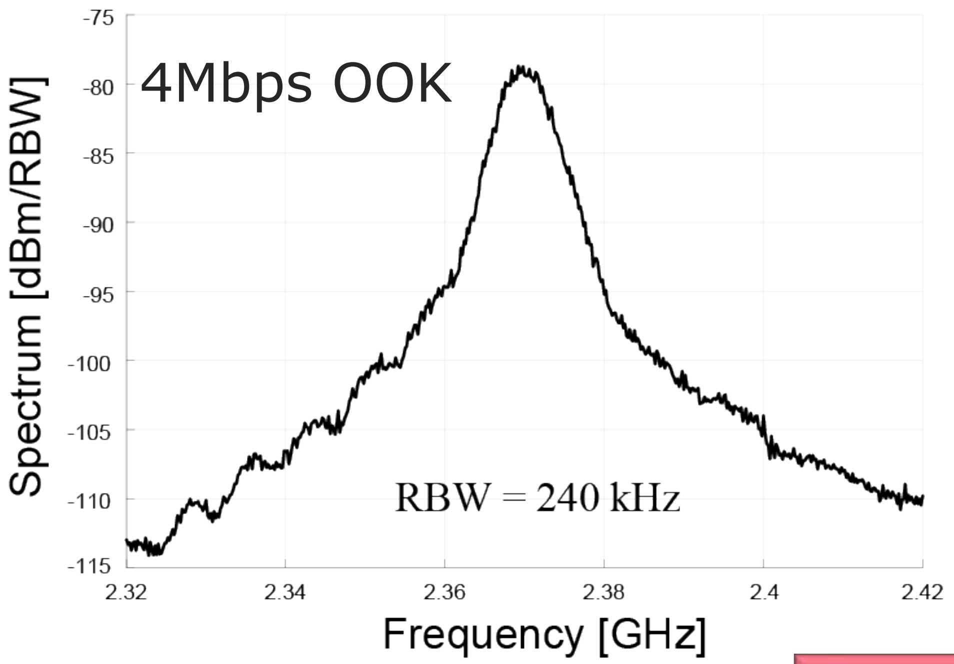
Minimize power of load circuits (especially RF), and perform energy harvesting

G. Burra et al., ULP Short-Range Radios (Mercier & Chandrakasan, Eds.), Springer'15

Near-zero-power RF transmitter

Direct-RF 2.4GHz Power Oscillator w/ 2.8mm loop antenna

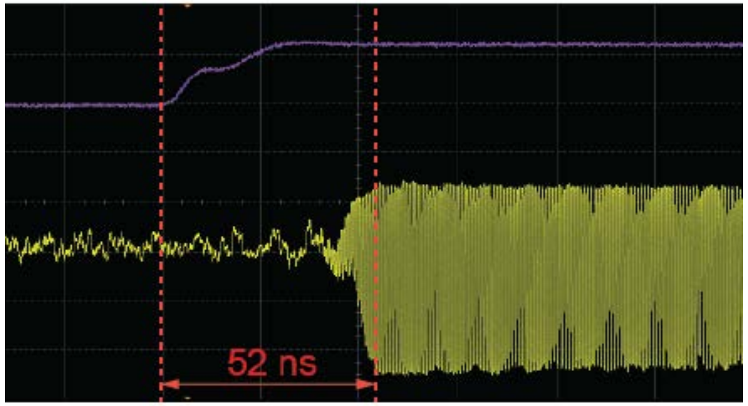




Active power:
154μW

Sleep power:
500pW

Average power:
2.4nW

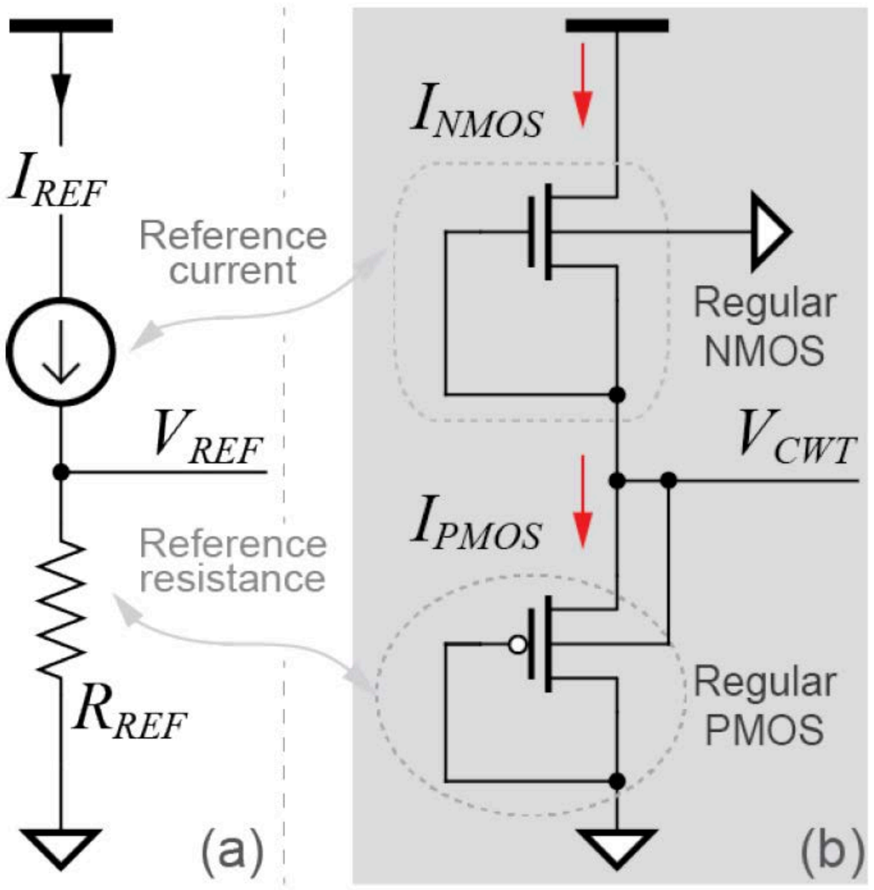


Start-up time < 52ns

If TX power can be so low, the power consumption of even basic building blocks begins to matter

H. Wang et al., JSSC'18

Ultra-Low-Power Voltage Reference Generator

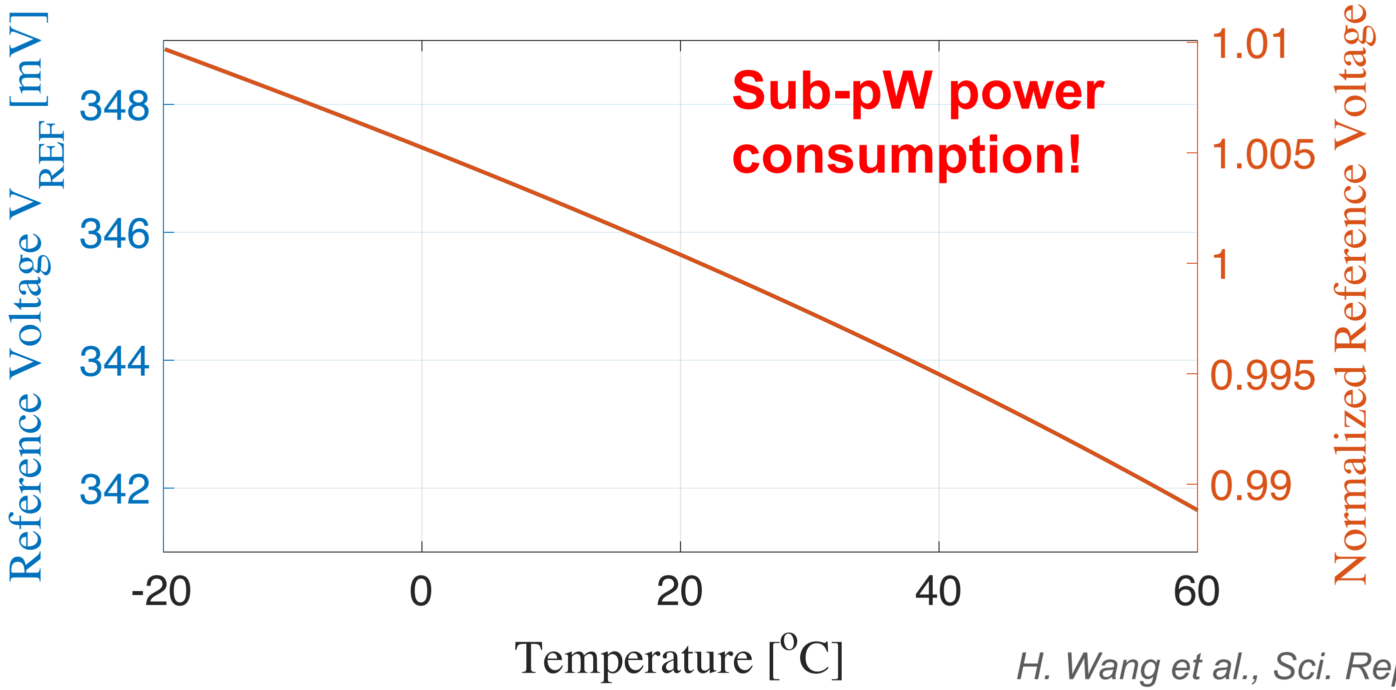


Inspired by Seok et al., JSSC'12

$$\mu_1 C_{ox1}\frac{W_1}{L_1}(n_1-1)\phi_t^2 e^{\frac{0-V_{th1}}{n_1\phi_t}} = \mu_2 C_{ox2}\frac{W_2}{L_2}(n_2-1)\phi_t^2 e^{\frac{V_{ref}-V_{th2}}{n_2\phi_t}}$$

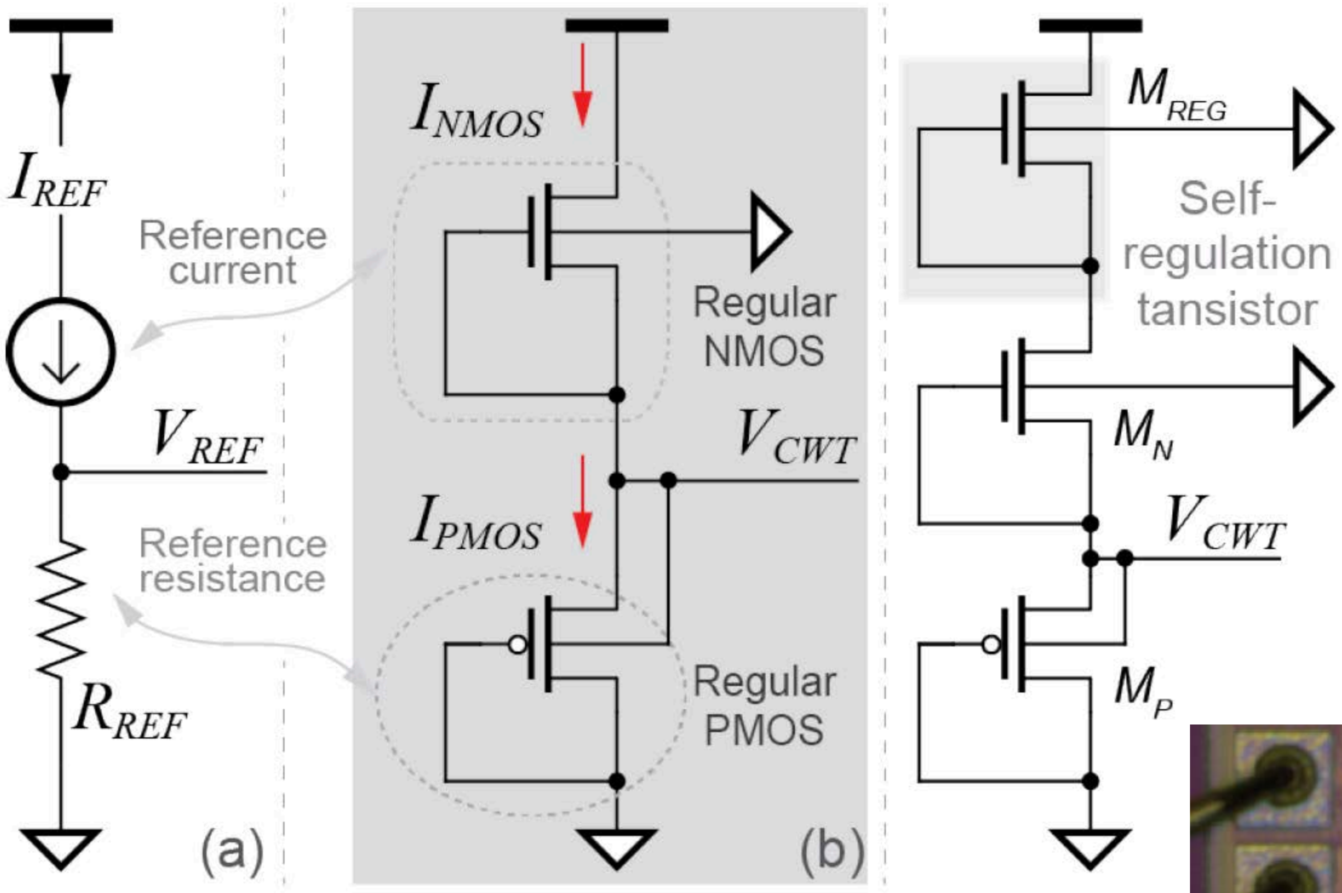
$$V_{ref} = n_2\phi_t ln\frac{\mu_1 C_{ox1}(n_1-1)W_1 L_2}{\mu_2 C_{ox2}(n_2-1)W_2 L_1} + \frac{n_1 V_{th2} - n_2 V_{th1}}{n_1}$$

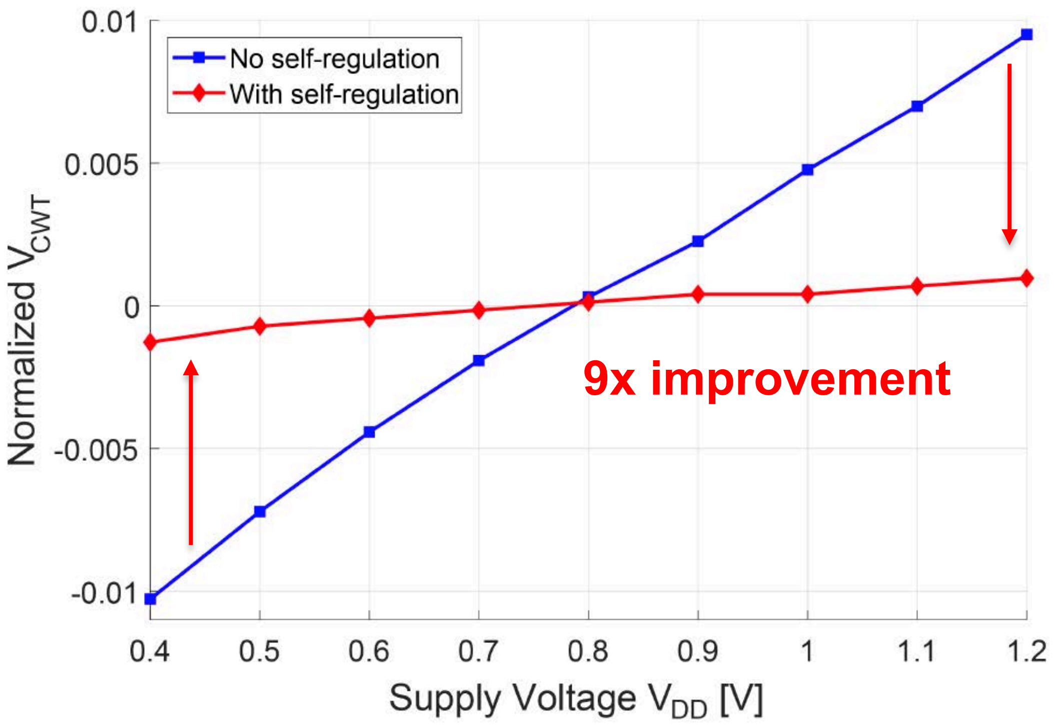
$$\frac{\partial V_{ref}}{\partial T} = 0 \Rightarrow \frac{(\frac{W_1}{L_1})}{(\frac{W_2}{L_2})} = \frac{\mu_2 C_{ox2}(n_2-1)}{\mu_1 C_{ox1}(n_1-1)} e^{\frac{q(n_2 C_{V_{th1}} - n_1 C_{V_{th2}})}{n_1 n_2 k}}$$

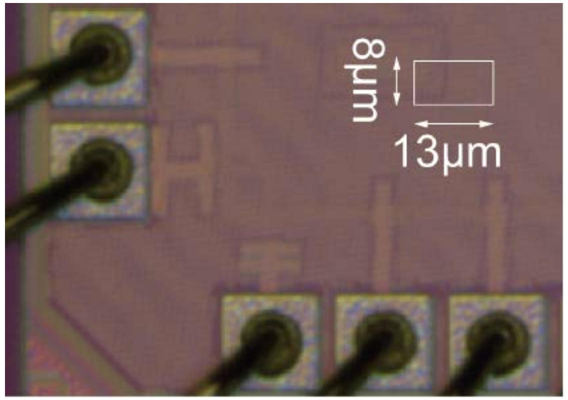


H. Wang et al., Sci. Rep.'17

A 420fW self-regulated 3T voltage reference generator







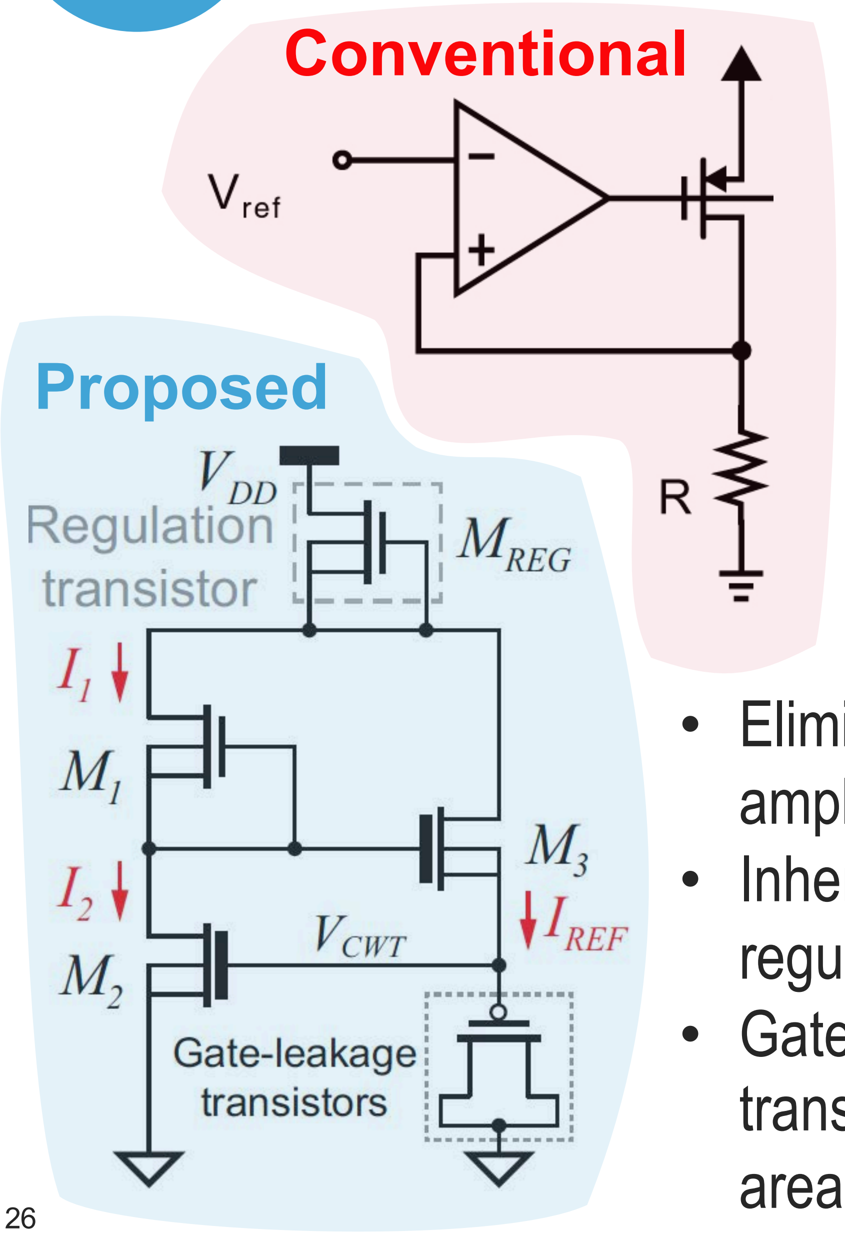
Power: 420fW

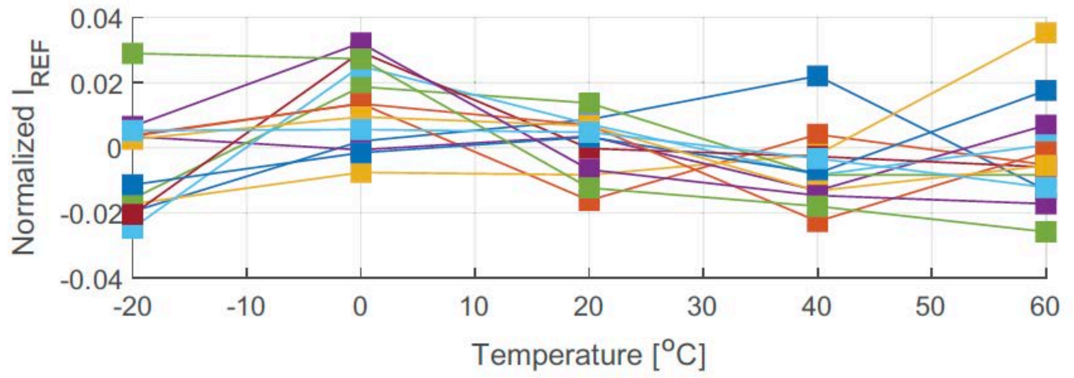
Temperature coefficient: 252ppm/°C (N=38 chips)

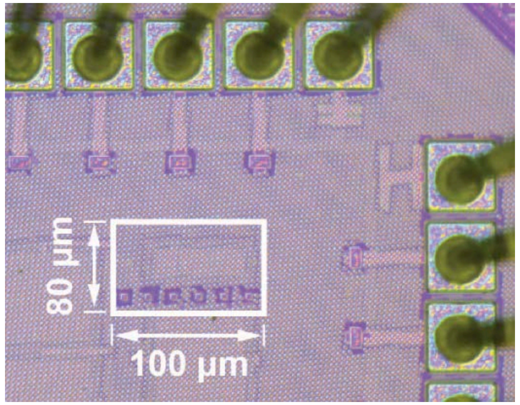
Line regulation: 0.47%/V

H. Wang et al., ESSCIRC'17

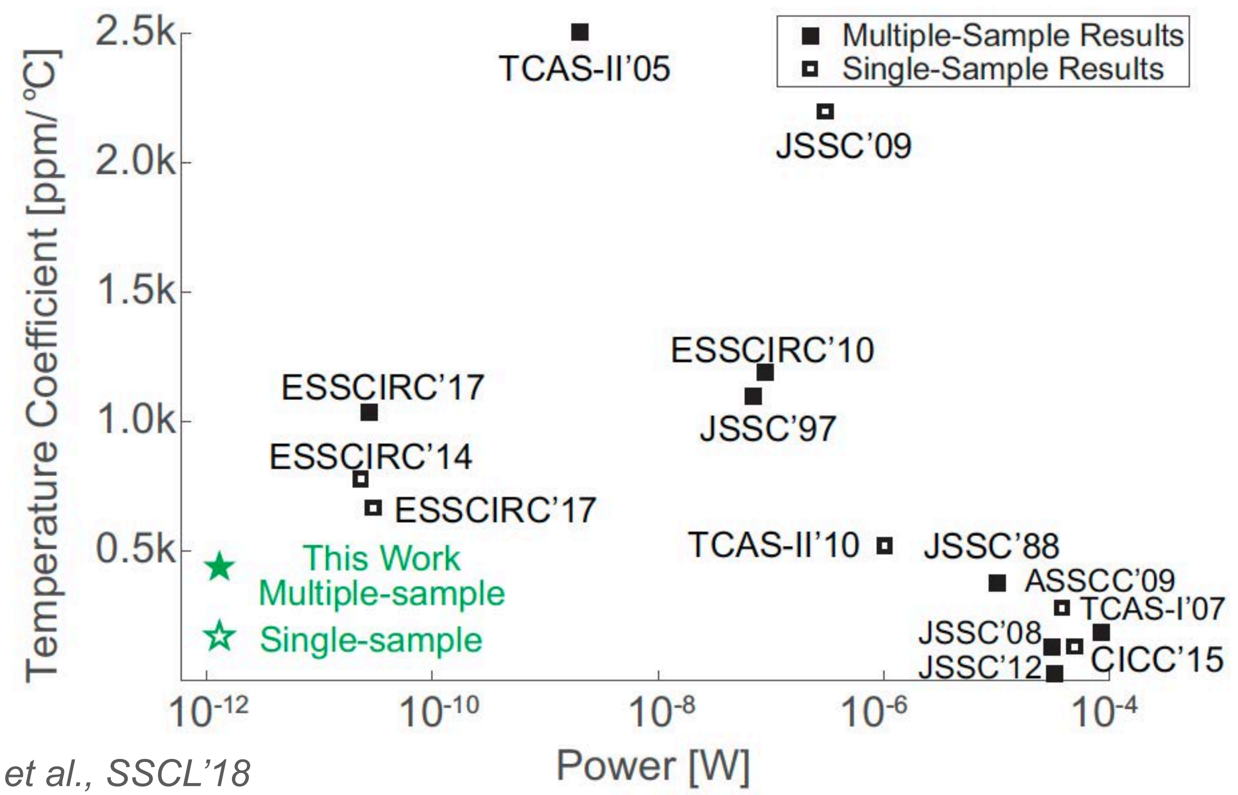
A 3.4pW 5T current reference generator







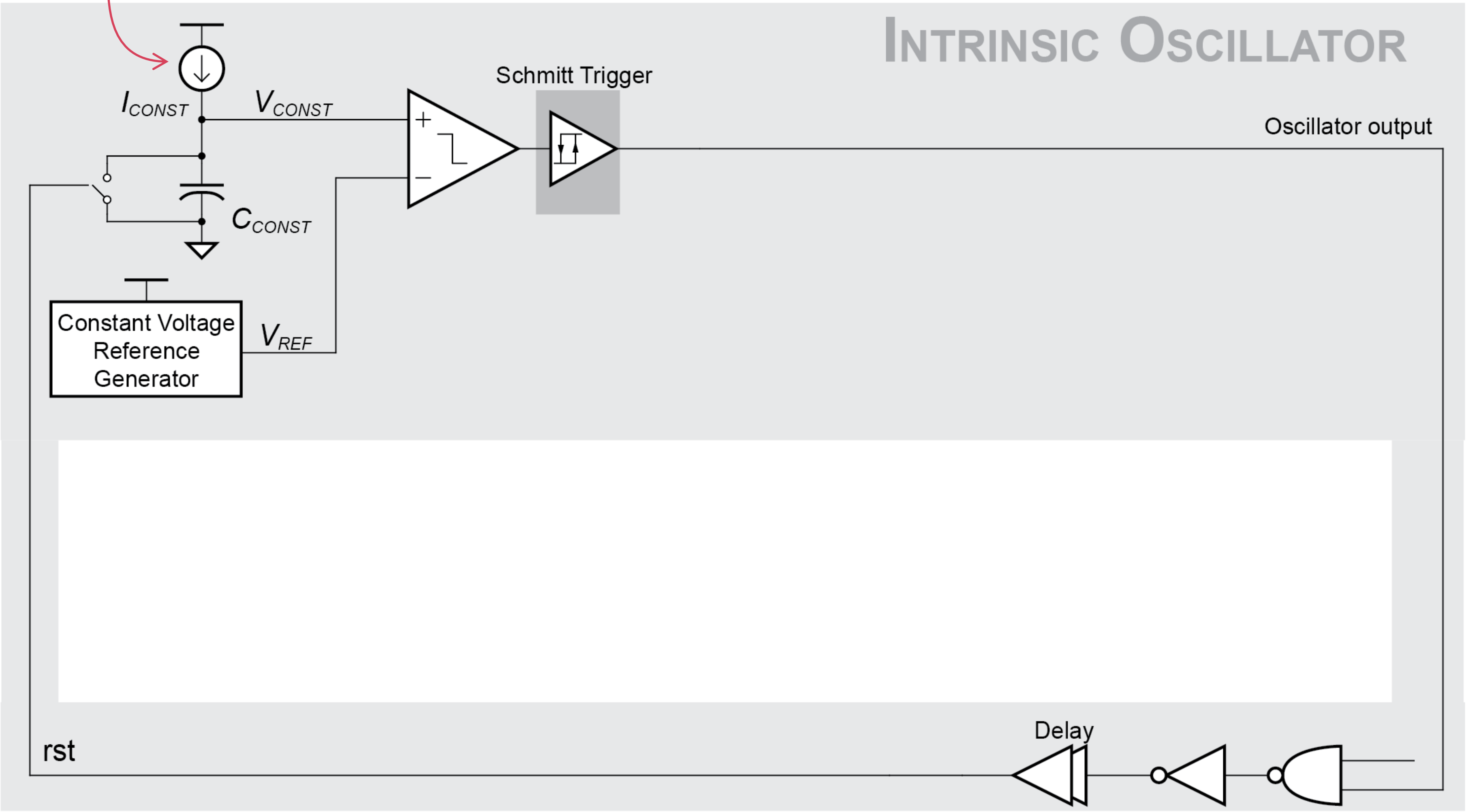
- Eliminates additional amplifier bias current
- Inherent self-regulation
- Gate-leakage transistor to reduce area



H. Wang et al., SSCL'18

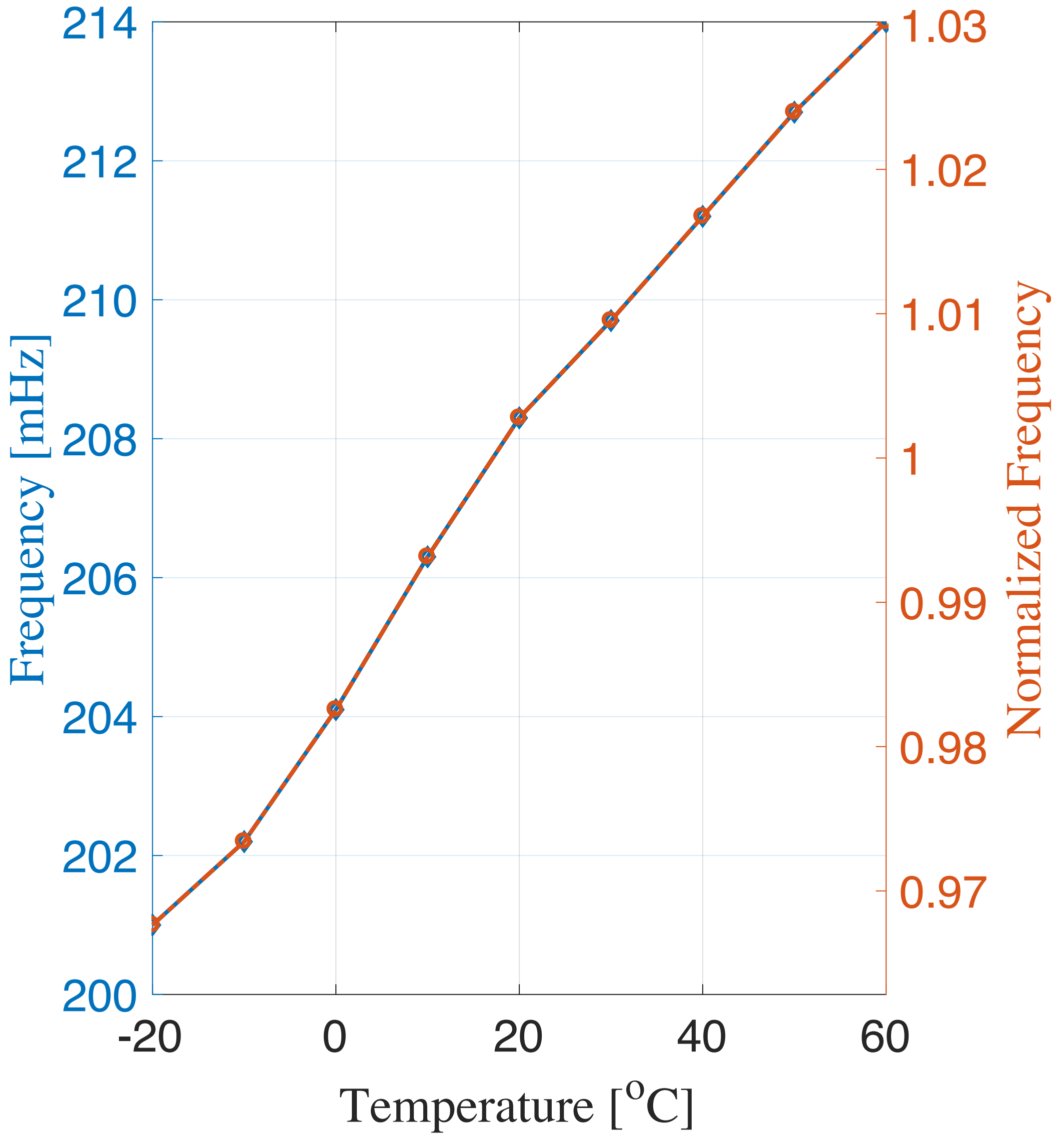
pW relaxation oscillator

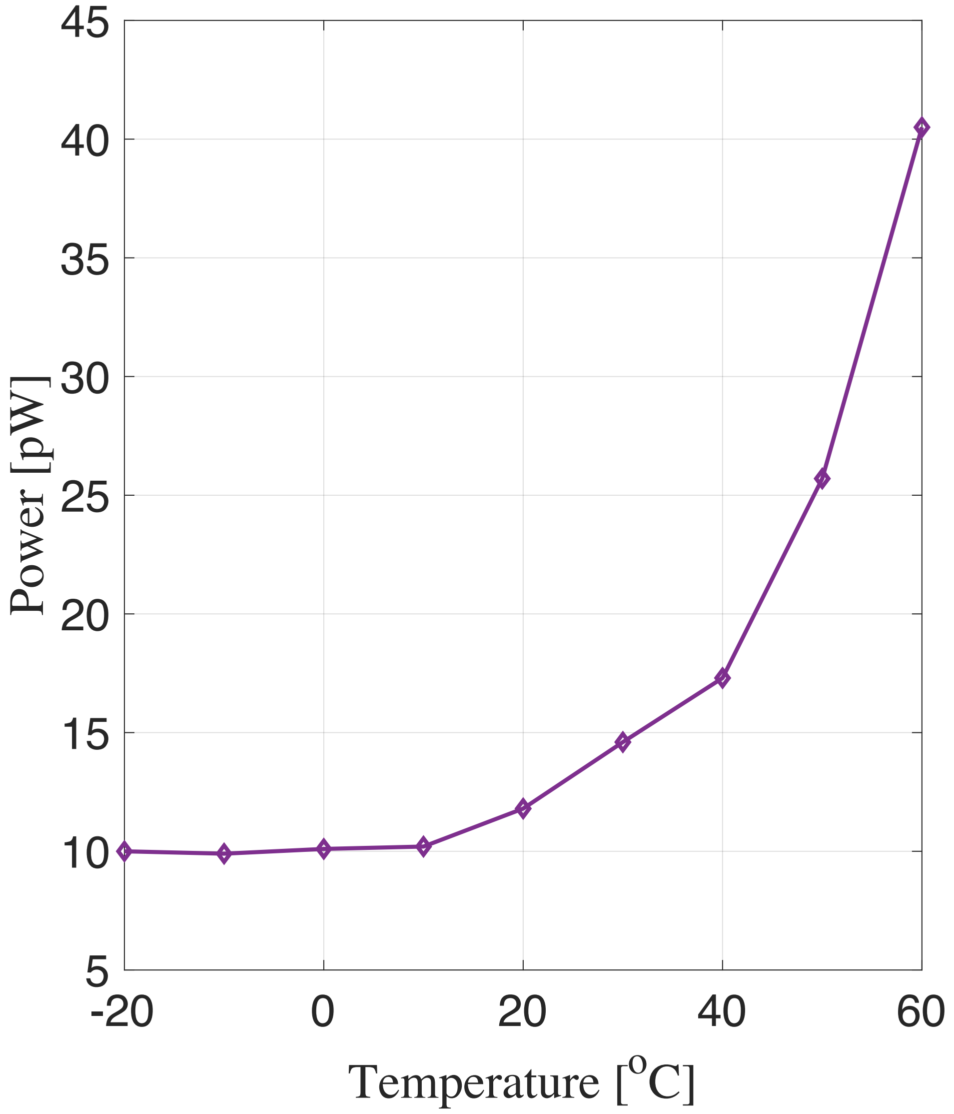
pW current reference



H. Wang et al., Sci. Rep.'17

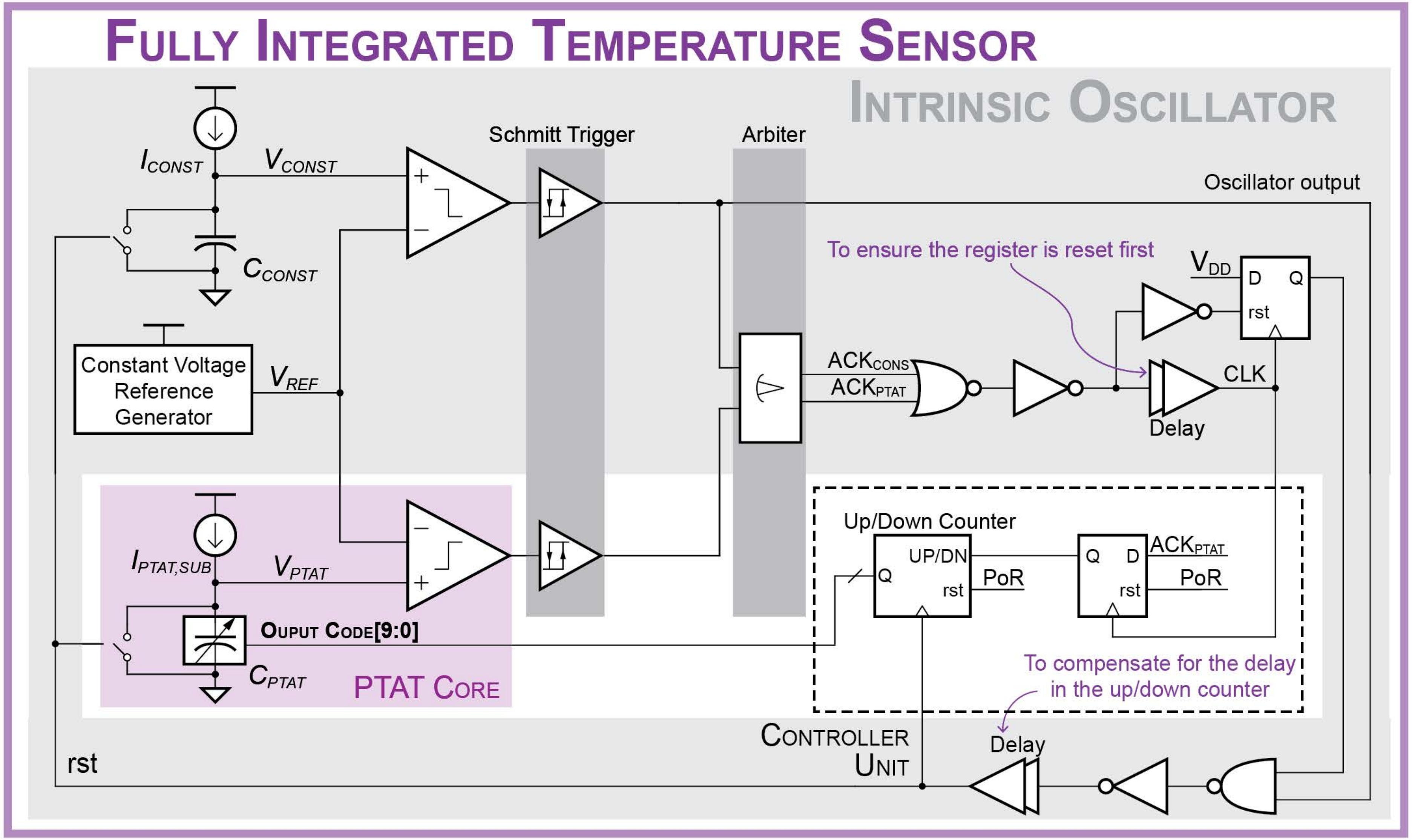
pW relaxation oscillator: 65nm test chip results





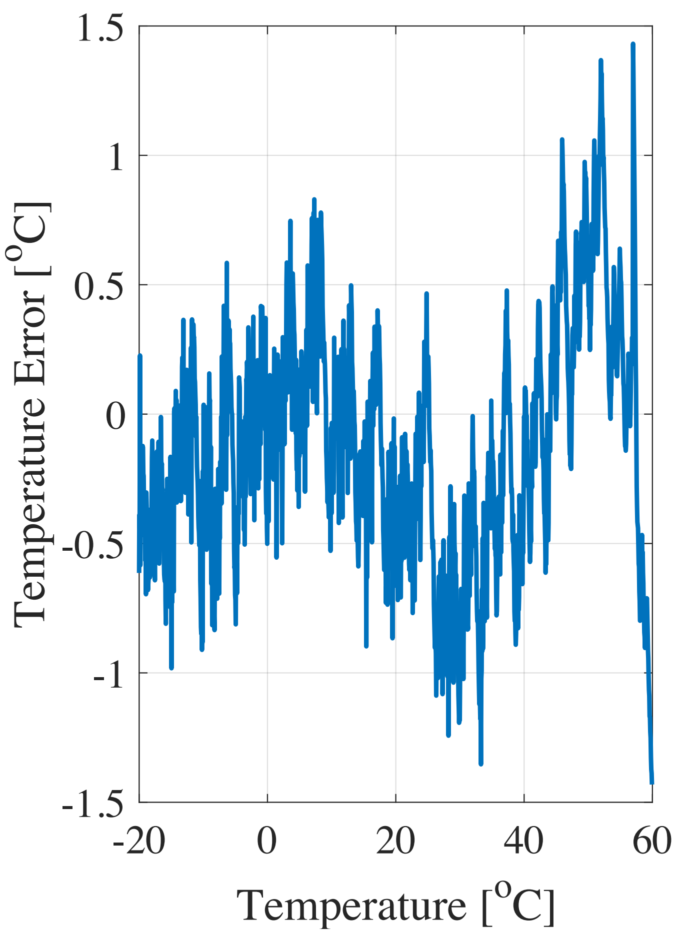
H. Wang et al., Sci. Rep.'17

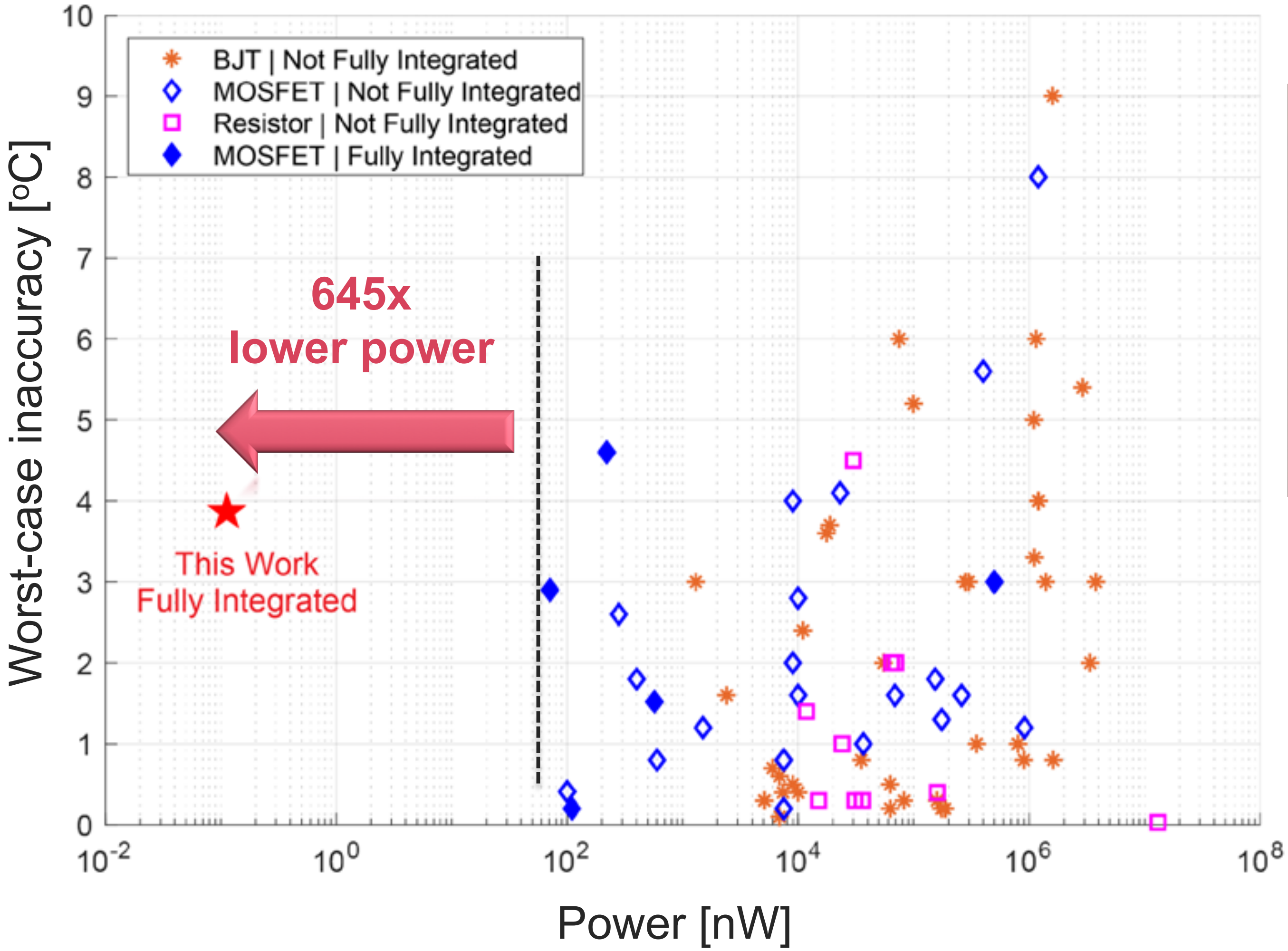
pW temperature sensor



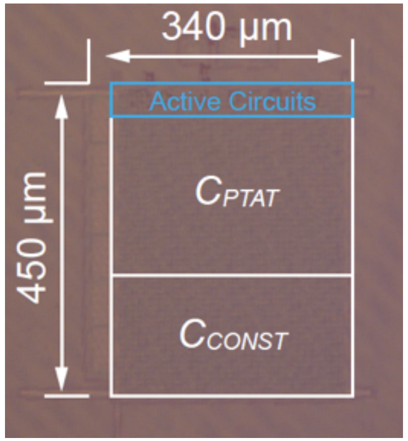
H. Wang et al., Sci. Rep.'17

Temperature sensor measurement results





65nm prototype

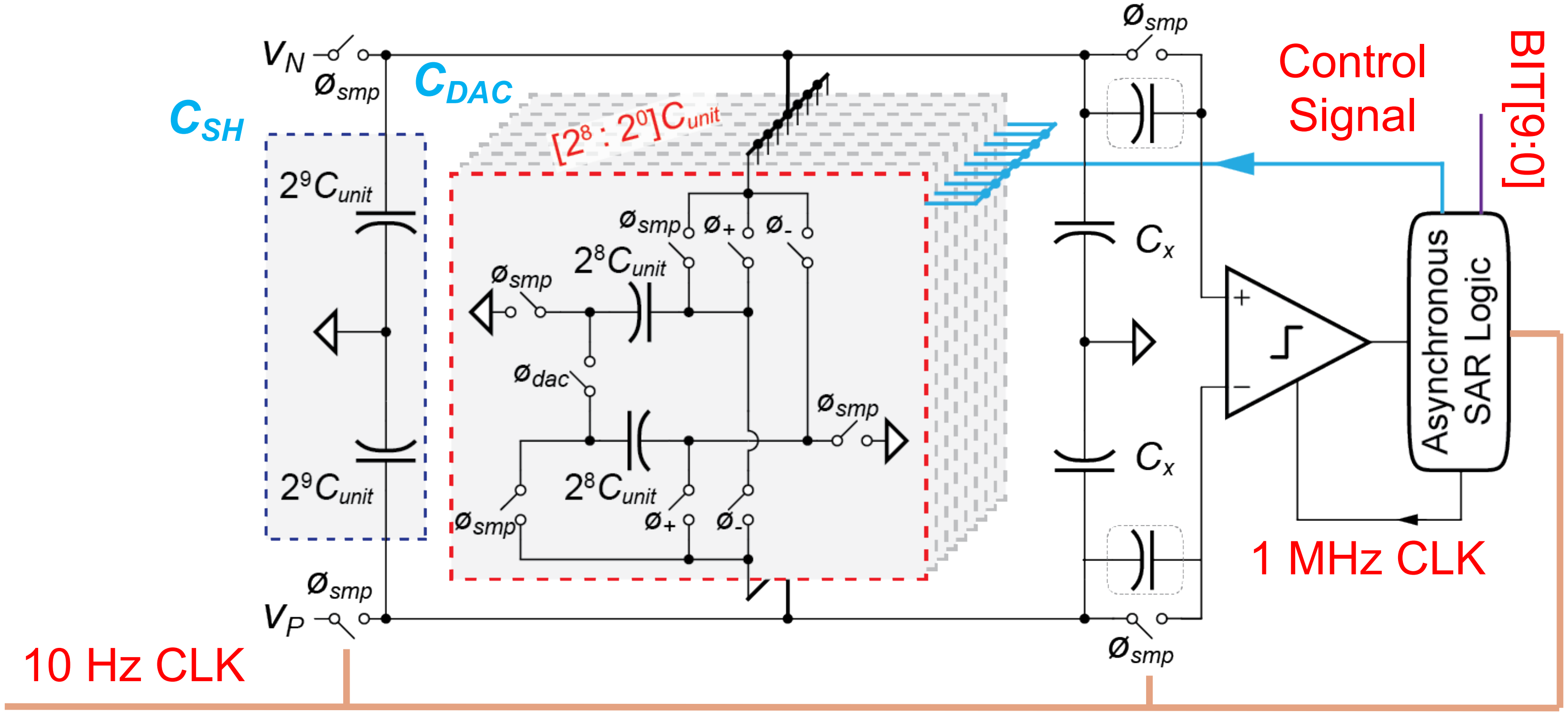


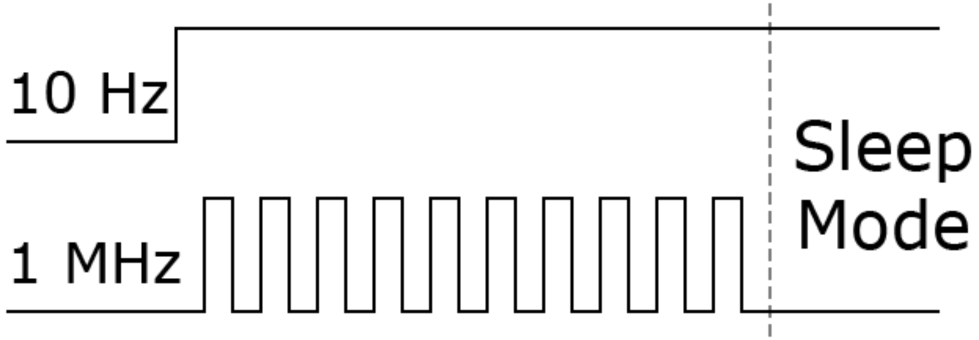
Consumes only 110pW with +/- 1.9°C inaccuracy

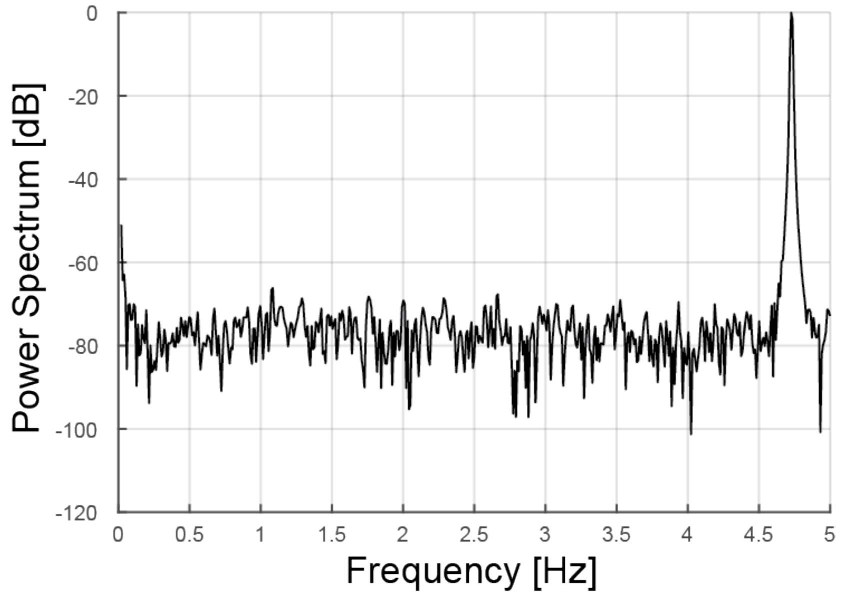
New design with better performance under review

H. Wang et al., Sci. Rep.'17

Sub-nW SAR ADC



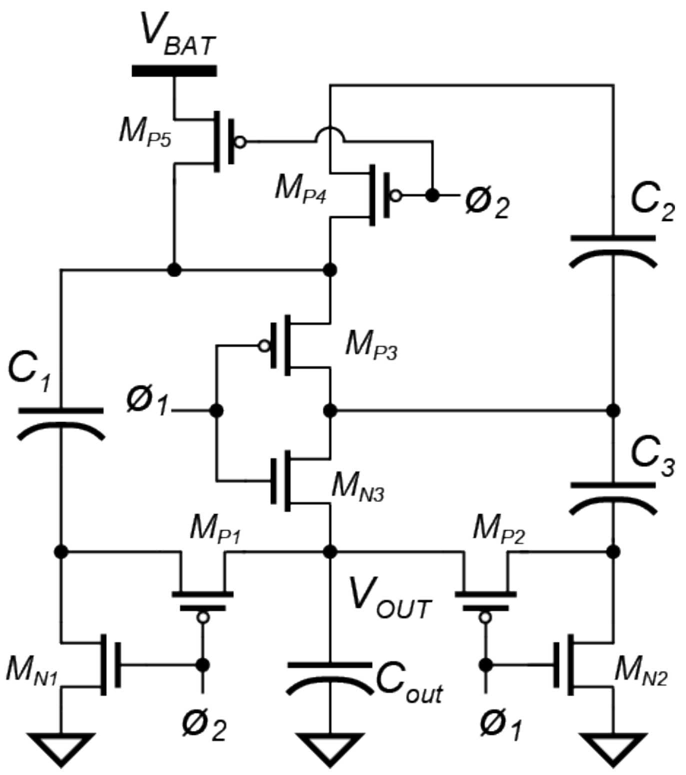


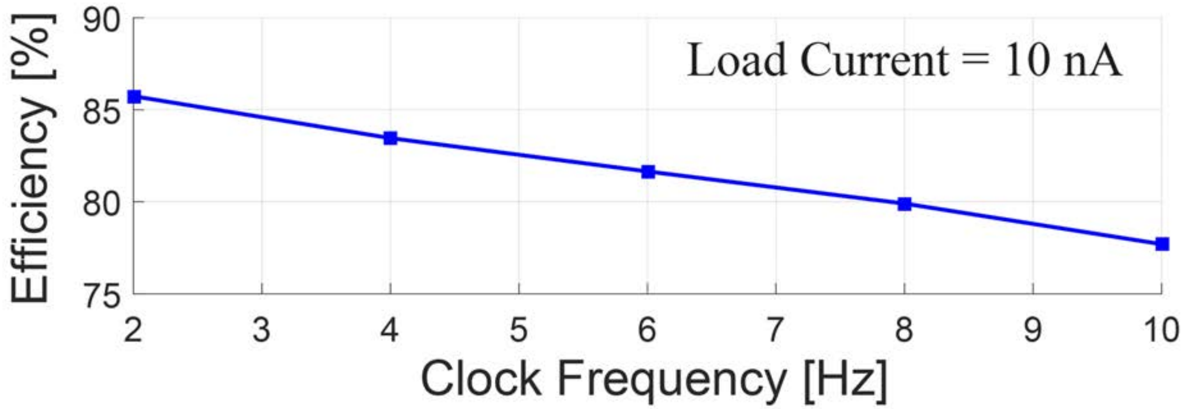


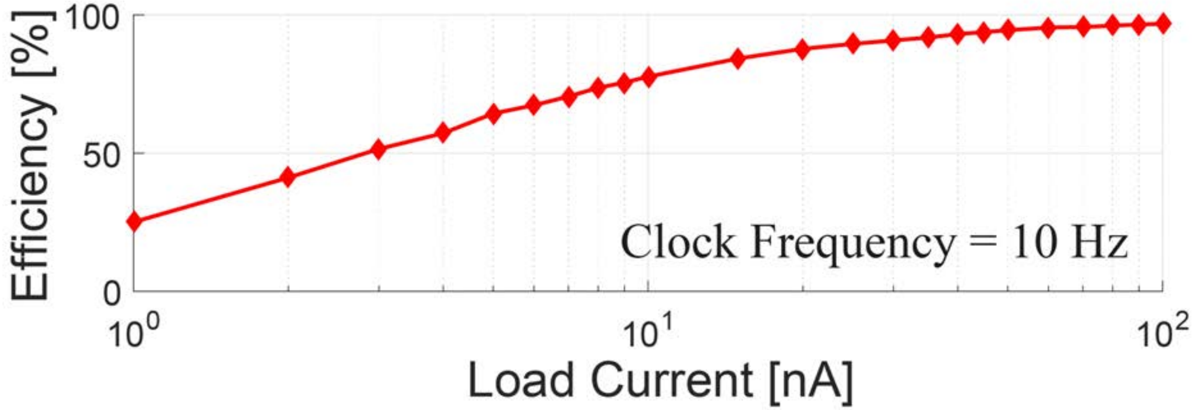
Power: 780pW
Sampling rate: 10 S/s
ENOB: 8.3b

H. Wang et al., JSSC'18

Power Management Unit



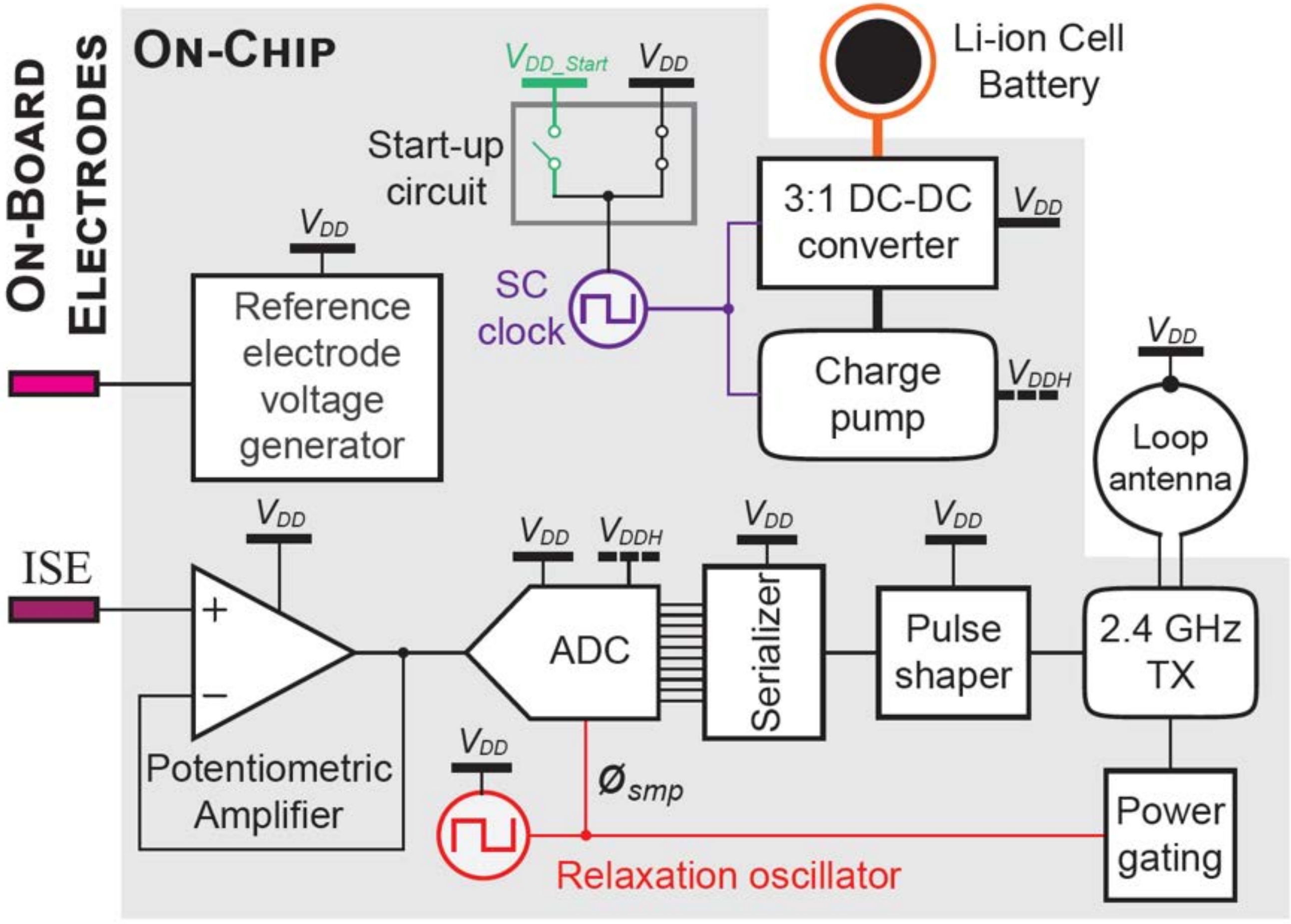


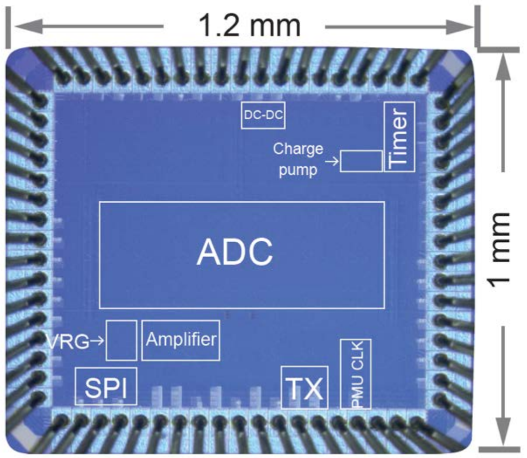


- 1.8V battery to 0.6V load conversion via a 3:1 Dickson topology
- Minimized leakage power and high SSL metric
- Non-overlapping clock reduces quiescent power by 21%
- Peak efficiency: 96.8% at 100nA, 10Hz

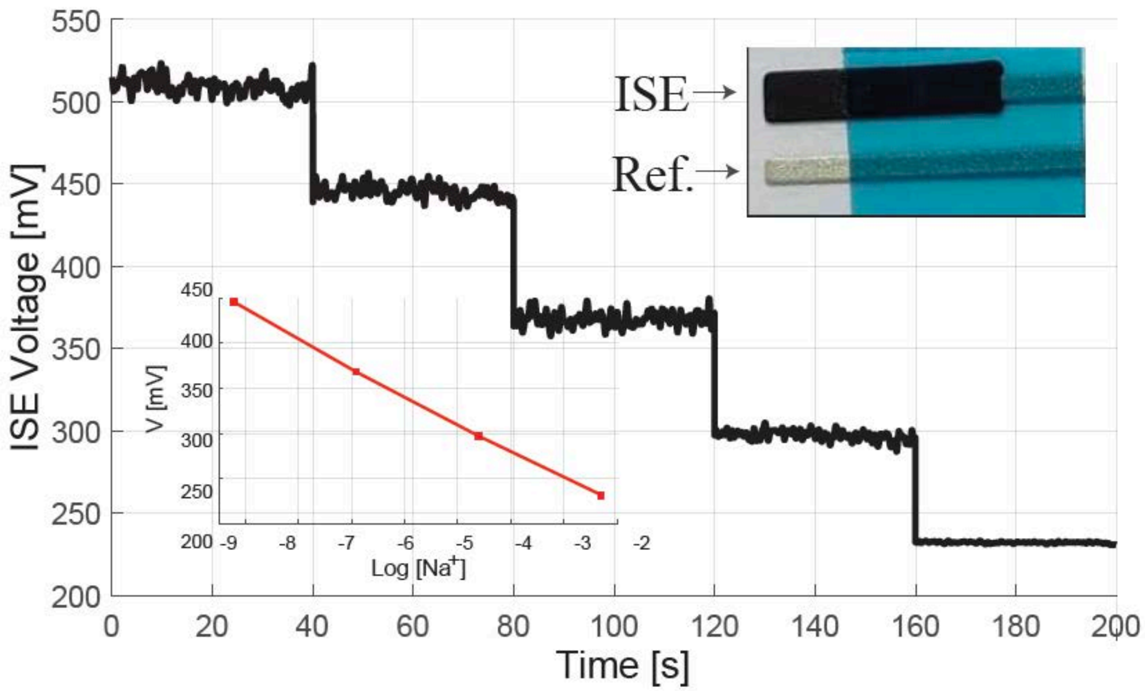
H. Wang et al., JSSC'18

A 5.5nW Wireless Ion-Sensing System





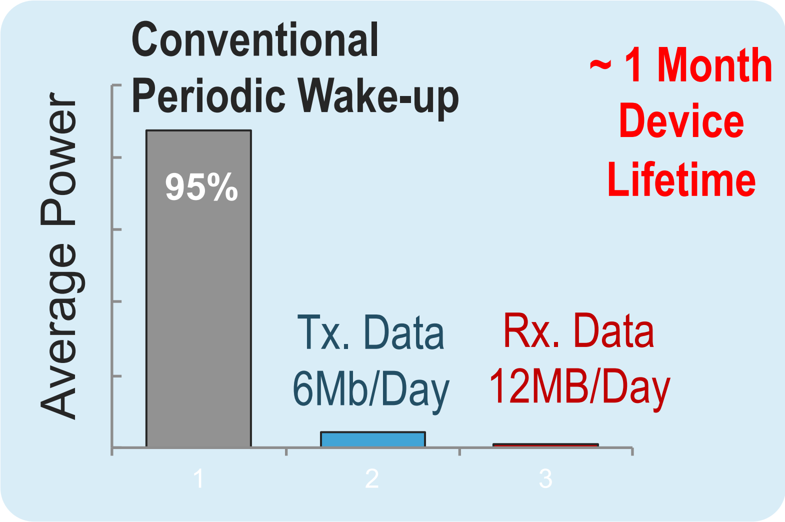
Average power consumption: 5.5nW



H. Wang et al., JSSC'18

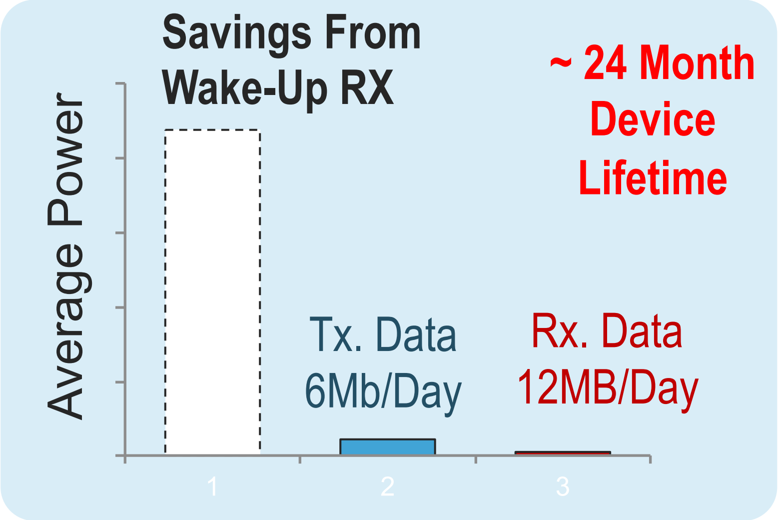
Power-saving receiver approach: wake-up receivers

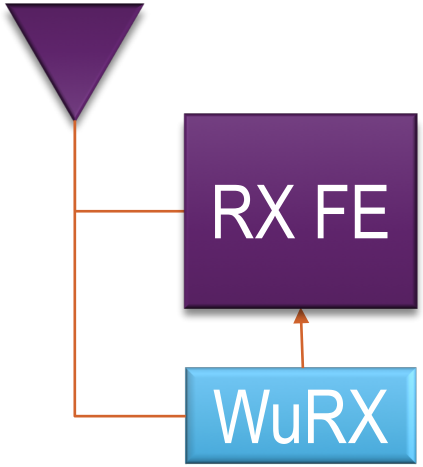
Conventional "wake-on" radio



Courtesy of Troy Olsson (DARPA)

Wake-up receiver (WuRX)





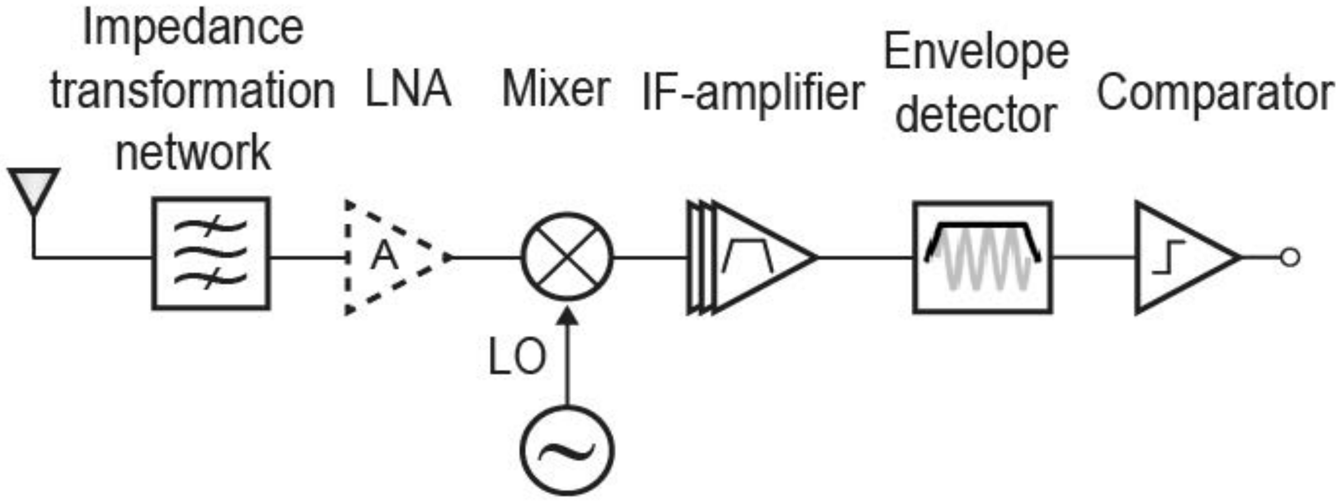
Near-zero power WuRXs can greatly extend lifetime in low-average throughput scenarios

Wake-up receiver requirements:

- Low-power (always on)
- Good sensitivity (ideally comparable to main radio for good network coverage)
- Reasonable latency (depends on application)
- Robustness to interferers (may operate in congested environments)

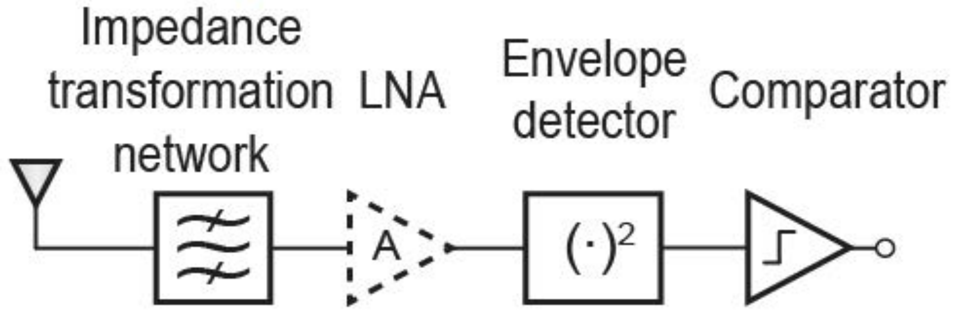
Conventional WuRX Architectures

IF/uncertain-IF:



Problem:
Power hungry LO generation and IF amplification

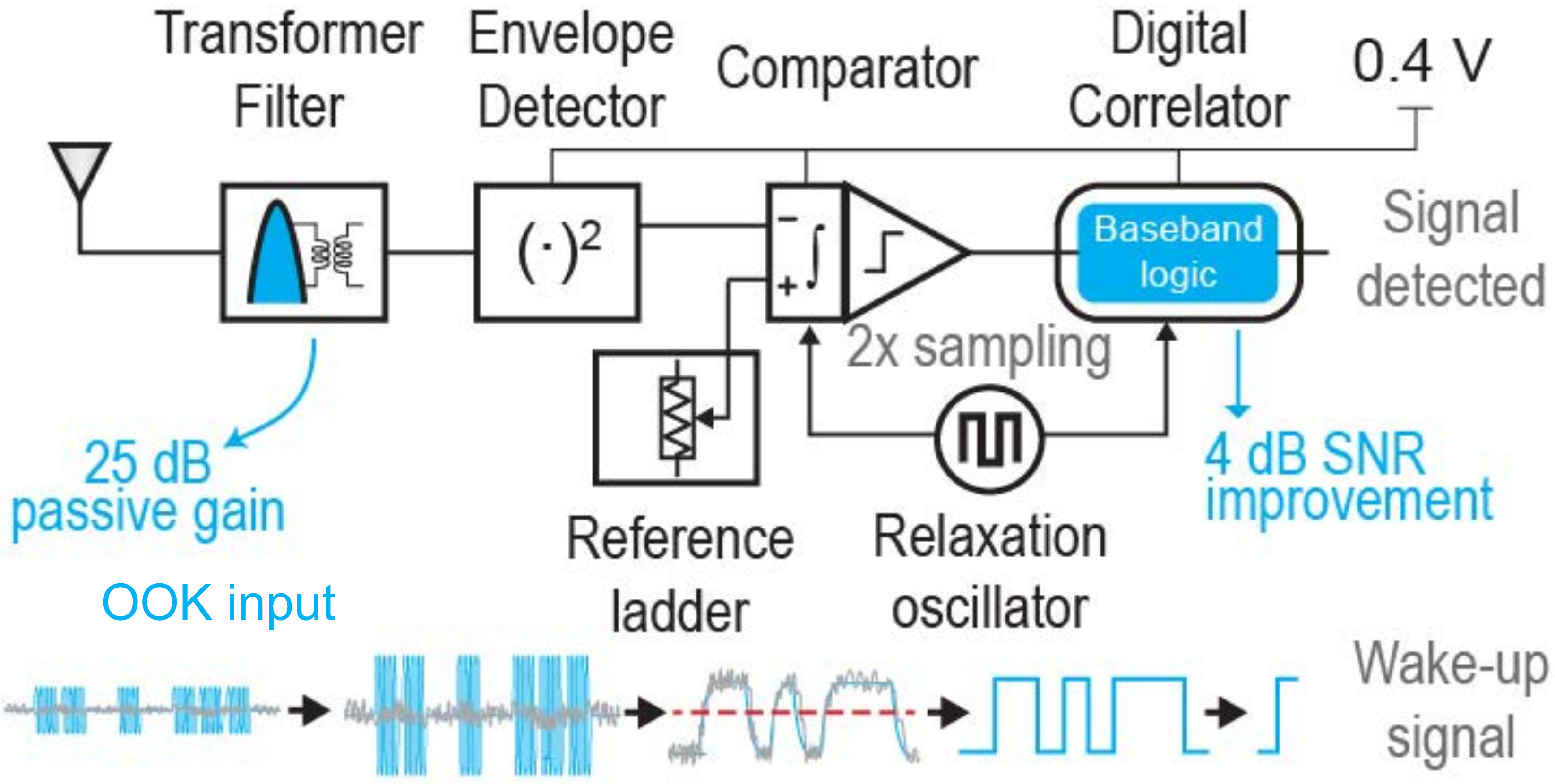
Direct envelope detection:



Problems:
Moderate RF/conversion gain
→ poor sensitivity
Low-*Q* front-end
→ poor interferer tolerance

Challenge: achieving both high gain and low power

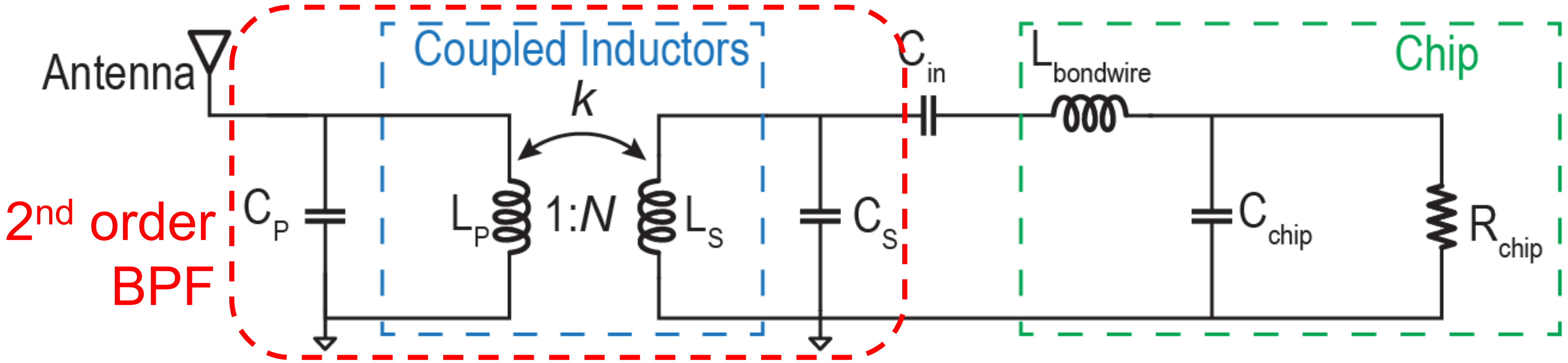
A nW Wake-up Receiver



High R_{in} ED supports high passive gain front-end w/ high-*Q* filtering at low power

H. Jiang / P.-H. Wang et al., ISSCC'17 / JSSC'18

Transformer Filter



25dB gain → 1:316 impedance transformation ratio

Requirements:

1. High ED R_{in} (>15.8kΩ)
2. Large L_s/L_p ratio (=316)
3. Small, well-controlled k (≲0.04)

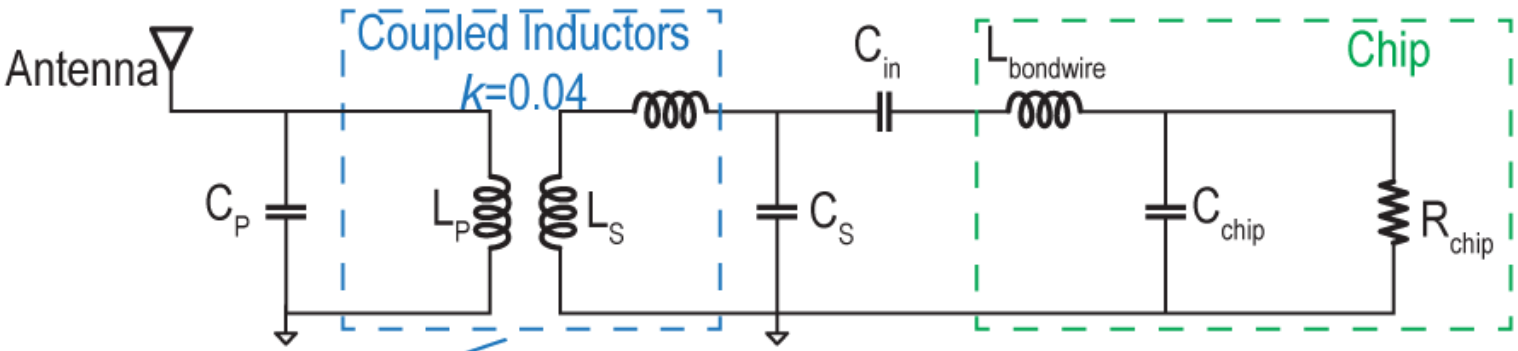
Implementation options:

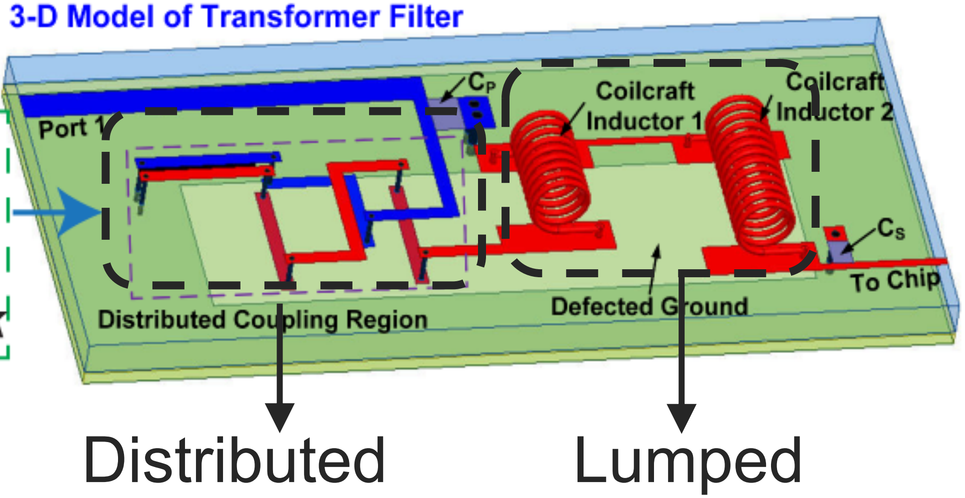
1. Lumped L_p/L_s
   → Large L, but poor-defined k
2. Distributed L_p/L_s
   → Well-controlled k, but small L

Challenge: implement large L_p/L_s ratio with low and well-controlled k

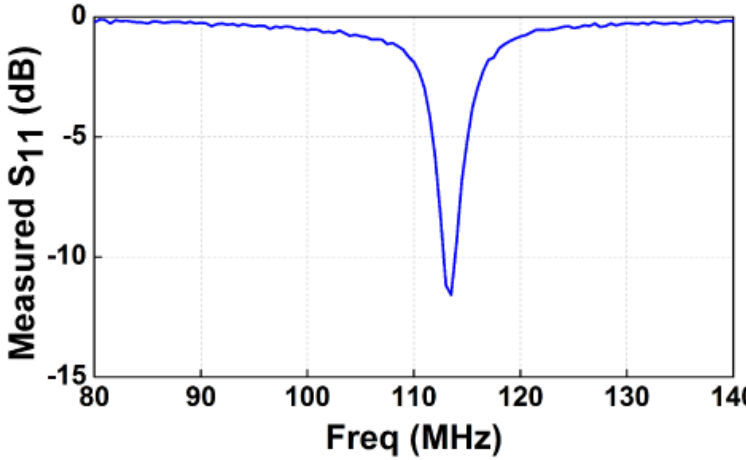
H. Jiang / P.-H. Wang et al., ISSCC'17 / JSSC'18

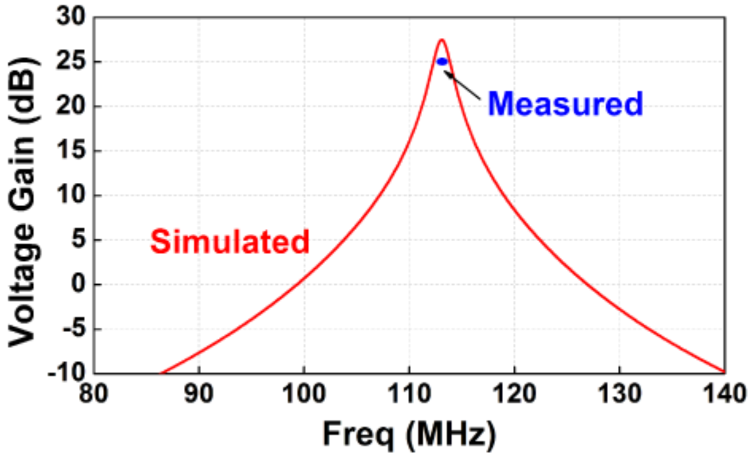
Transformer Filter





L_P: Distributed
+
L_S: Lumped+Distributed
Realize large *L* with well-controlled *k*

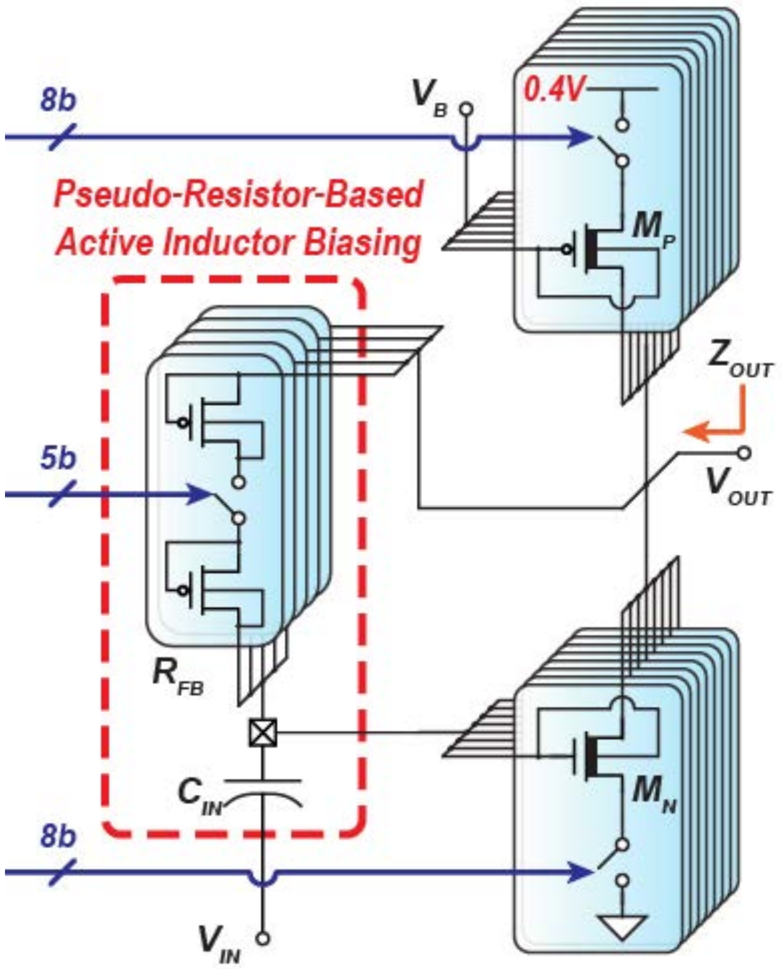




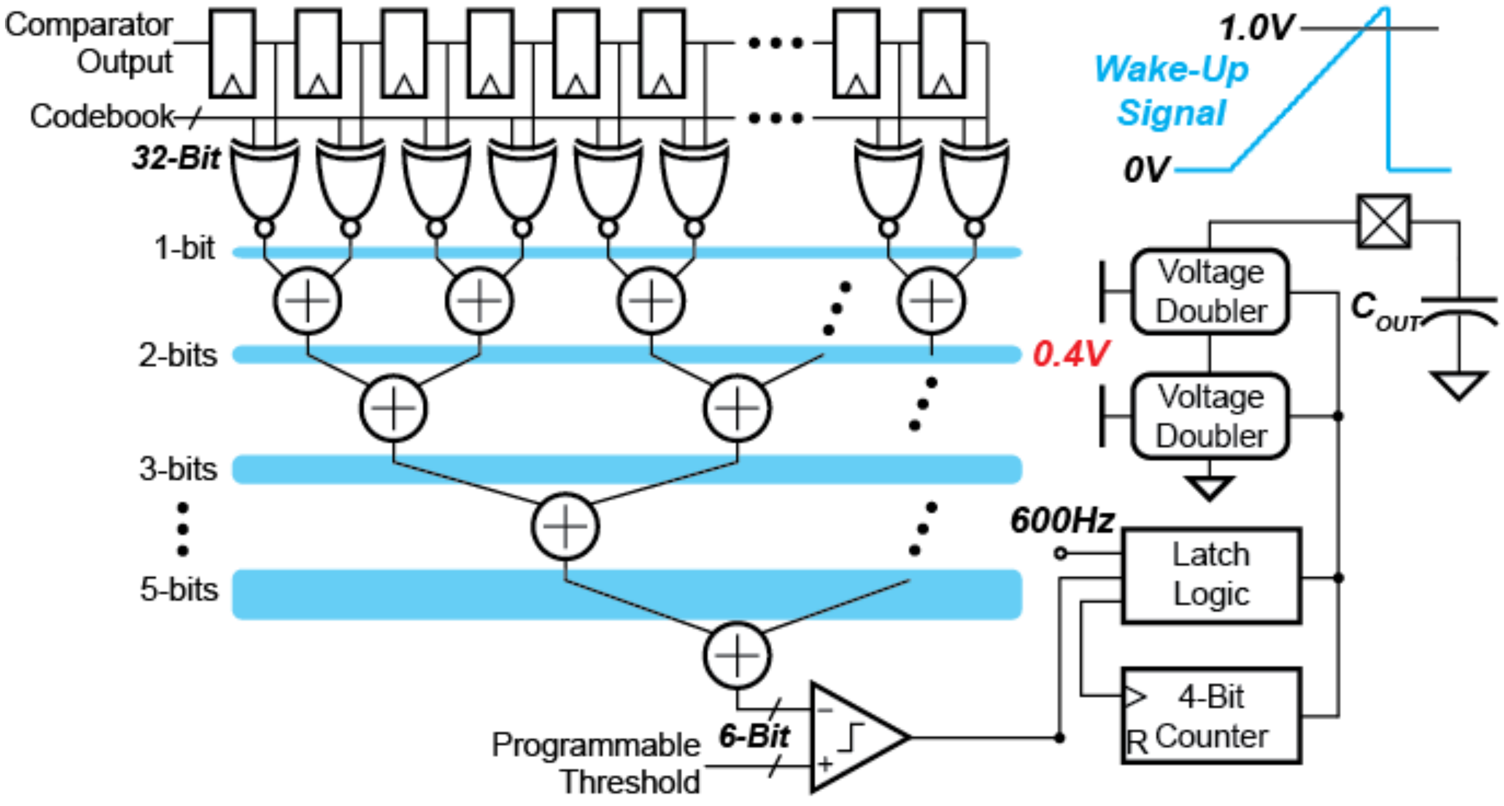
Discrete inductors + stripline inductor control *k* precisely

H. Jiang / P.-H. Wang et al., ISSCC'17 / JSSC'18

Active Envelope Detector & Digital Baseband



Active-inductor bias improves SNR by 3-25dB over conventional common-source

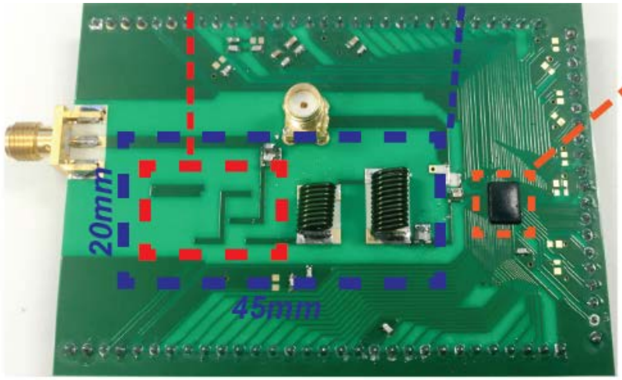


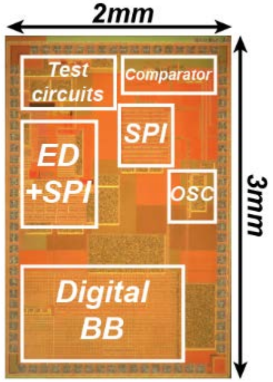
Optimal 16b code improves SNR by 4dB at ~1nW power cost

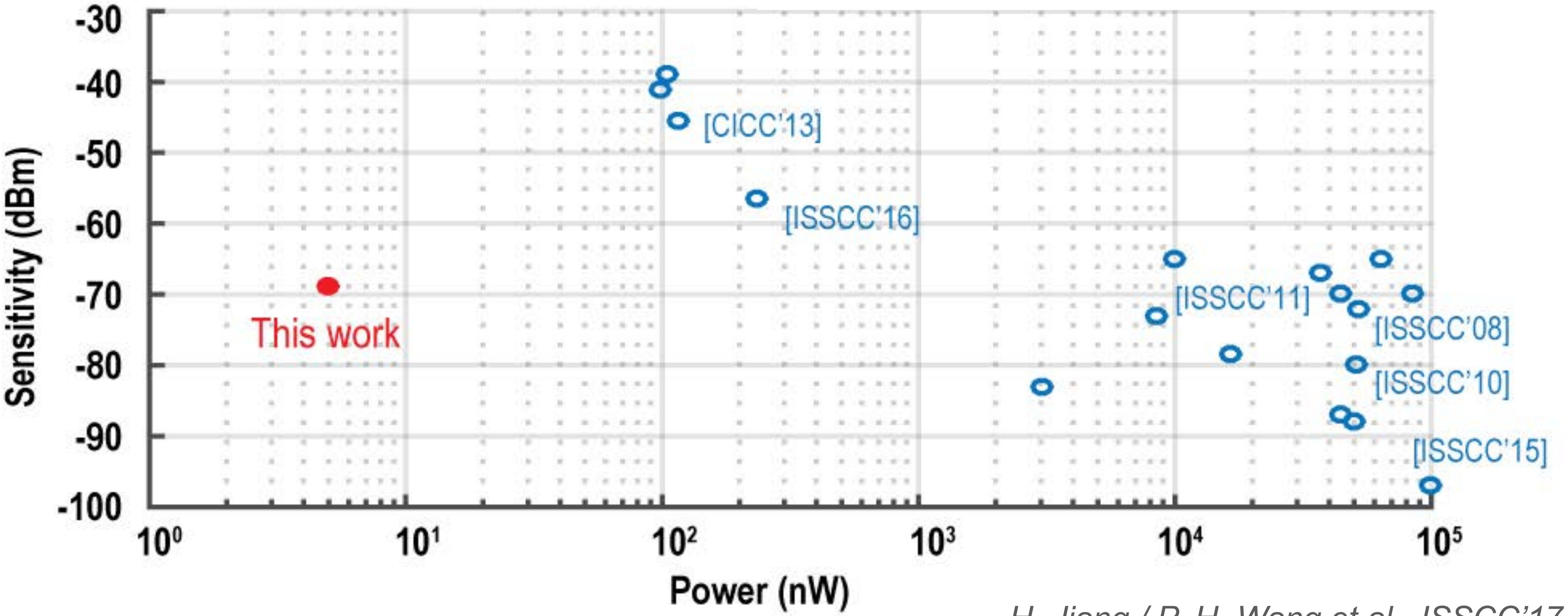
H. Jiang / P.-H. Wang et al., ISSCC'17 / JSSC'18

WuRX Measurement Results

- Power consumption: 4.5nW
- Sensitivity: -69dBm
- Wake-up latency: 53ms



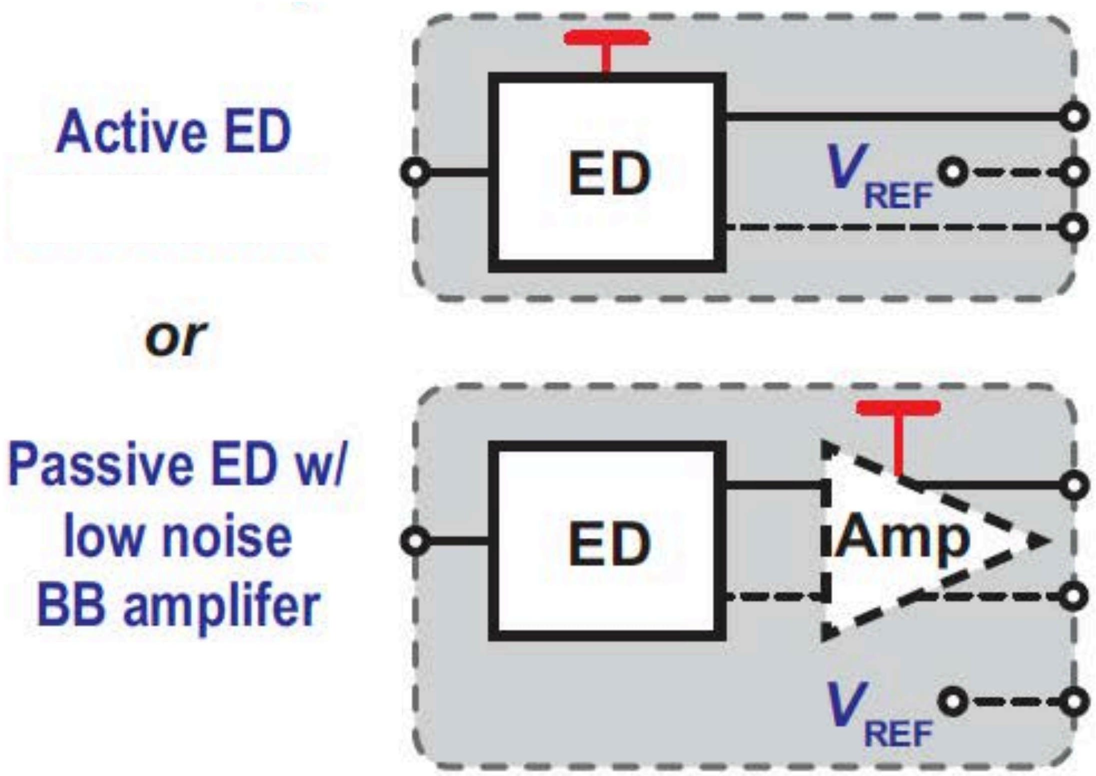


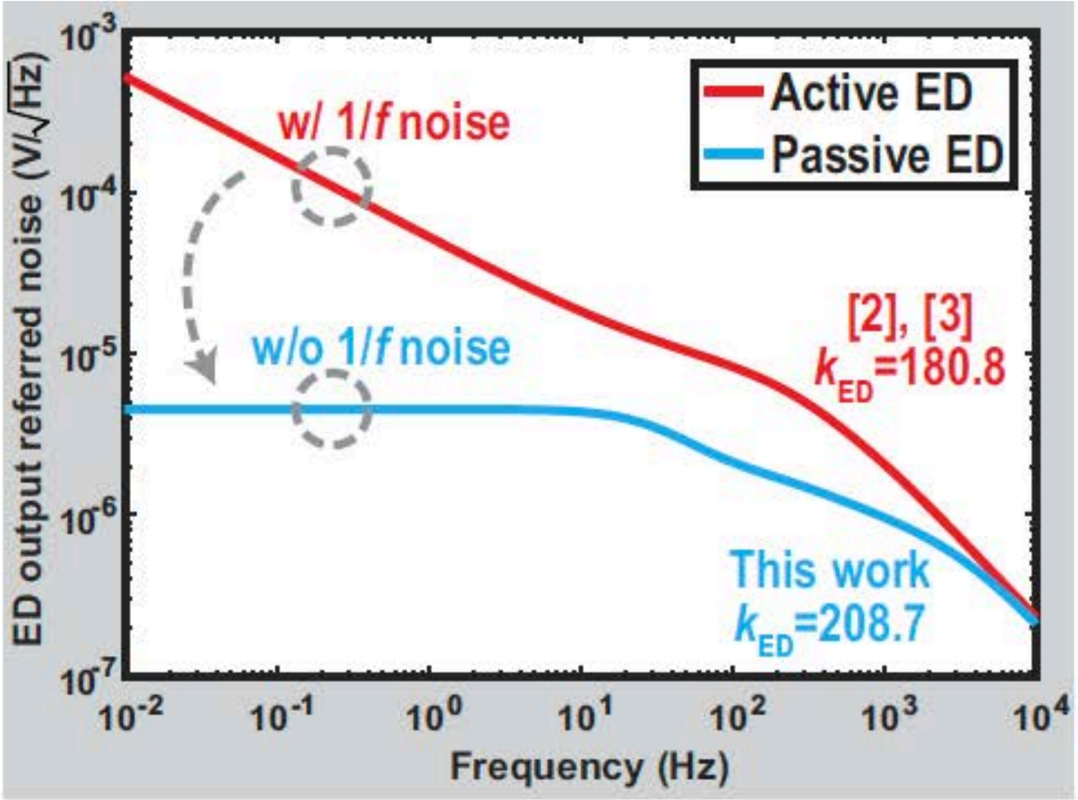


H. Jiang / P.-H. Wang et al., ISSCC'17 / JSSC'18

Improving WuRX sensitivity

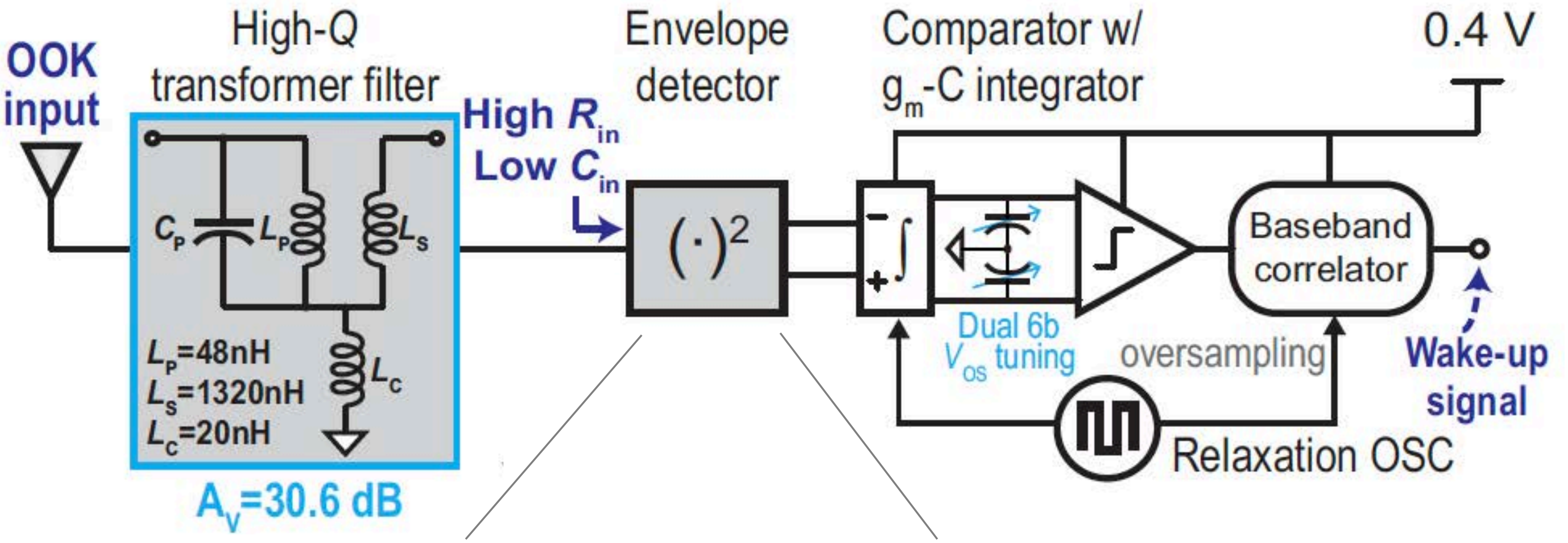
- Key limiter in previous work: ED noise
- Idea: replace active ED with passive ED → eliminates 1/f noise

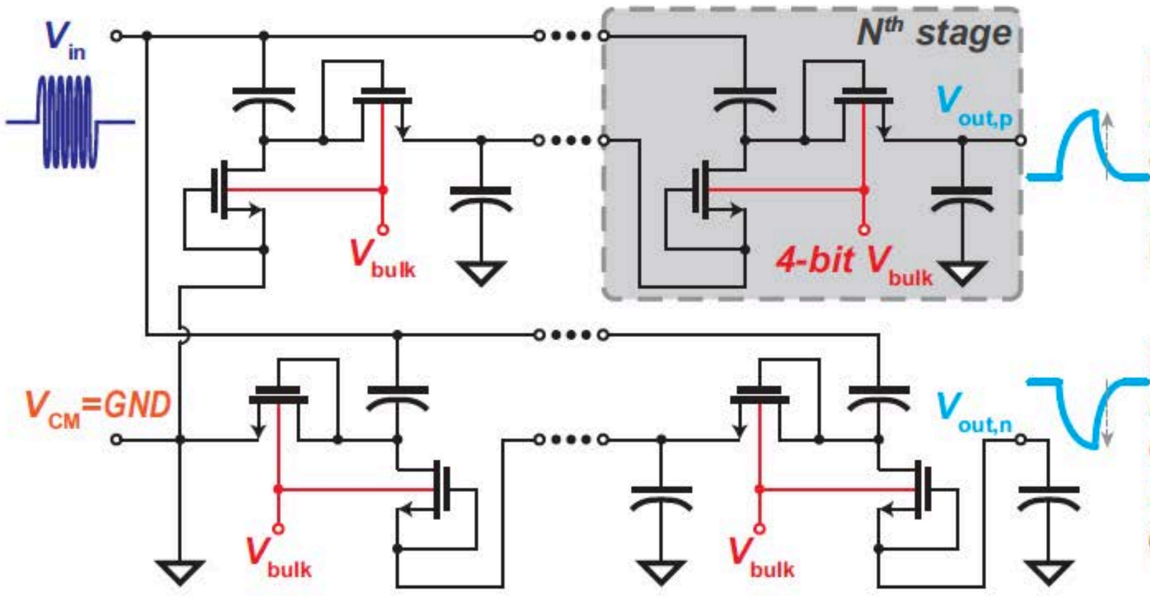




P.-H. Wang et al., SSCL, 2018

A 6.1nW Wake-up Radio with -80.5dBm Sensitivity





Pseudo-balun ED

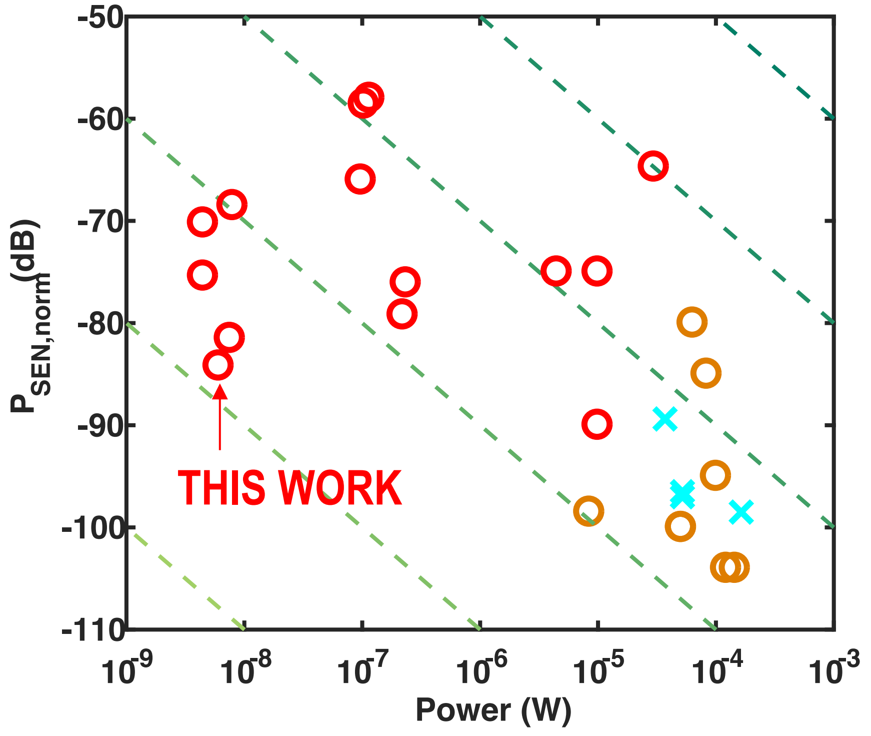
Benefit 1: 2X conversion gain w/o output bandwidth penalty

Benefit 2: 1.5 dB sensitivity improvement vs. single branch only

Bulk tuning unit cell

Benefit 1: tunable V_t for PVT or sizing for lower C_{in}

Benefit 2: no extra loading @ RF for biasing network

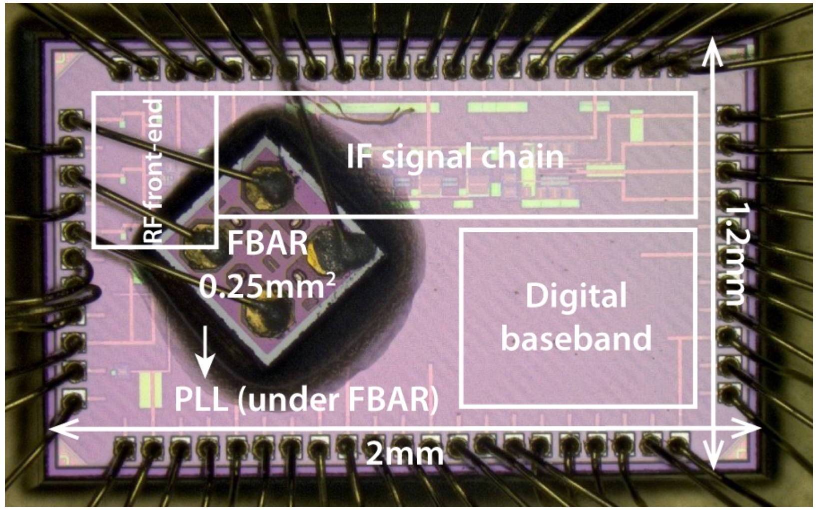


Challenges:

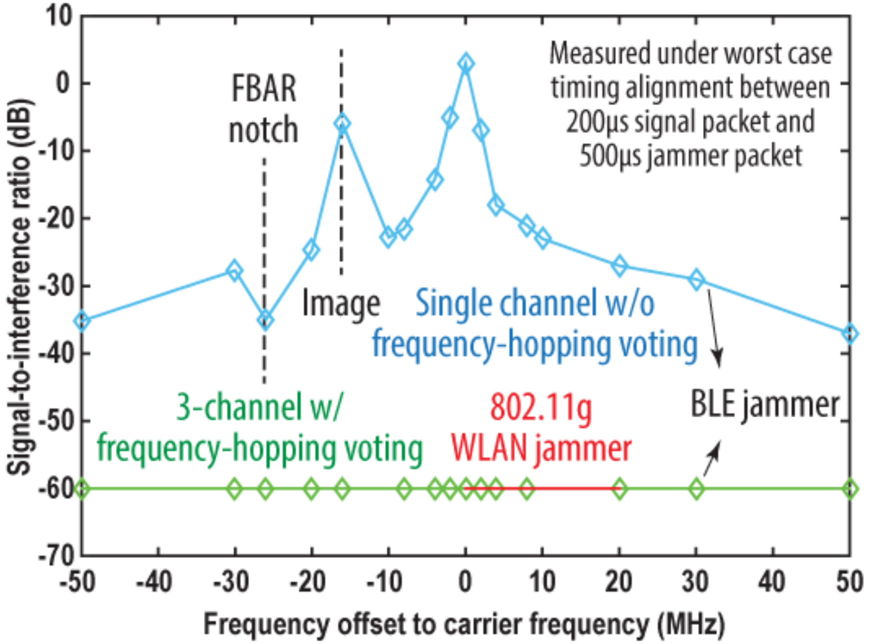
1. Not standard compliant
2. Low-frequency operation @ FM band
3. Susceptible to interferers

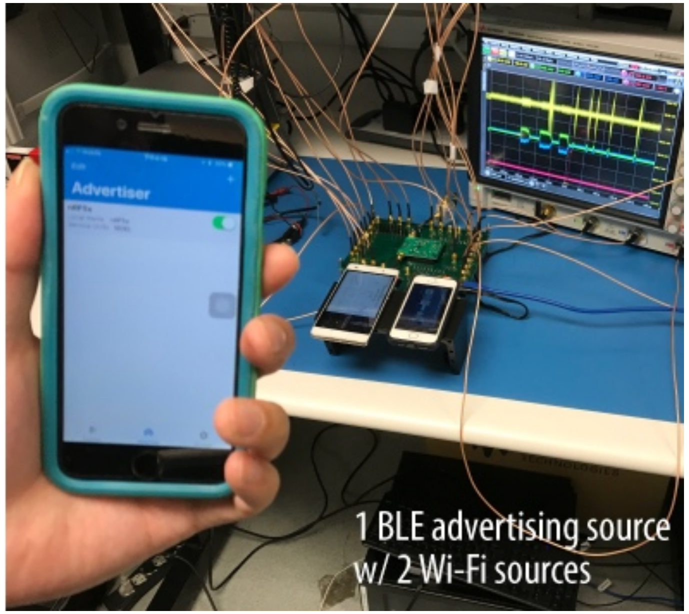
P.-H. Wang et al., SSCL, 2018

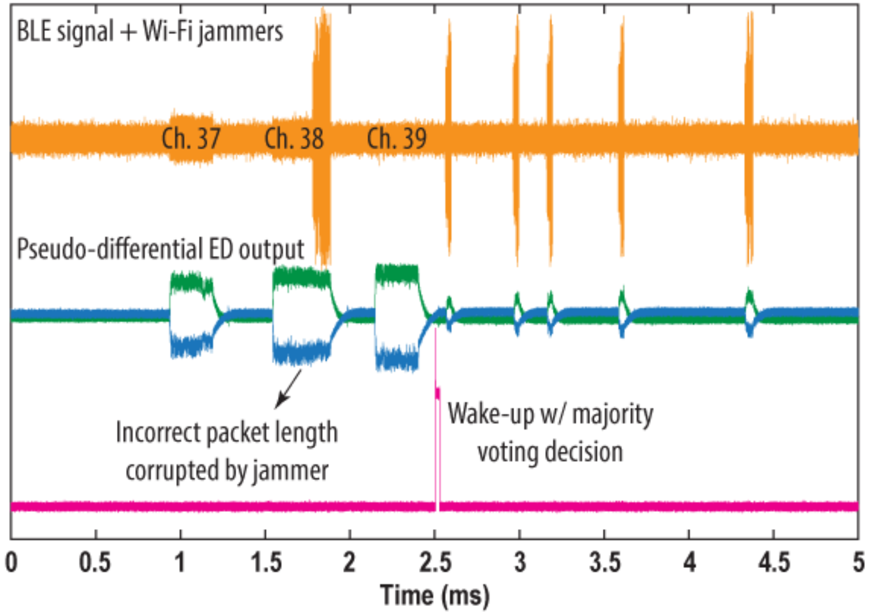
An Interference-Robust BLE-Compliant Wake-up Receiver



- ❑ **Sensitivity:** -85dBm @ 220μW
  - ❑ 27.5dB better than prior-art
- ❑ **Latency:** 200μs-to-1.47ms
- ❑ **SIR:** at least -60dB SIR (limited by measurement setup)

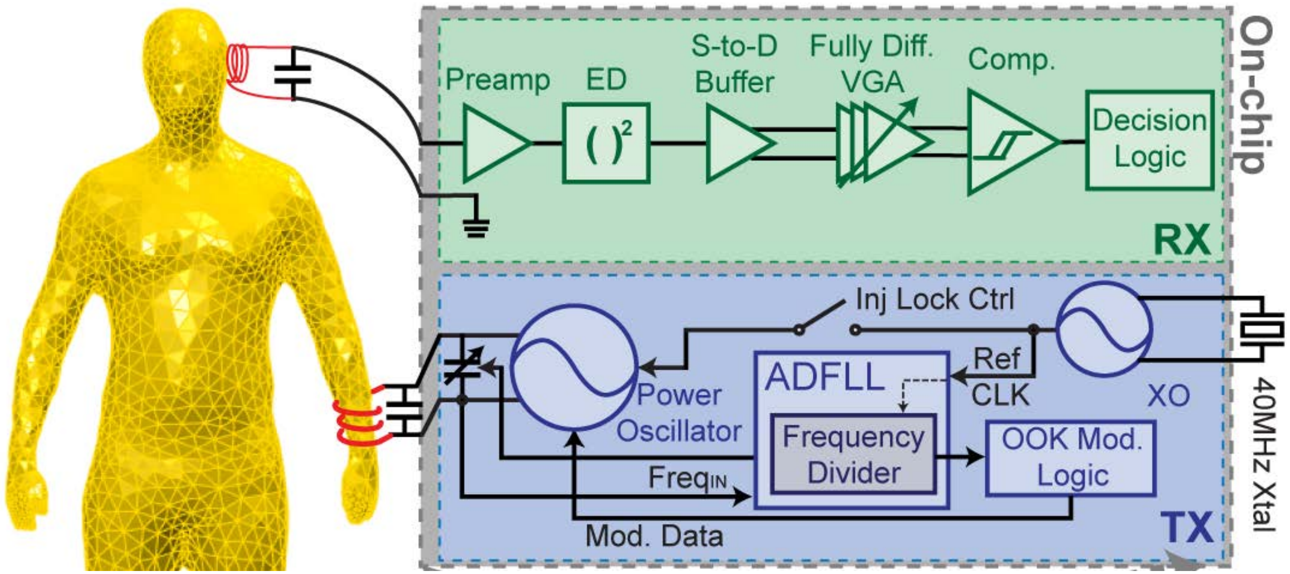


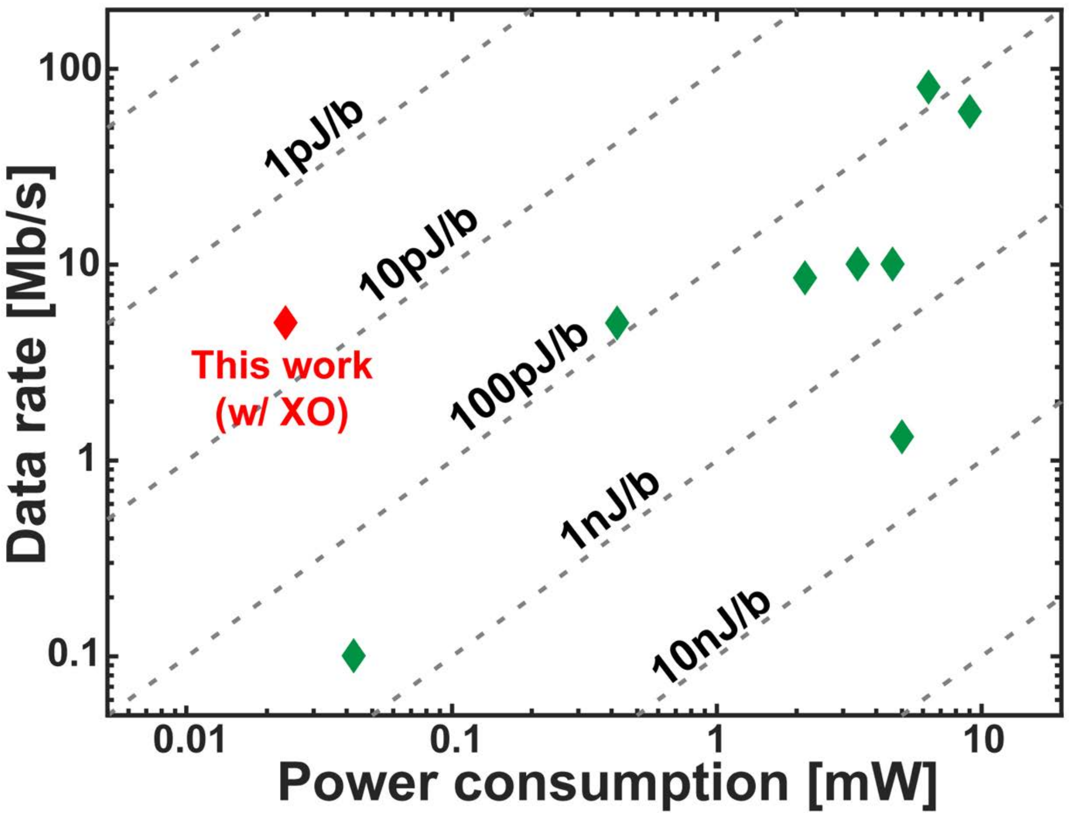


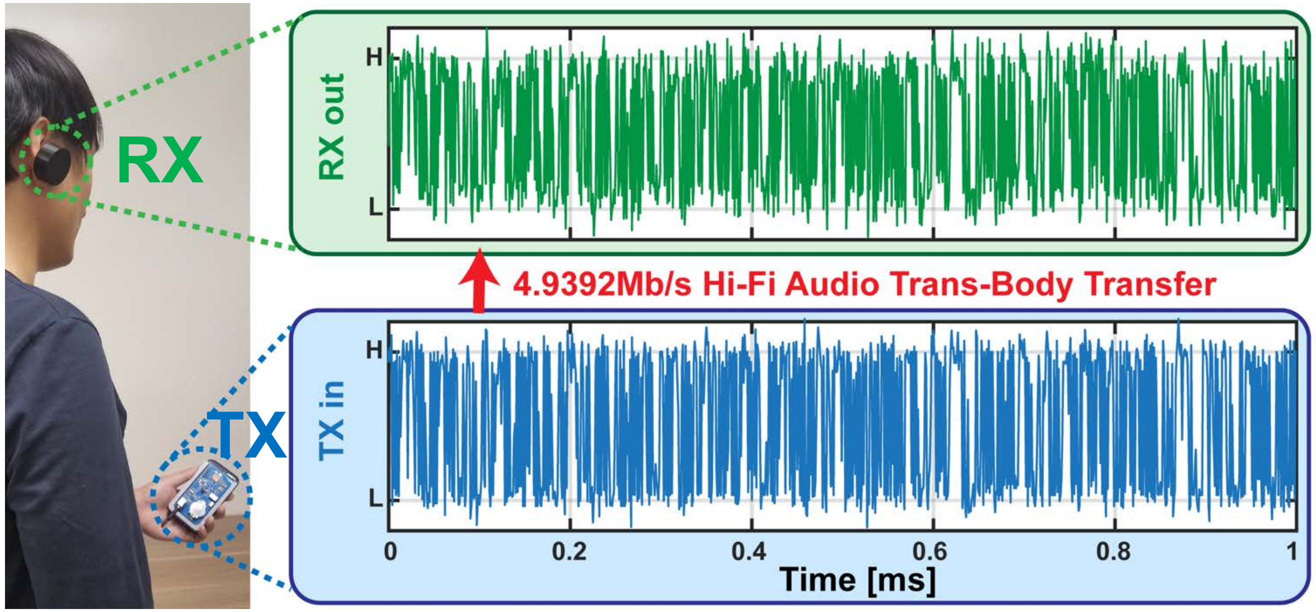


P.-H. Wang et al., ISSCC'19

Magnetic Human Body Communication



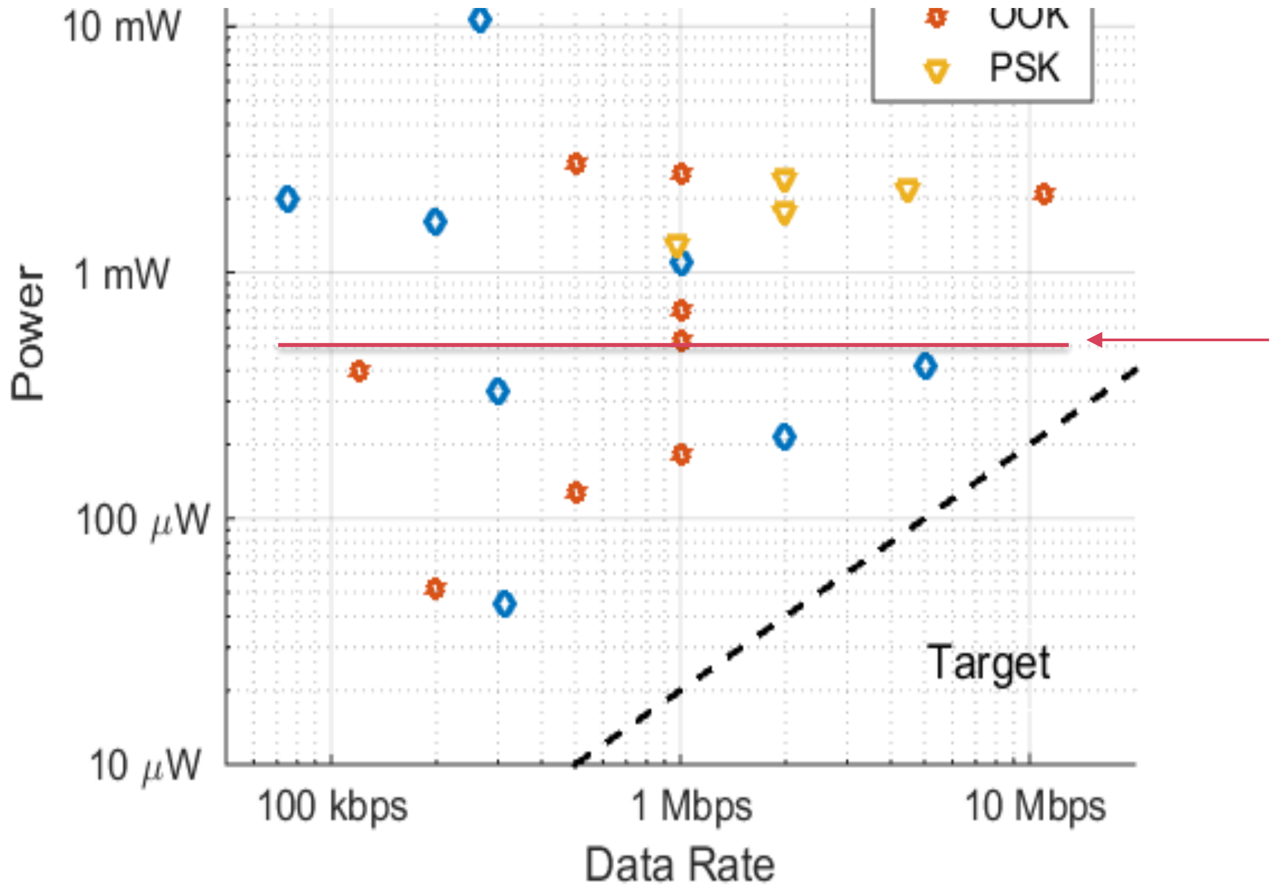




<40μW @ 5Mbps across the body:
<8pJ/bit!

J. Park et al., ISSCC'19

Ultra-low-power radios & spectral efficiency



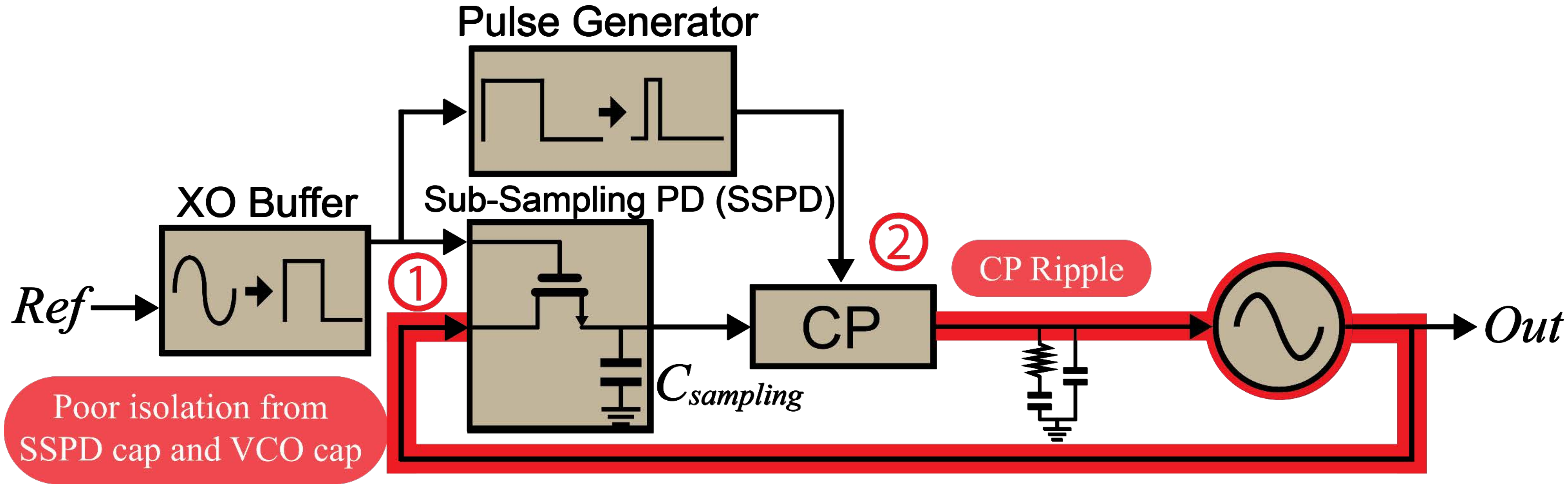
No PSK-capable receivers under 1mW

Why?
Because PLLs with sufficient phase noise require > 1mW at 2.4GHz

All low power radios designs utilize OOK or FSK modulation
→ extremely spectrally inefficient

Research Need: **Low-power high performance PLLs**

Sub-Sampling PLLs: Low-Power and High-Performance

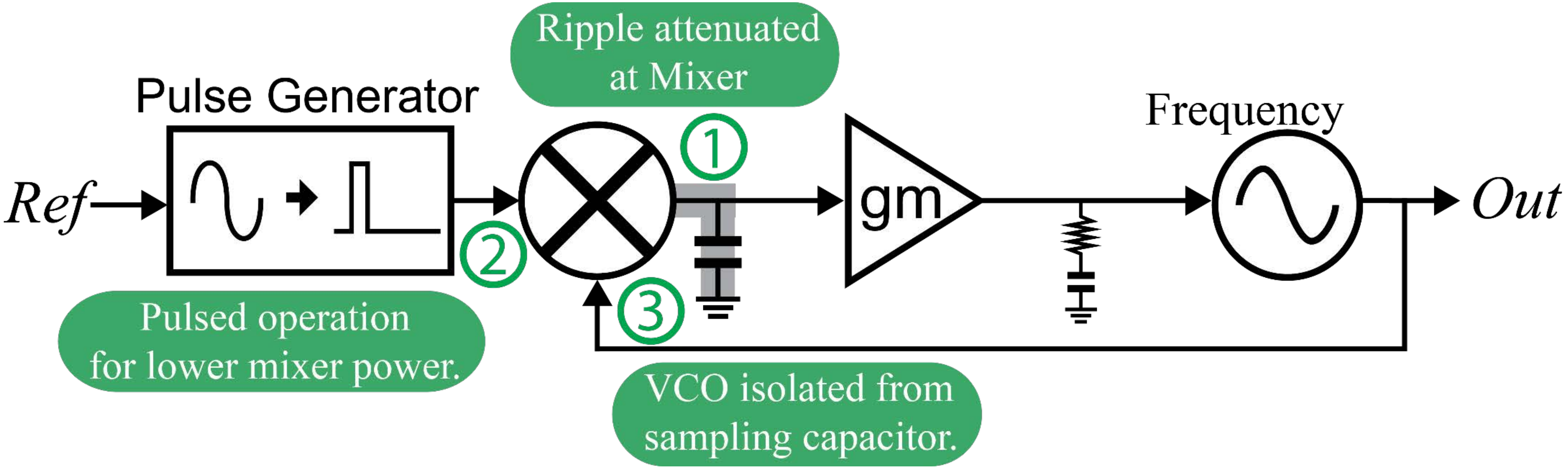


Advantage: No divider leads to lower in-band noise, lower power

Challenges:

1. Periodic connection between SSPD cap and VCO resonator yields spurs
2. Charge pump ripple attenuated only by 1st order RC filter

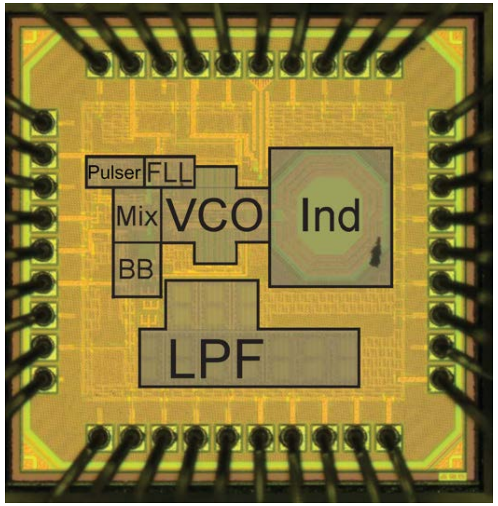
Active mixer-adopted sub-sampling (AMASS) PLL

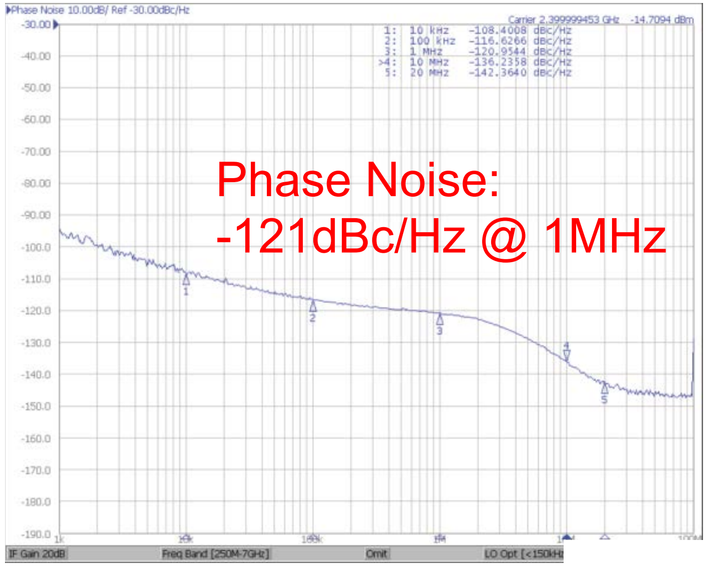


- Sub-sampling phase detector switches essentially perform passive mixing between LO and pulse generator
- **Main idea:** perform active mixing instead for improved isolation of VCO and more ripple attenuation
  - Additionally, pulse active mixer to reduce power (by ~50x)

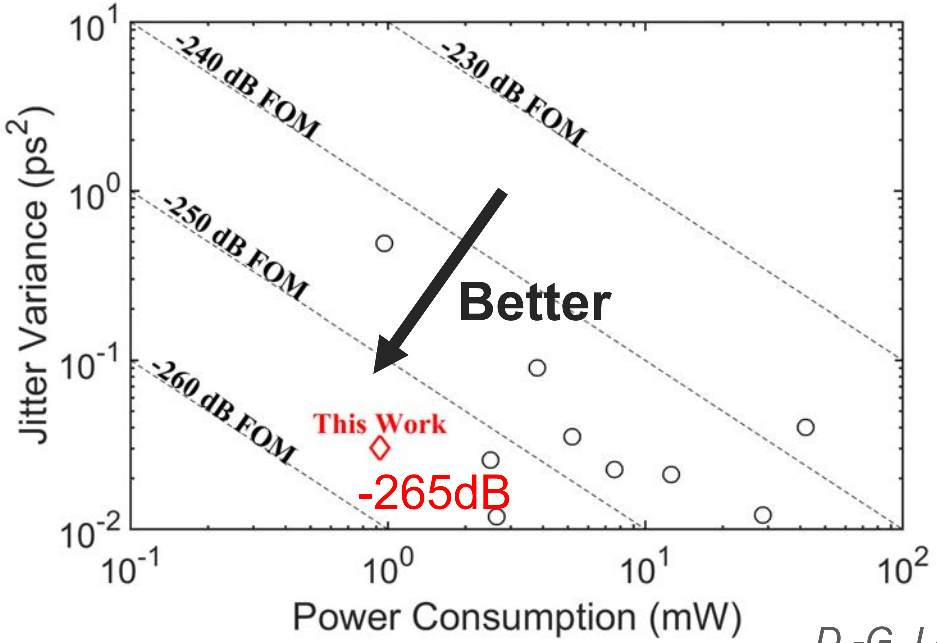
D.-G. Lee et al., VLSI Symposium, 2018

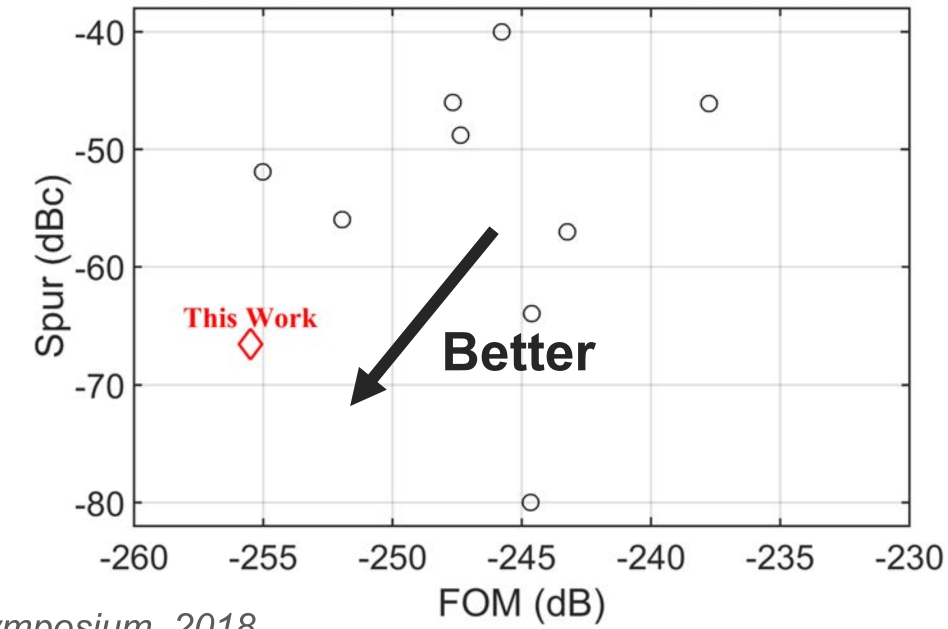
AMASS-PLL: Measurement Results





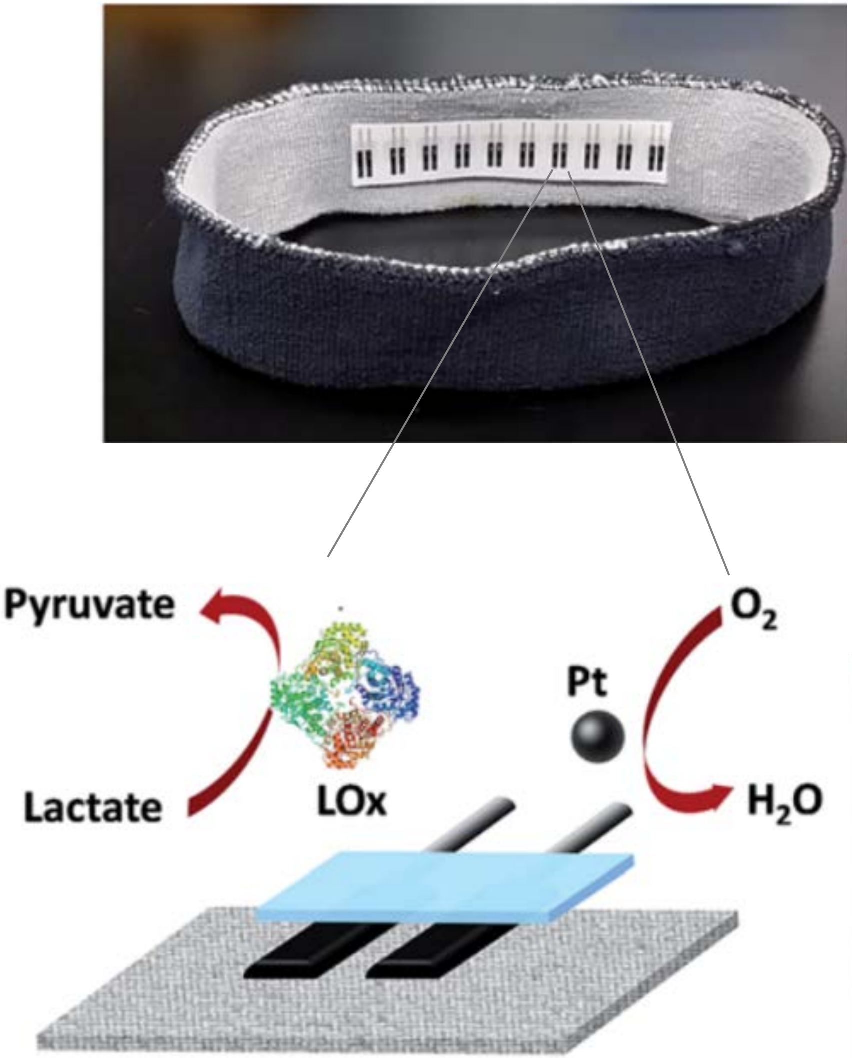
Sub-mW power with excellent performance: record-setting FoM with low spurs





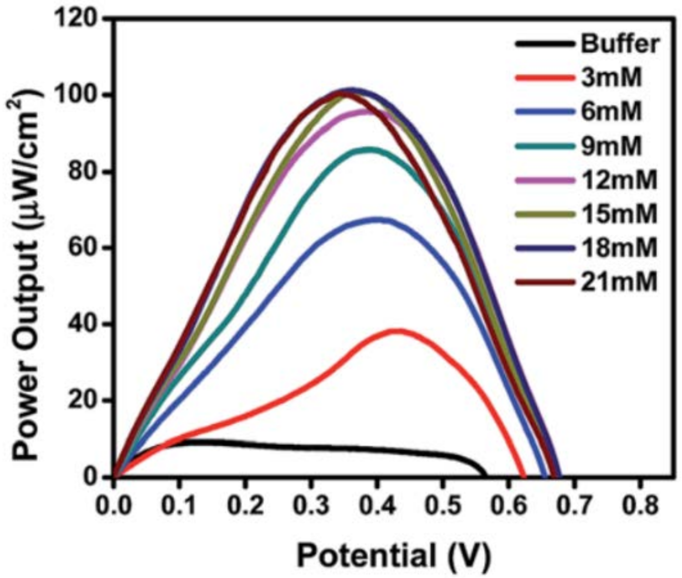
D.-G. Lee et al., VLSI Symposium, 2018

Harvesting energy from human perspiration via lactate biofuel cells



Watch “OFF”

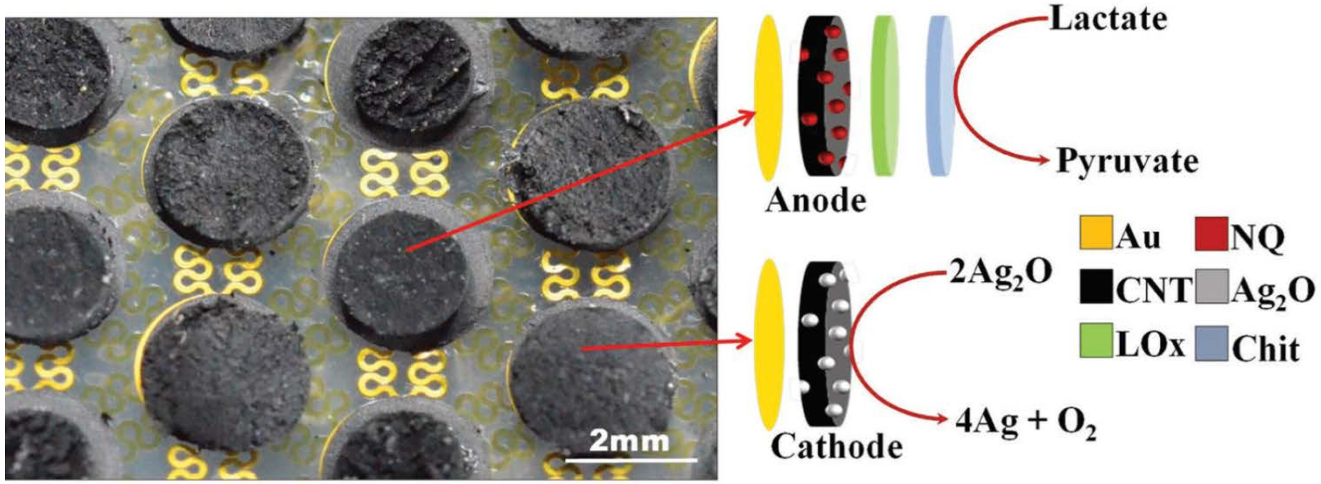
Watch “ON”

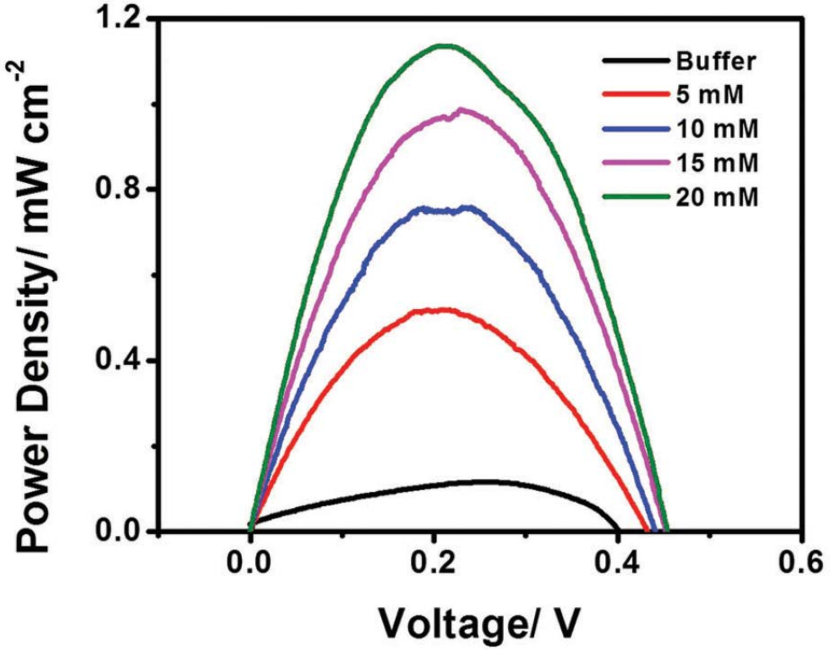


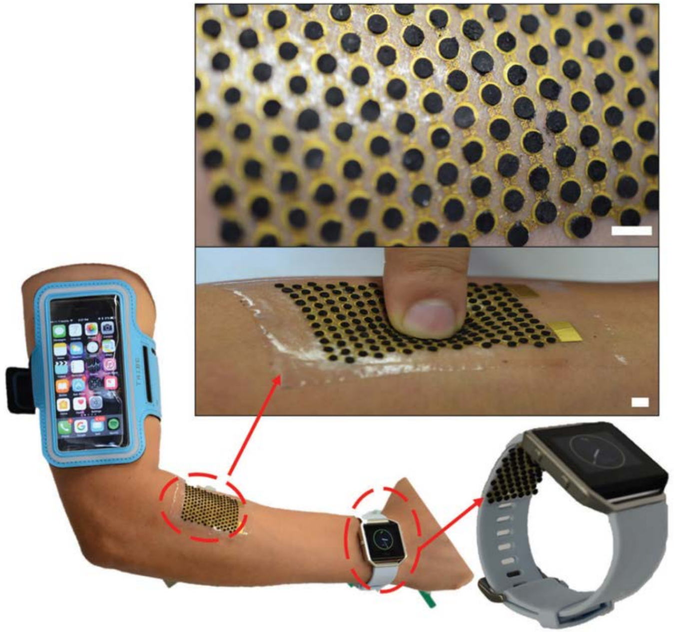
J. Wenzhao et al., J. Mat. Chem., 2014

Increasing BFC power density

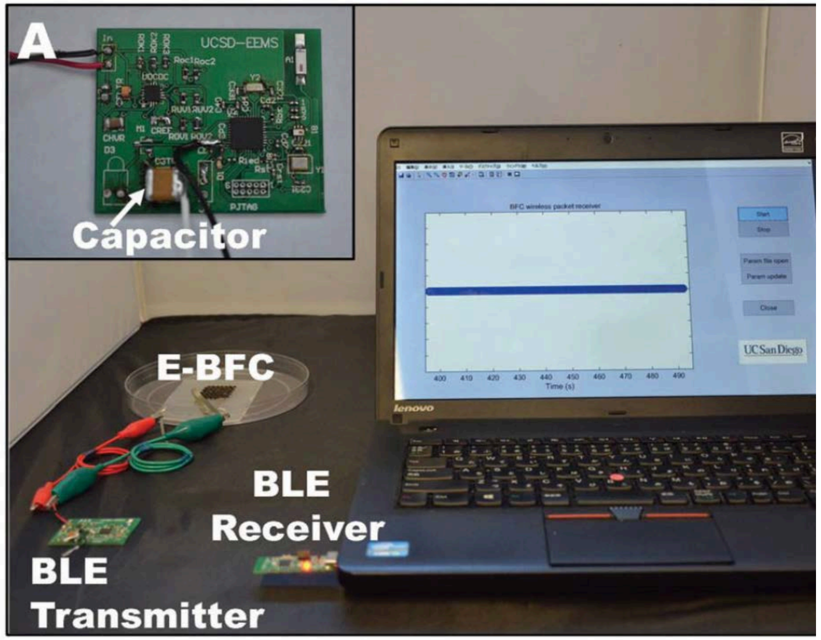
Islands-bridge structure enables high power density (**1mW/cm²**) while retaining stretchability





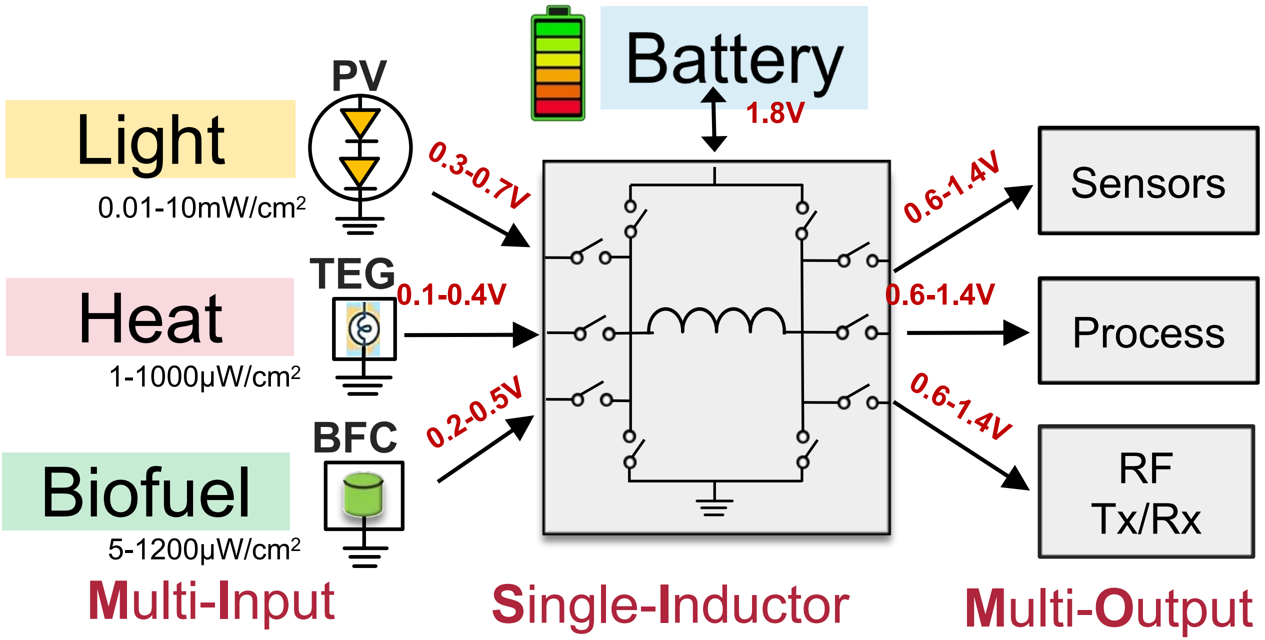


Sufficient power to operate a Bluetooth radio

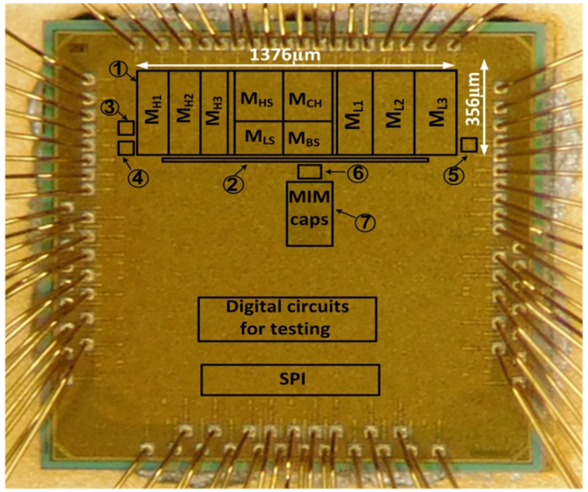


A.J. Bandodkar et al., Energy & Environmental Science, 2017

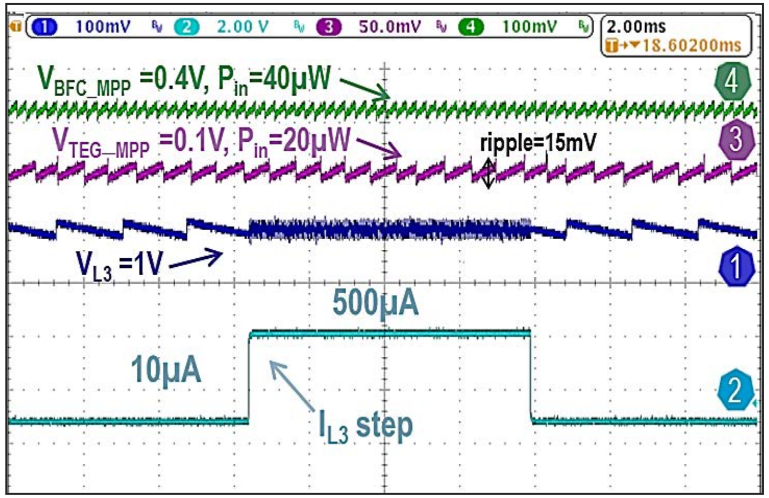
Small and efficient energy harvesting electronics



MISIMO



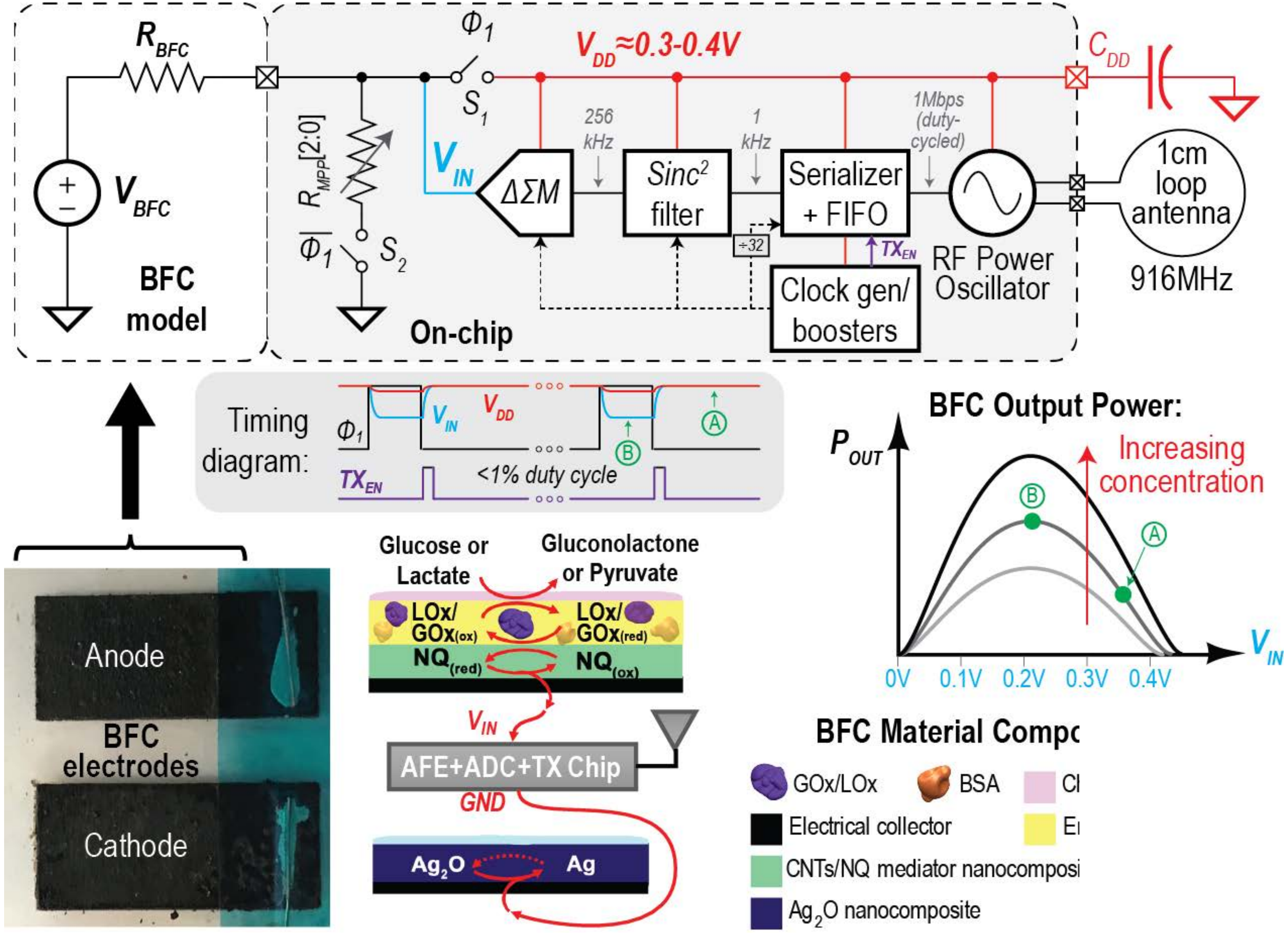
28nm FDSOI test chip



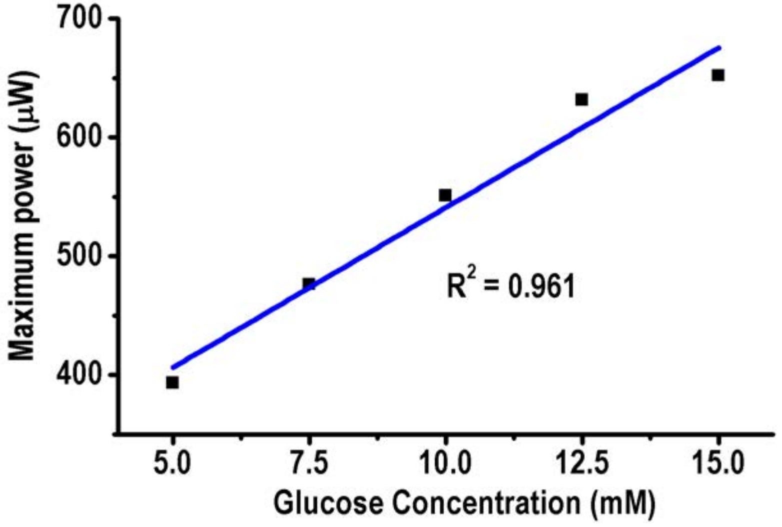
- Multi-input maximum power point tracking *AND* multi-output regulation, all with a single inductor
- 89% peak efficiency
- >70% efficiency from 1μW-60mW

S.S. Amin et al., ISSCC/JSSC, 2018

Self-powered glucose sensing



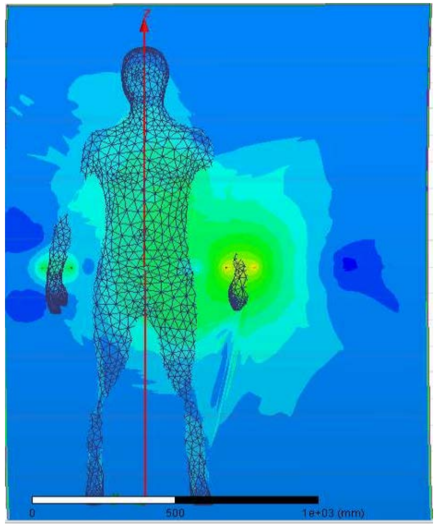
- No DC-DC converter
  - All circuits optimized to operate at 0.3V
- Full wireless capabilities
- 1μW average power

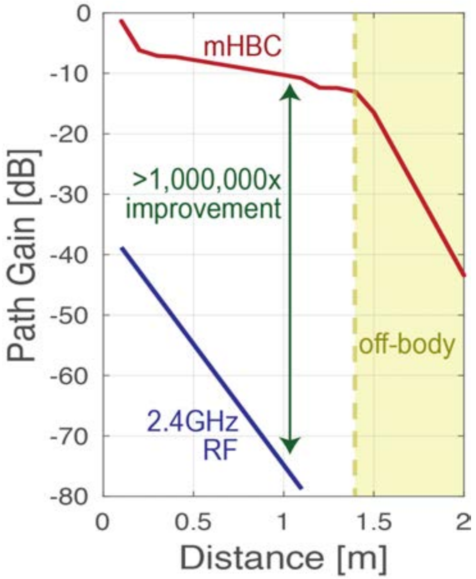


A.F. Yeknami et al., ISSCC/JSSC, 2018

Energy-Efficient Microsystems Group
Other Research Topics

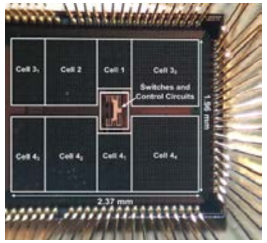
Magnetic Human Body Communication



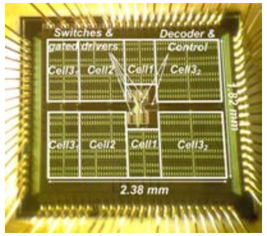


J. Park et al., EMBC'15 / ISSCC'19

New DC-DC Converters Topologies



ISSCC'14



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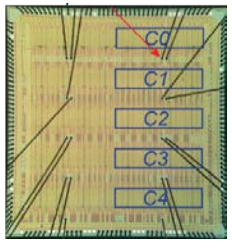

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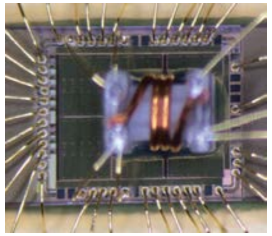

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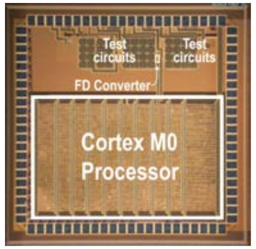
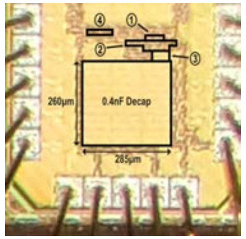
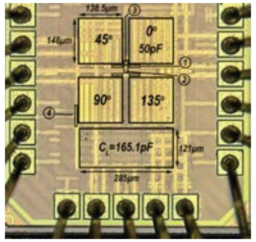


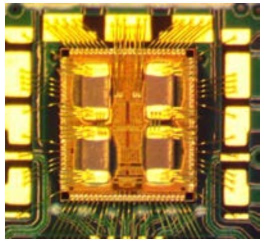
ISSCC'16



ISSCC'17

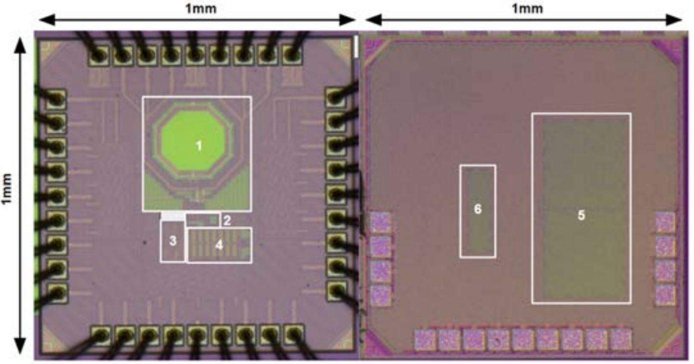


ISSCC'18



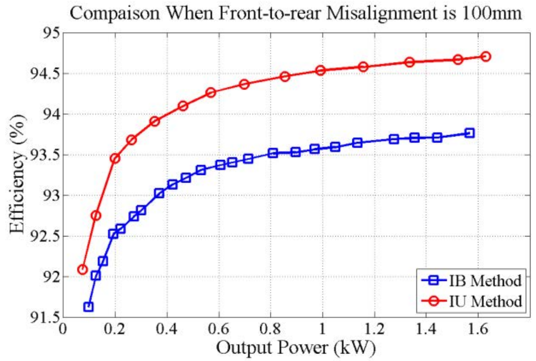
ISSCC'19

High-Dynamic Range Bio-Front Ends

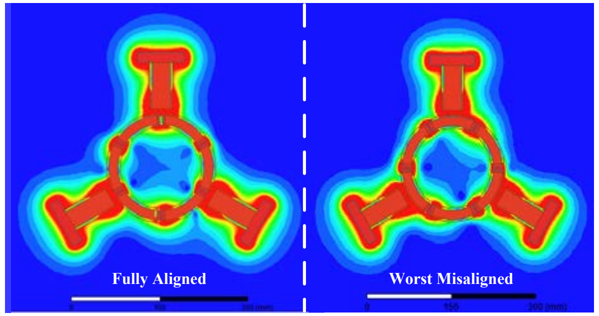


J. Warchall et al., ISSCC'19

Wireless Power Transfer



T. Kan et al., TPEL'18



T. Kan et al., TPEL'18

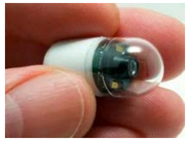
Conclusions

- Next generation IoT, mobile, and “unawearable” devices require:
  - New sensors and sensing techniques
  - Small form factors
  - Long/infinite battery life
- Meet these needs through:

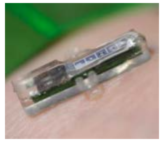
Application Engineering
- Sample rate adjustment to fit application needs
- New sensor development

Architectural Innovations
- New sensor transduction/digitization techniques
- New power conversion circuit topologies

New Circuit Techniques
- Topologically-defined “digitally-replaced analog”
- Deep subthreshold DTMOS


Exciting new ”unawearable” applications!



Acknowledgements

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KETI

CBAM Center for Brain Activity Mapping

KAVLI Institute for Brain & Mind

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