Nanoenabled Self-Powered Sensor Systems for Personal Health and Personal Environmental Monitoring

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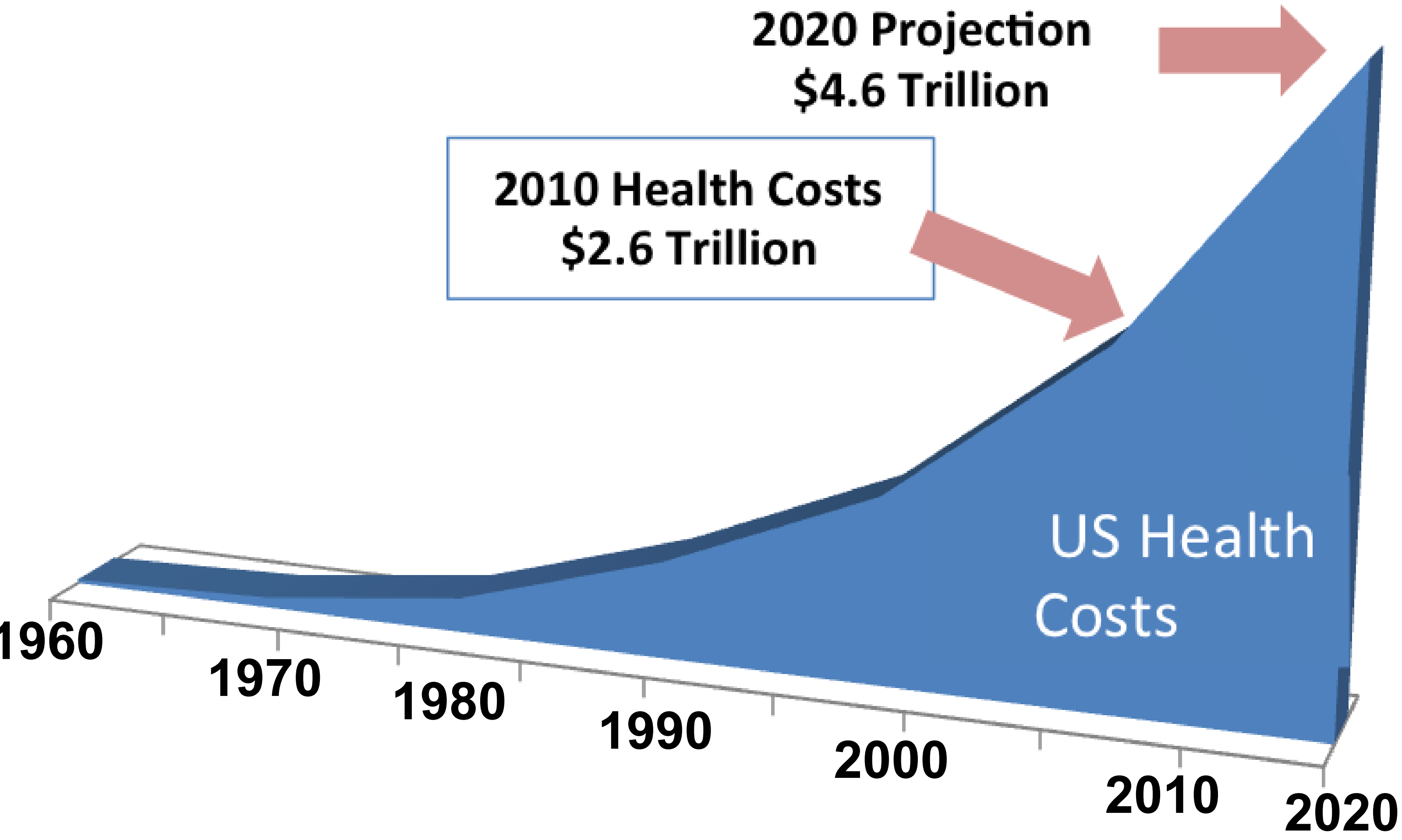
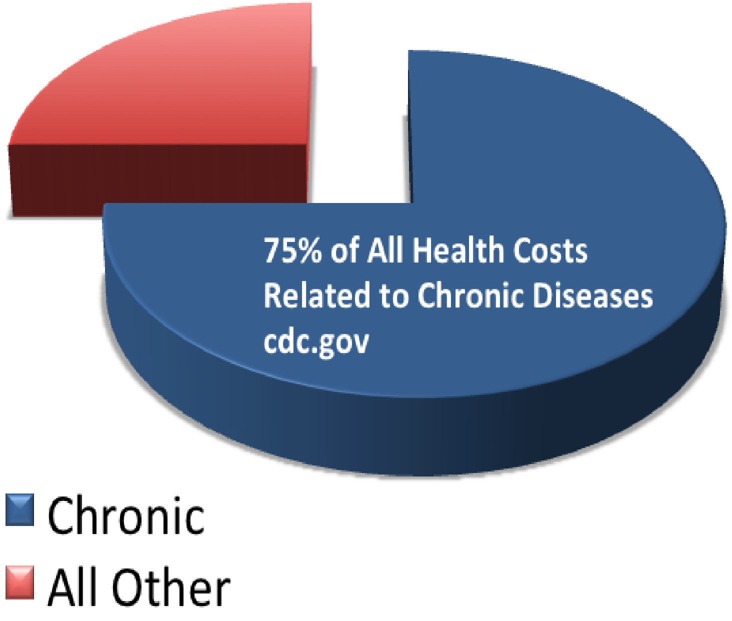
SSIST

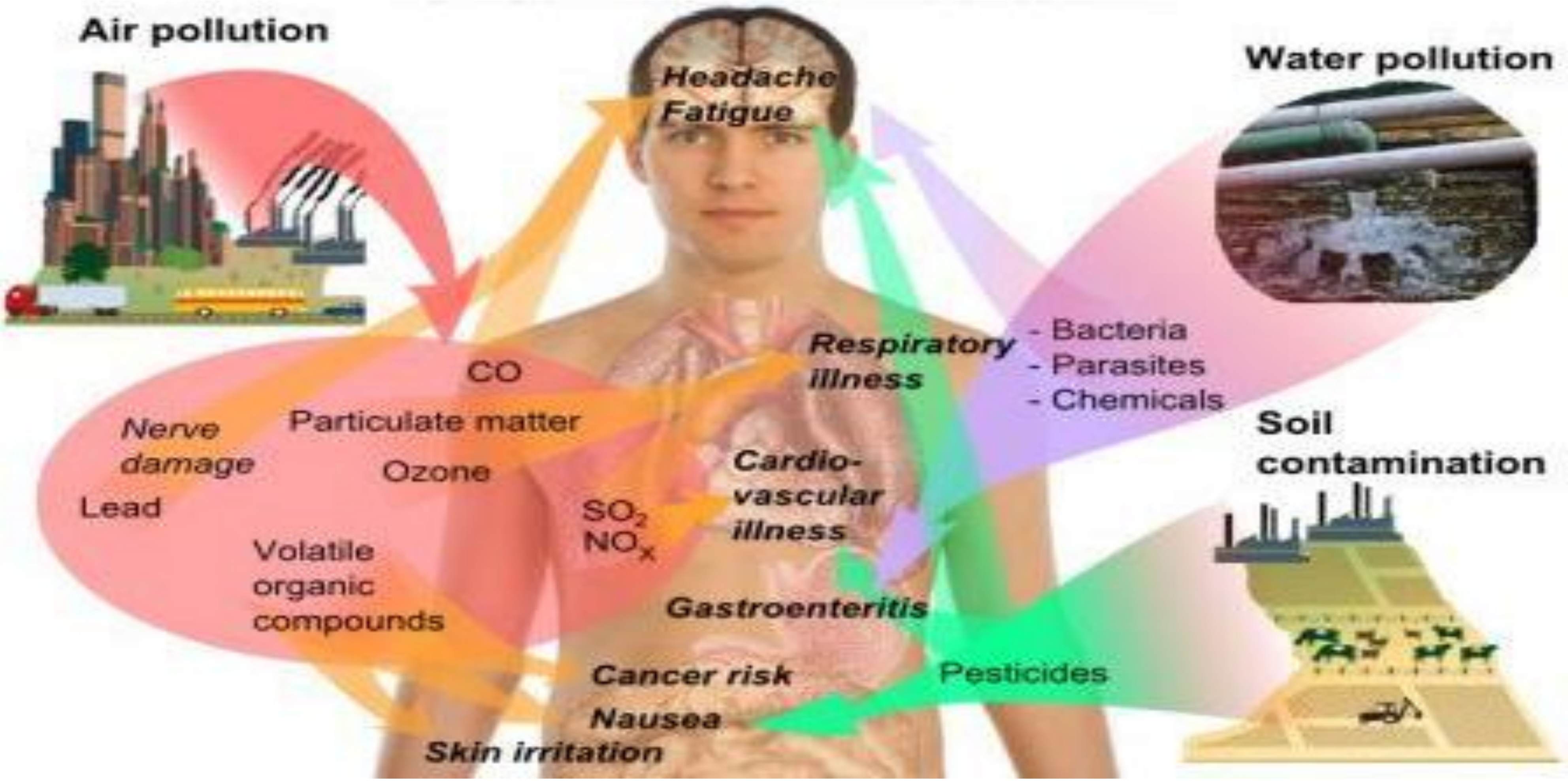


2020 Projection
$4.6 Trillion
2010 Health Costs
$2.6 Trillion
US Health
Costs
1960
1970
1980
1990
2000
2010
2020



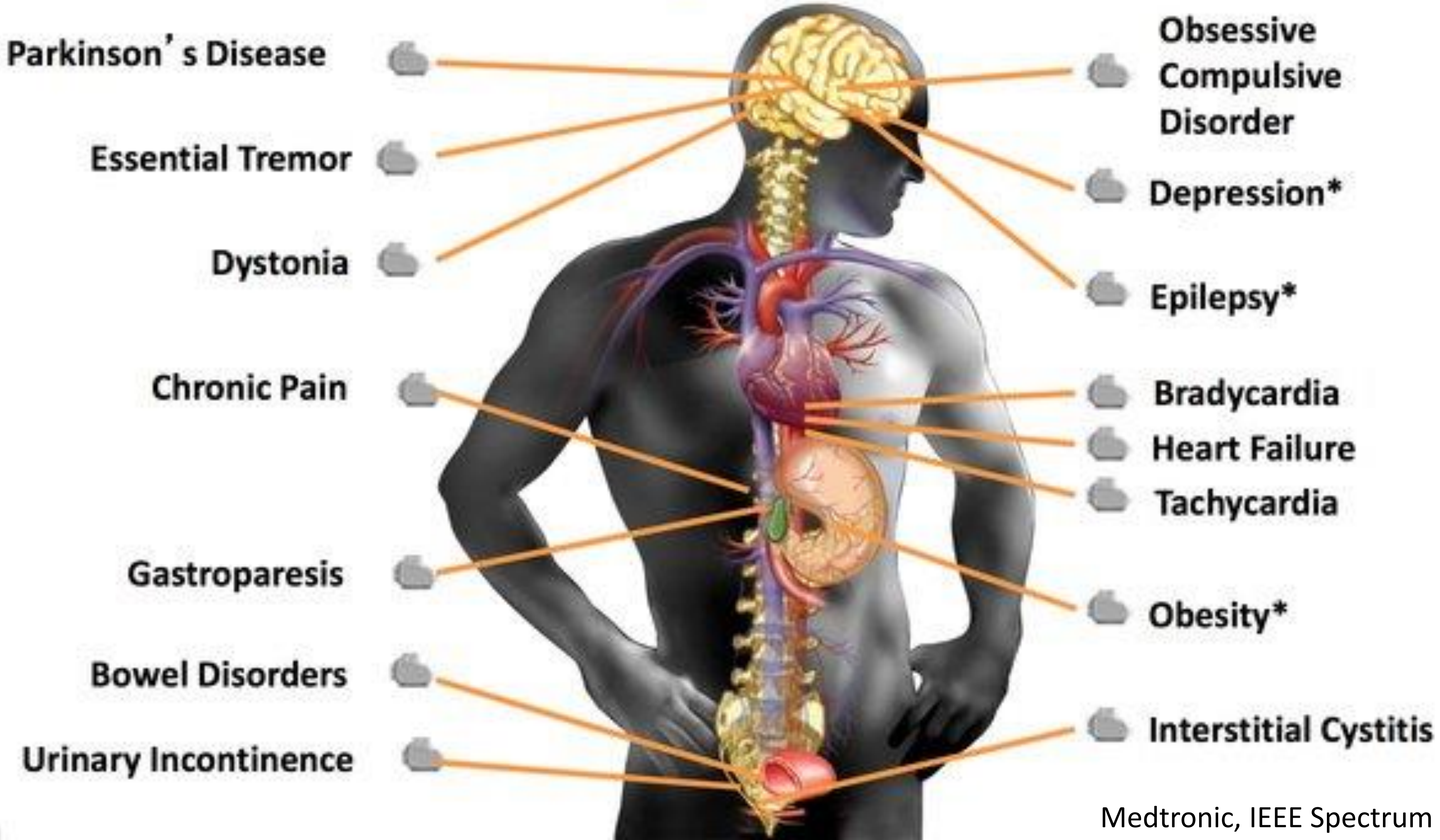
75% of All Health Costs
Related to Chronic Diseases
cdc.gov
Chronic
All Other


Thingprogress.org



Air pollution
Headache
Fatigue
Water pollution
Respiratory illness
- Bacteria
- Parasites
- Chemicals
CO
Nerve damage
Particulate matter
Ozone
Lead
Soil contamination
Cardio-vascular illness
SO_2
NO_x
Volatile organic compounds
Gastroenteritis
Cancer risk
Pesticides
Nausea
Skin irritation

Cardiac Pacing & Neuromodulation



Medtronic, IEEE Spectrum 2014

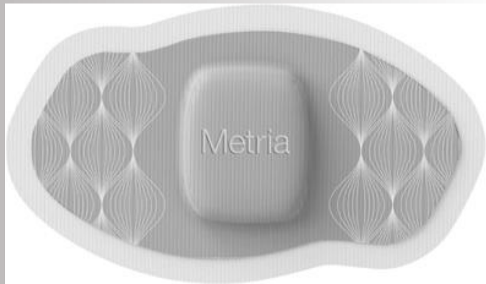
ASSIST Vision

- Direct correlation of personal health and personal environment

- Correlation of multimodal health sensing to produce a systemic picture of wellness

The Wearable Health Market

Vital Connect

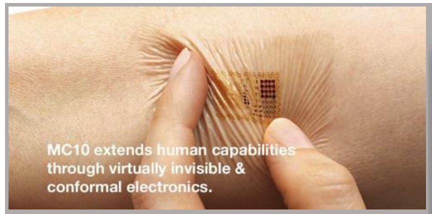


Metria Patch by Vancive

Proteus Digital Health

Sotera Wireless

FDA Approved



MC10 Hydration Sensor

Piix Heart Monitor

Nike Fuel

FitBit

Valencell

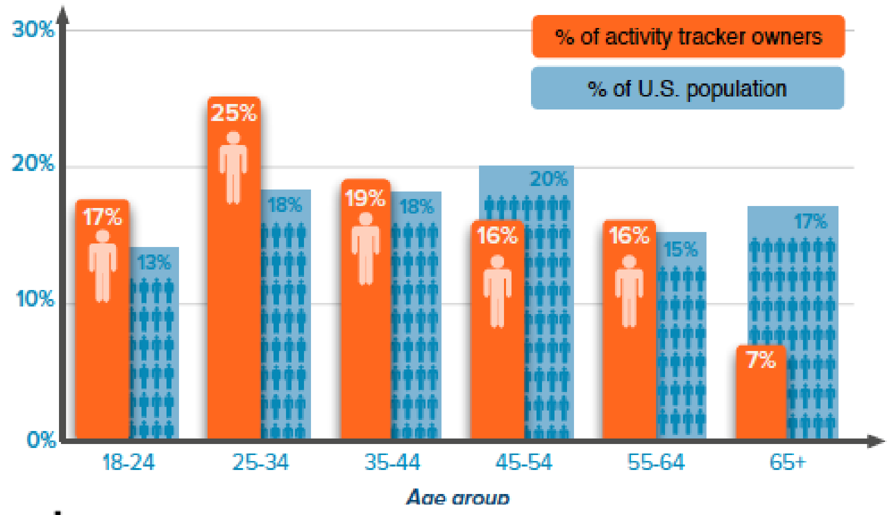
Consumer Products

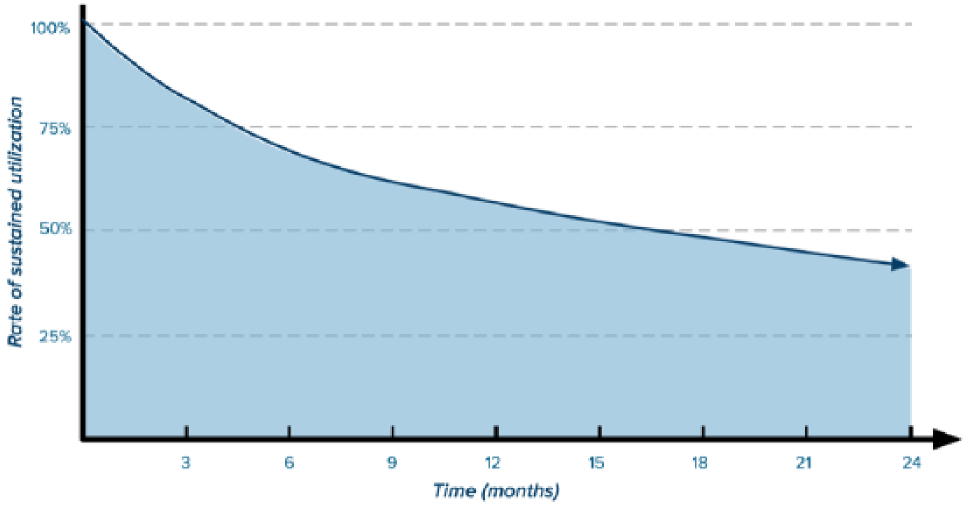
MISFIT

ASSIST technologies can provide disruptive advances in existing wearable products and influence the future generation of wearable systems

What are the gaps in these products?

Effectiveness of Wearable Health Products is lacking





Most wearable's are not being used by 65+ older citizens

Usage of sustained utilization drops below 50% in less then 15 months

A third of the users stop wearing the wearable device within 6 months

Endeavor Partners, May 2014

Why is Effectiveness Low?

- Human and Social Factors/User Feedback
- Form Factor/Design/Aesthetics
- Battery Life/Hassle
- Quality/Robustness/ Medically Validation
- Comfortable and biocompatible
- Actionable Information/Multiple Sensors
- Open Platforms

Potential Solutions?

- The right multimodal, unobtrusive sensors for health and environment
- The data backbone supporting these sensors
- Medically validated / reliable sensor data

AND

- Ultra Low Power Components to enable **ultra long battery lifetime**

AND

- Energy harvesting energy to **realize infinite lifetimes**

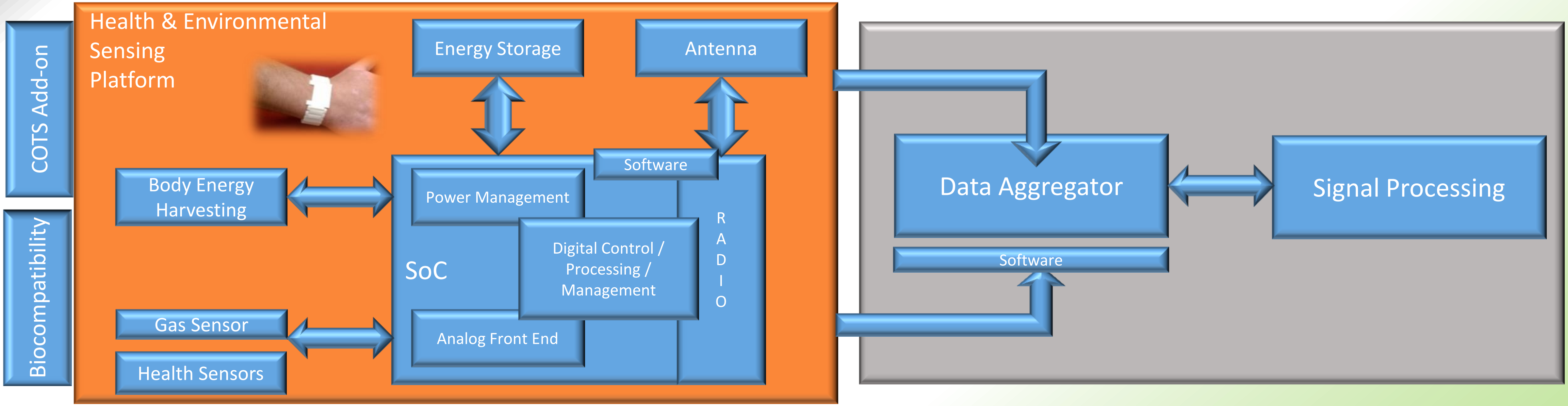
Ultra Low Power Components

- Computation
- Communication
- Sensors
- Power Management
- Interfaces

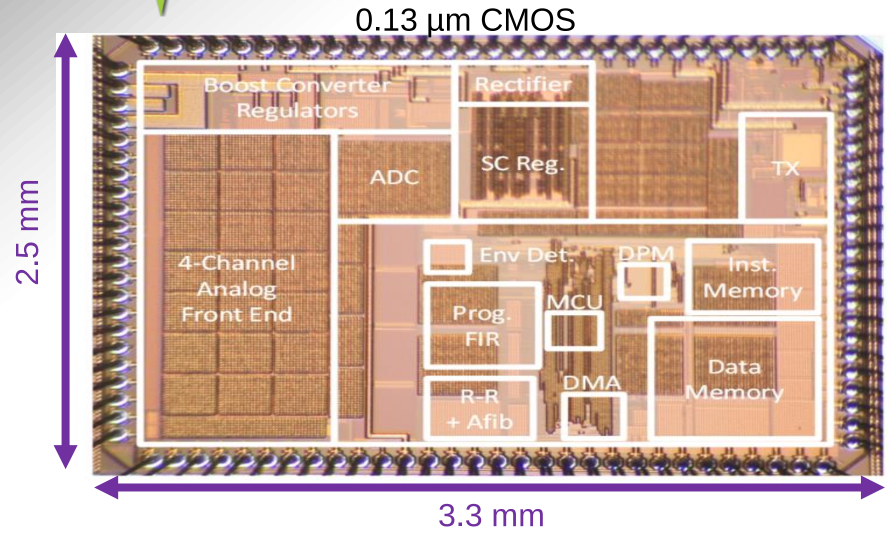
Nanotechnologies → Towards continuous monitoring

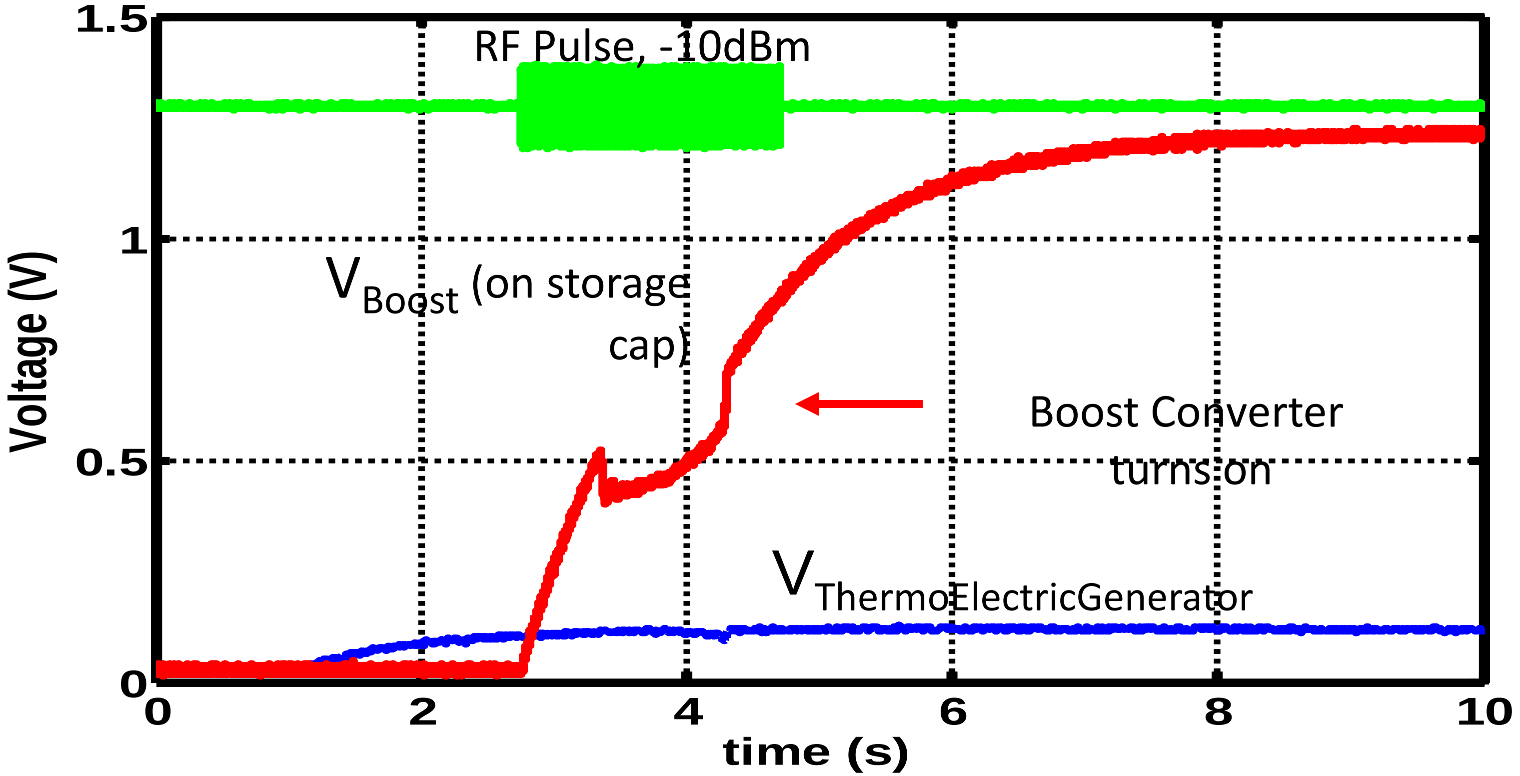
Optimizing the Power for Computation and Communication

EEC 1160483



Battery-free Energy Harvesting ExG with MICS-Band Radio

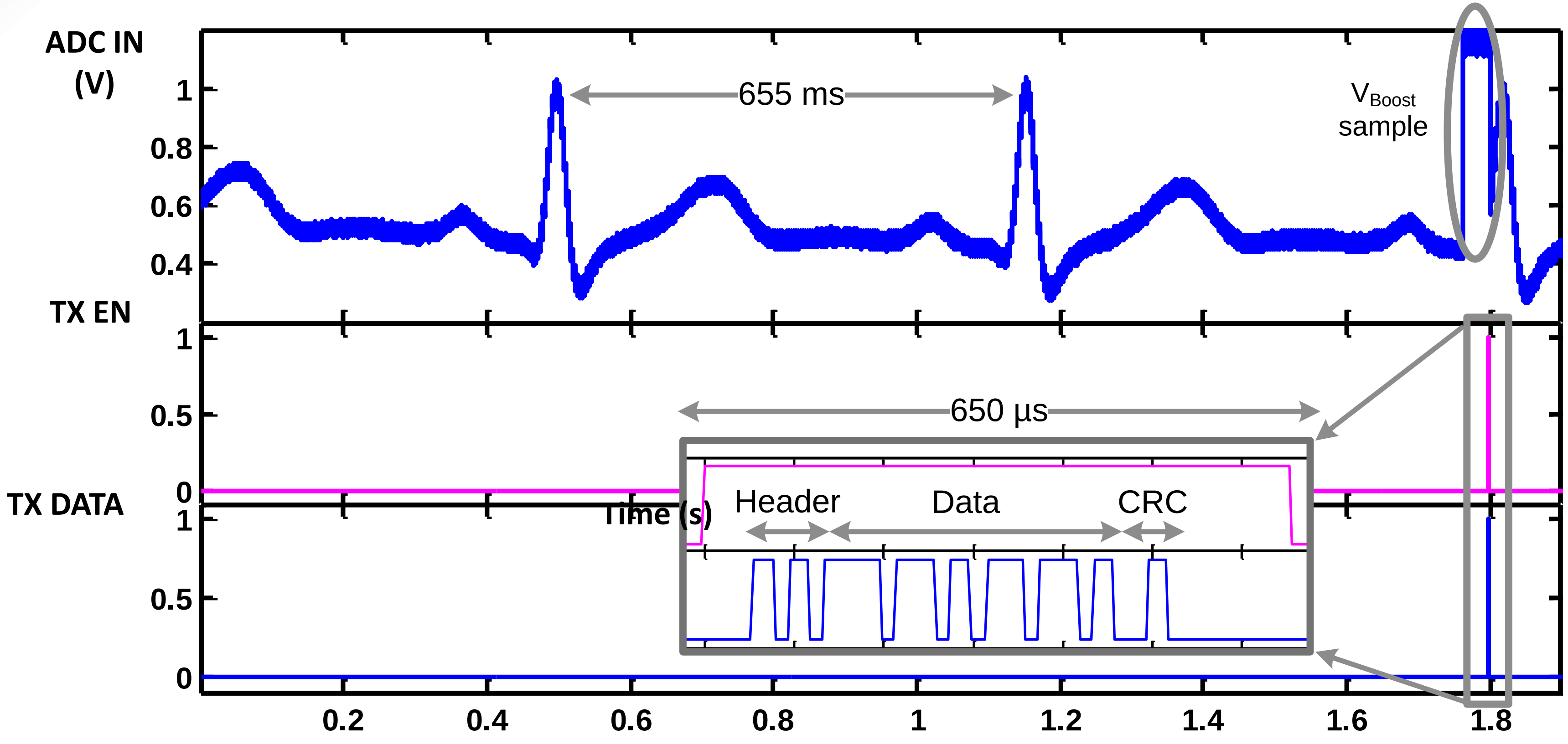




Source: Calhoun et al., ISSCC 2012

- 4 Channel ExG
- MICS Radio
- 5 DC-DC converters
- MCU + Dig Accelerators
- Integrated Power Management
- MUCH more integration than any other wireless BSN SoC
- Wireless RF pulse provides one-time kick-start
- Runs indefinitely thereafter on thermal energy

Ultra Low Power SoC



19µW total chip power from 30 mV input supply

Source: Calhoun et al., ISSCC 2012

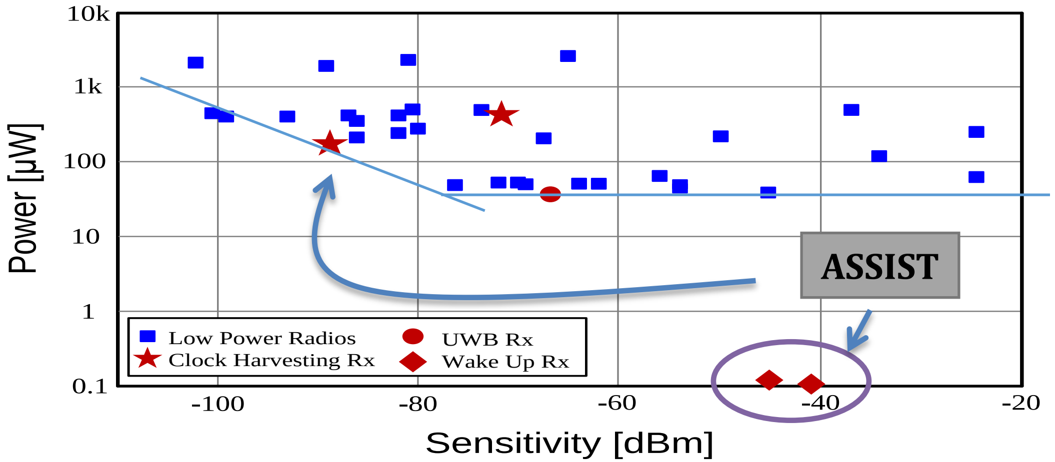
EKG < 20µW relying only on energy harvesting and storage capacitors

Boost converters < 10mV

Highlight: Measured Radio Performance

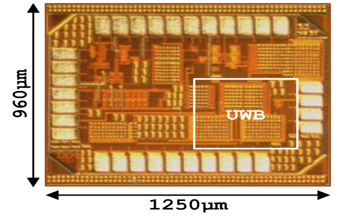
ASSIST Receivers

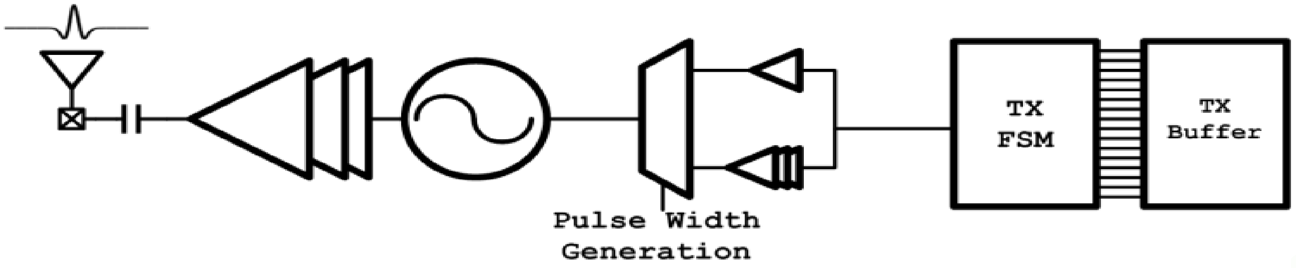
- Best in class power vs sensitivity
- ~100nW Wakeup RX



ASSIST Ultra wideband (UWB) Transmit

- ULP TX for system level energy savings





Spec	Value	Unit
Power	**7.44**	**µW**
Data Rate	**187.5**	**kbps**
Center Frequency	3.8	GHz
Bandwidth	490	MHz
Output power	---	dBm

Wentzloff, UMich

How low is ULTRA low when it comes to Power

	ASSIST SoC / processo	EnOcean STM 31xC	IMEC ISSCC'14	Semtech SX1282
Supply voltage	0.5V	2.1V to 5.0V	1.2V	1.0V to 1.6V
Processor	16b MSP430	custom	32b ARM Cortex M0	8b CoolRISC
Processor perf.	<1µW @ 200 kHz	5.1mA @3-5V	Not reported	1.2µW @ 32 kHz, 600 µW typical
Power harvesting	Yes. RF, Solar, TEG	Yes.	No.	No.

	ASSIST Radios	EnOcean STM 31xC	IMEC ISSCC'14	Semtech SX1282
Supply voltage	0.5V to 1.0V	2.1V to 5.0V	1.2V	1.0V to 1.6V
TX power consump.	6µW @200kbps	30mW @ 125 kbps	4.6 mW	~40mW
RX power consump.	200µW WBAN RX 120nW @12.5 kbps WU	40mW	3.8 mW	~12mW

	ASSIST Antennas	State of the Art
Form factor	~50mm x 50mm	~ twice as big
Front to back ratio	~19 dB (**3X – 4X more range**)	~ 5 dB
Signal suppression	3-5 dB (**>50X less power**)	20-30 dB
Out of band rejection	30 dB	5-10 dB

SSIST

Requires a systems driven, nanotechnology enabled approach to realize low-power wearable sensors for environmental and physiological monitoring

Gas/particulate sensing

Ozone, NO_x, H_2S, VOCs, particulate matter

- Nano-structured MOx
- Polymer coated MEMS
- Optical particulate sensing

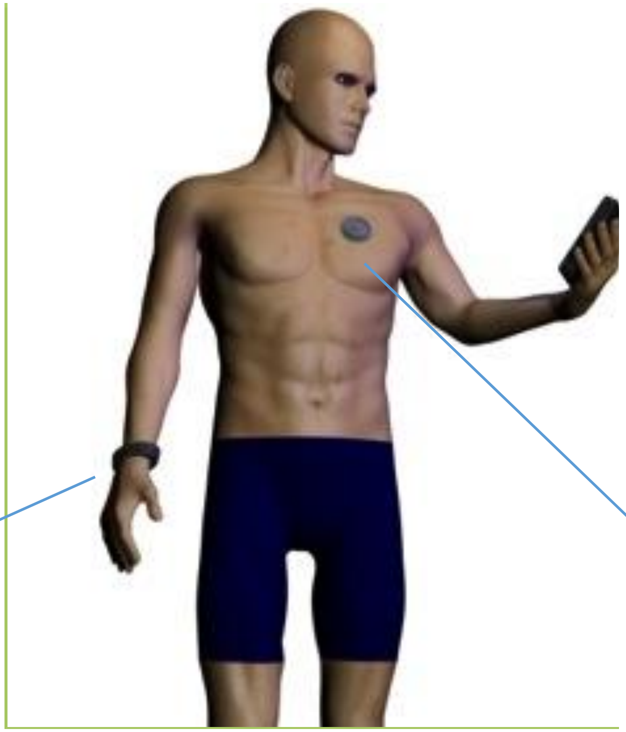
Asthma, cardiovascular health

Biophotonic sensing

Pulse oximetry

- Optical TX/RX
- Low-power controller/radio

Cardiovascular health



Acoustic sensing

Body sounds

- COTS microphone

Asthma

Biochemical sensing

Cortisol, epinephrine electrolytes/hydration

- Hydrogel skin interface
- Polymer coated sdAb

Stress, cardiovascular health

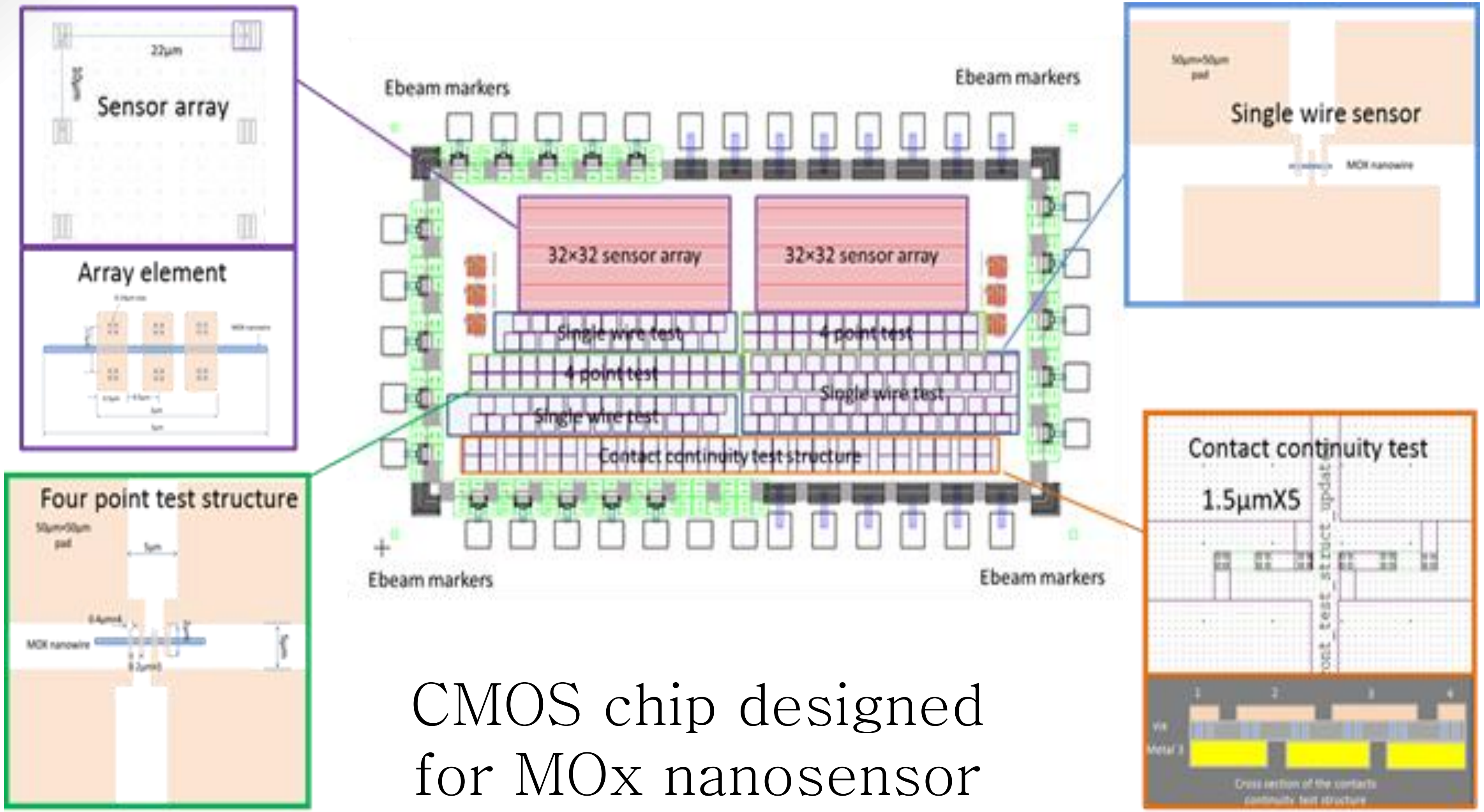
Bioelectrical sensing

ExG, hydration

- AgNW electrodes
- Conductive hydrogels

Hydration, cardiovascular health

Metal-oxide nanowire based gas sensors are amenable to integration with CMOS



CMOS chip designed for MOx nanosensor integration

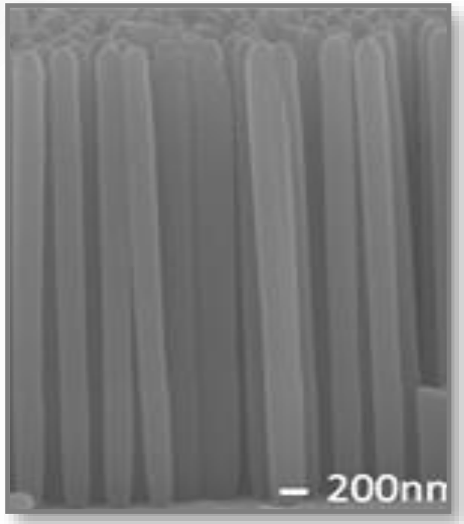
Sensors 2012, 12, 5517-5550

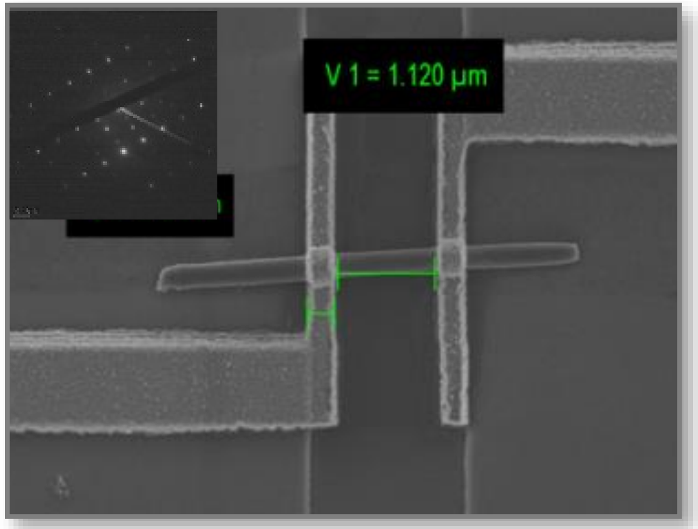
Metal-oxide nanowire based gas sensors amenable to integration with CMOS

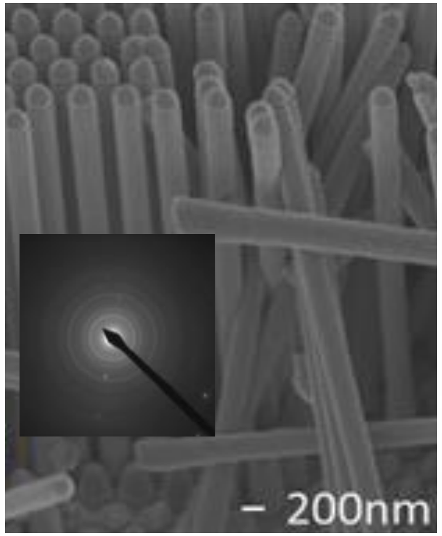
MOx coated Si NWs self assembled on CMOS

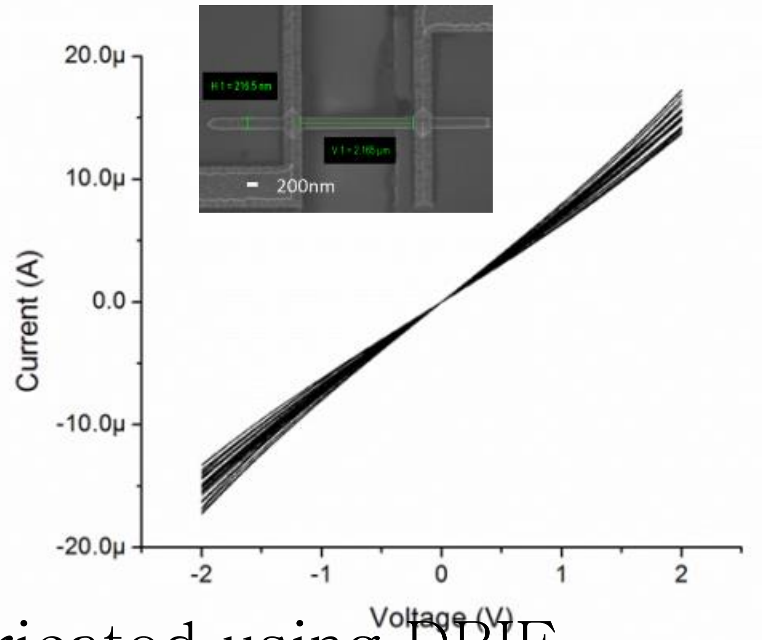
Anatase TiO_2 chemiresistor □

Rutile SnO_2 chemiresistor □







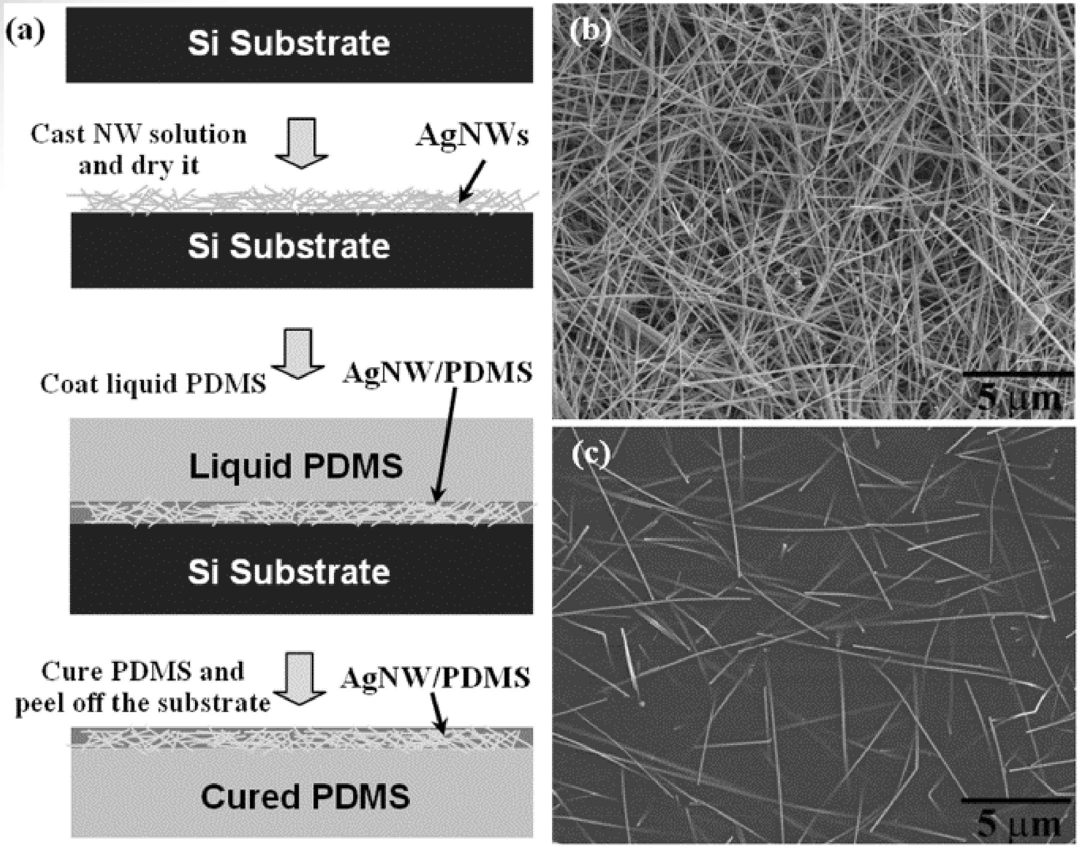


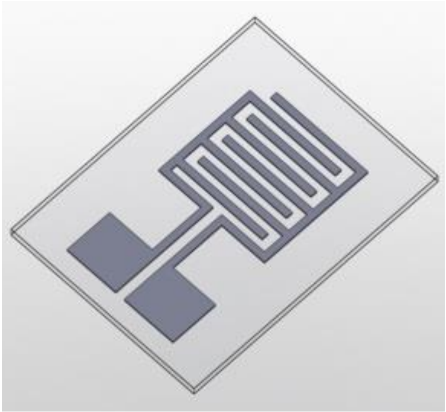
Crystalline metal-oxide-coated Si nanowires were fabricated using DRIE and ALD, and self-assembled on electrode arrays

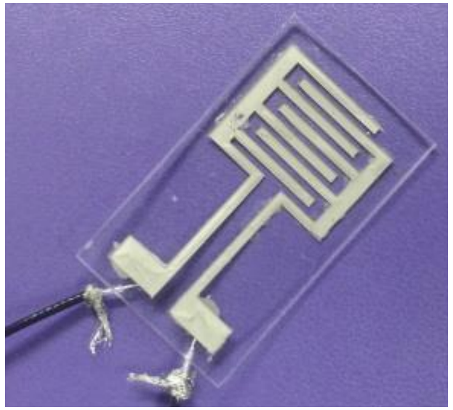
Self heating to 175°C with <20 µW power consumption is possible by thermal insulation

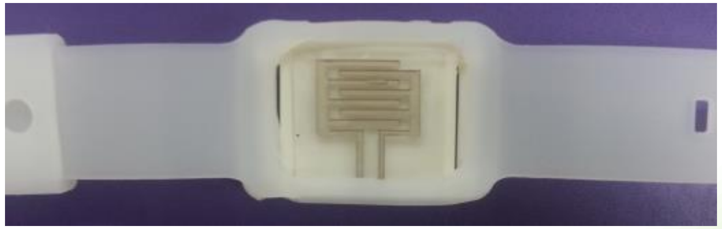
Sensors 2012, 12, 5517-5550

Silver nanowire electrodes on soft materials for bioelectrical sensing







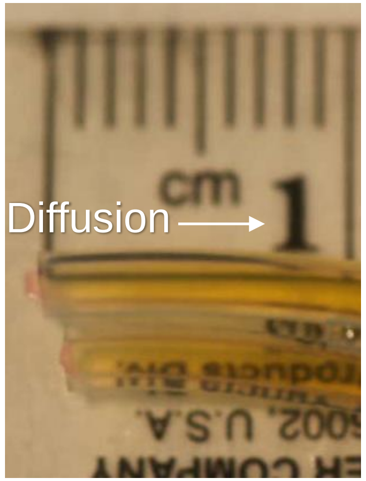


Hydrogel-based noninvasive passive skin interfaces for sweat sampling

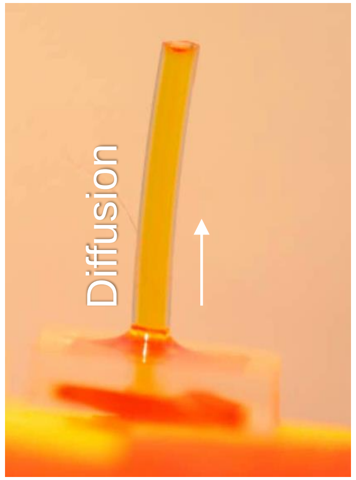
Sweat	Methyl Red Color Spectrum	PAAm
pH <4.4	4.4<pH<6.2	pH > 6.2

Used pH-color indicators to visually monitor diffusion of acidic fluids (sweat mimics) through hydrogels

Sweat Diffusion

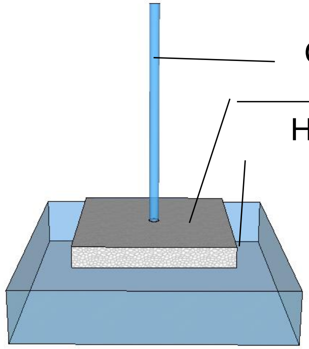


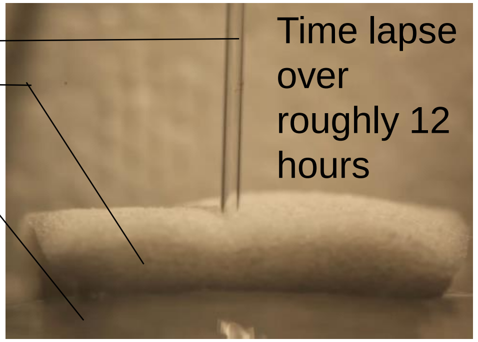
Peach pH Sensor

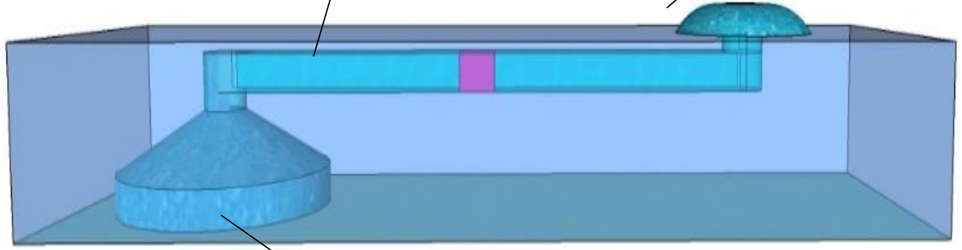


Future Work: Create a **Capillary-Osmotic Pump** for continual-passive sweat intake

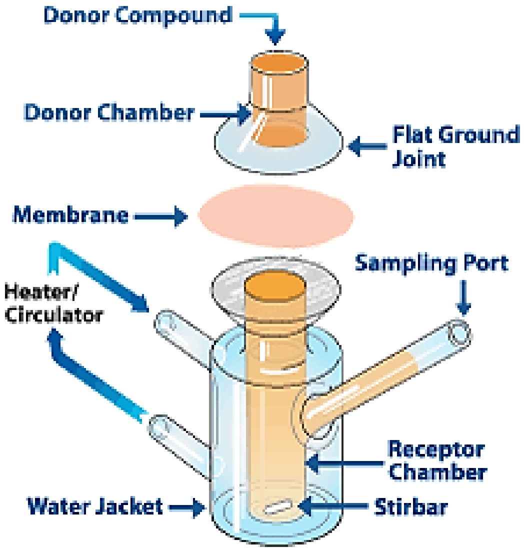
Fluid transfer from superporous hydrogel to a capillary

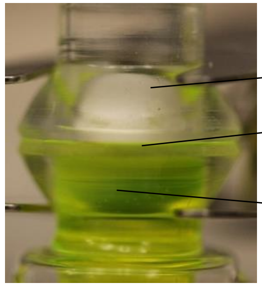


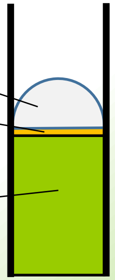




Establish a skin mimic for interfacing and sensor testing



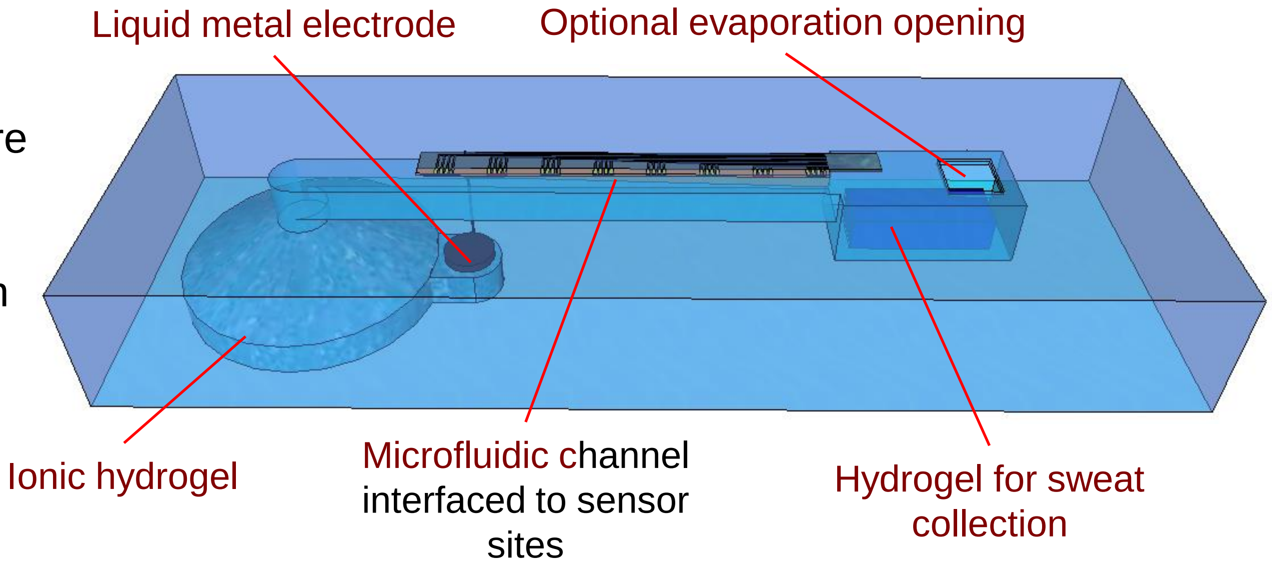




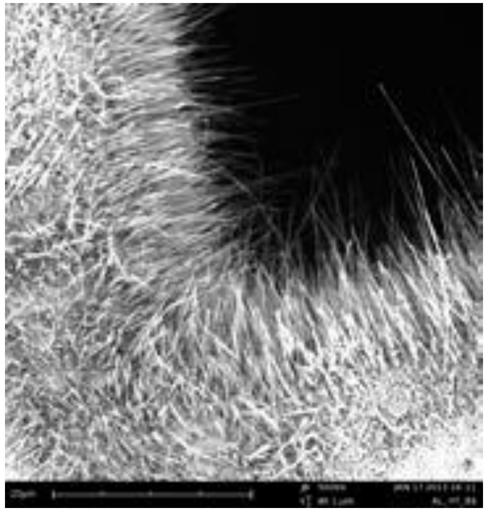
Usually used for drug penetration; we will use for sweat collection with various skin (membrane) materials

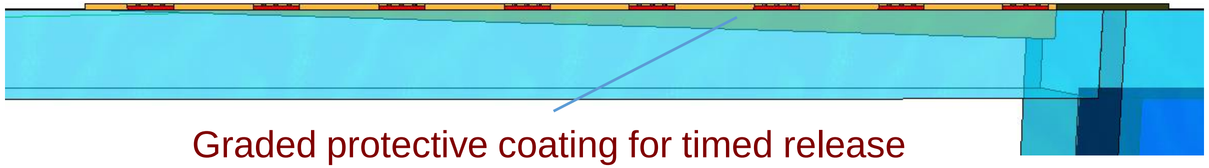
Building the basic building blocks for a skin-coupled biochemical sensor to monitor cortisol levels in sweat

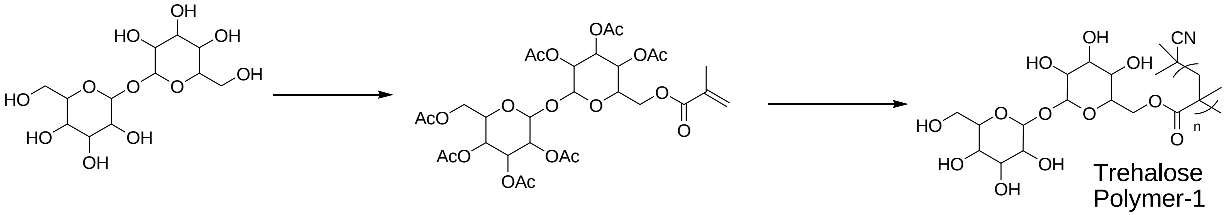
Intake rates via osmotic uptake were measured as ~15 nL/cm^2min, much greater than human sweat rates (0.01 – 1 nL/cm^2min)



Potentiodynamic electrochemical measurements using functionalized NW-enhanced IDTs



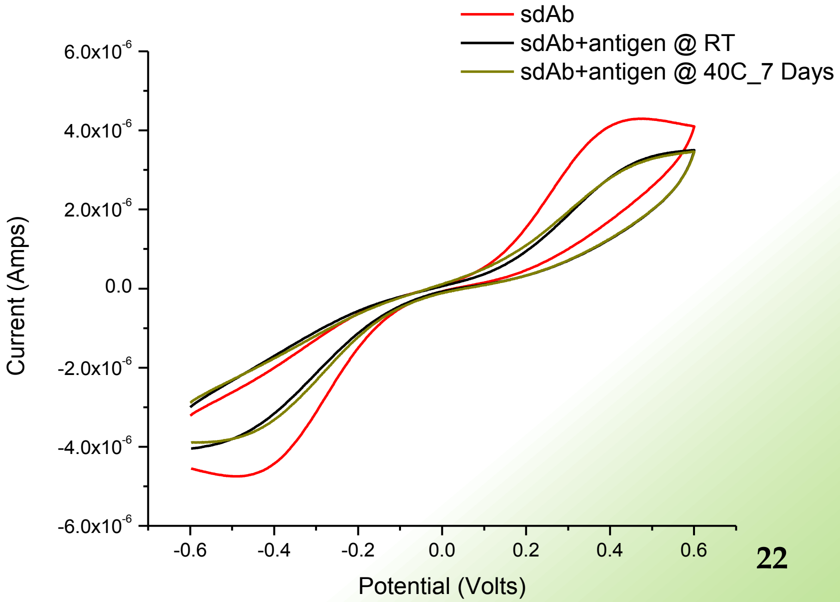


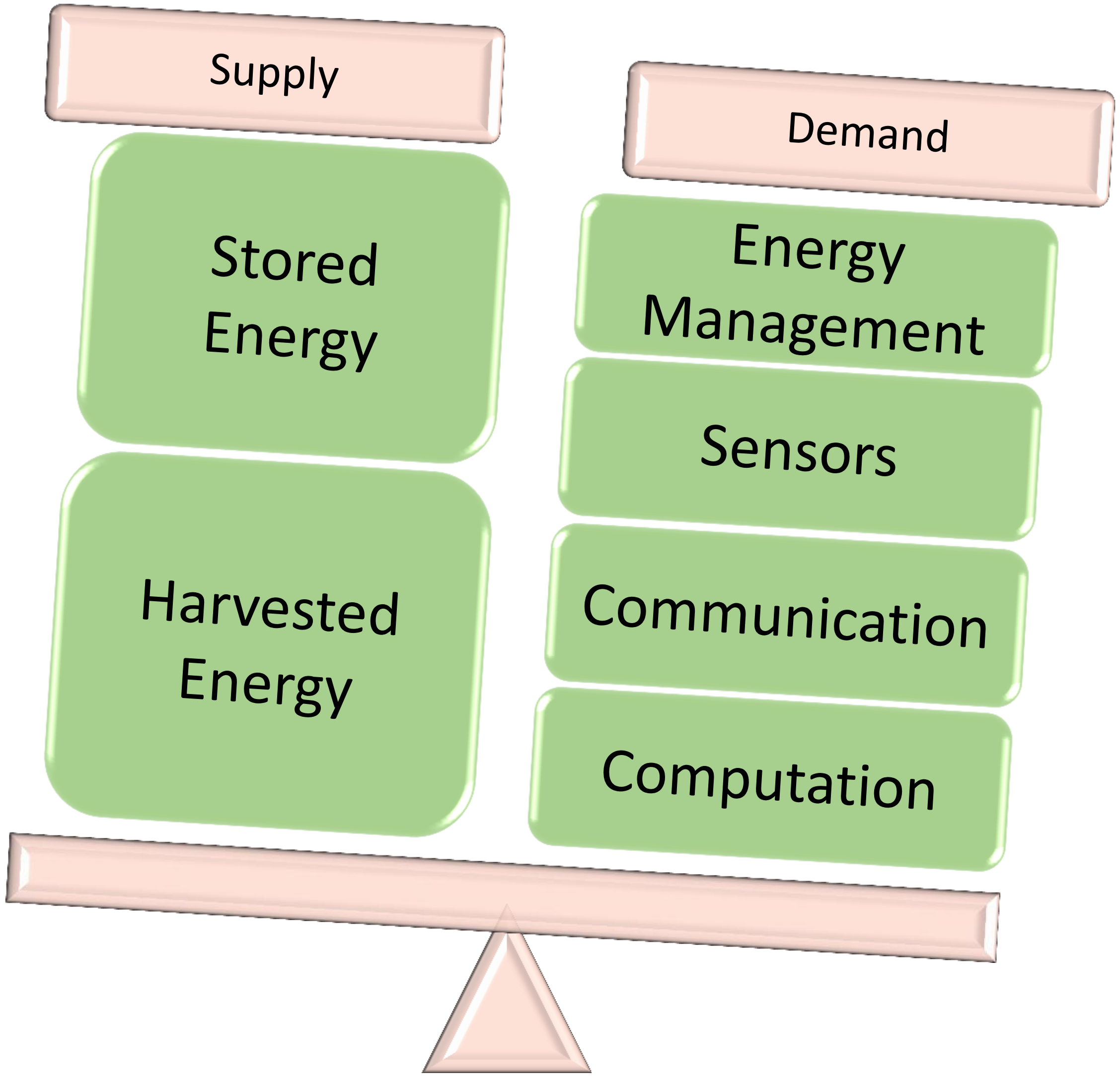


Trehalose Polymer-1

Encapsulation of antibody with polymer/trehalose enables time delayed dissolution of coating to expose one sensor at a time for long term use

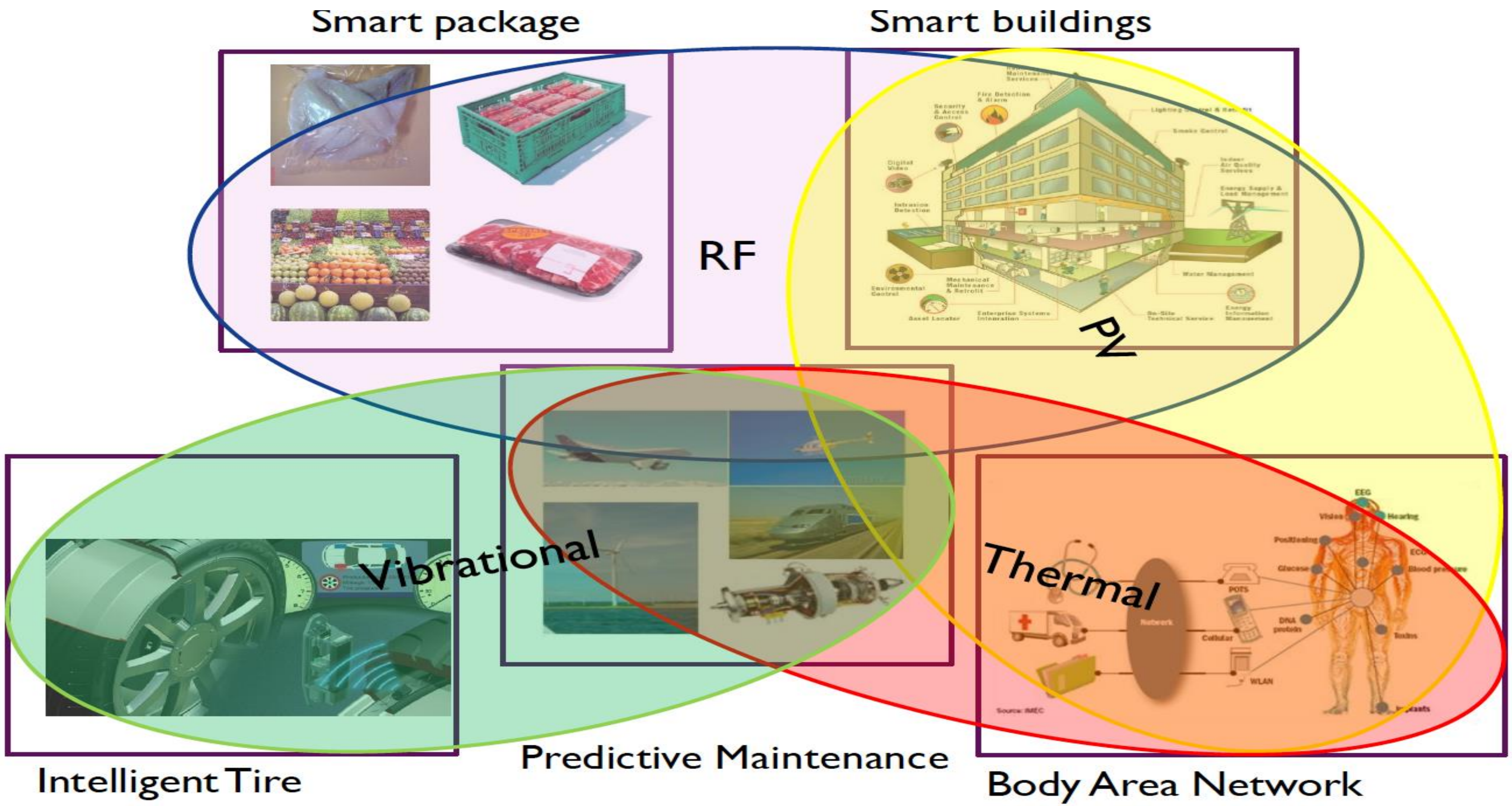
sdAb-antigen stability at 40^0C for 7 days was demonstrated.





Looking at both sides of the power equation → Towards Self-Powered Operation

Energy Harvesting
One harvester does not fit all?



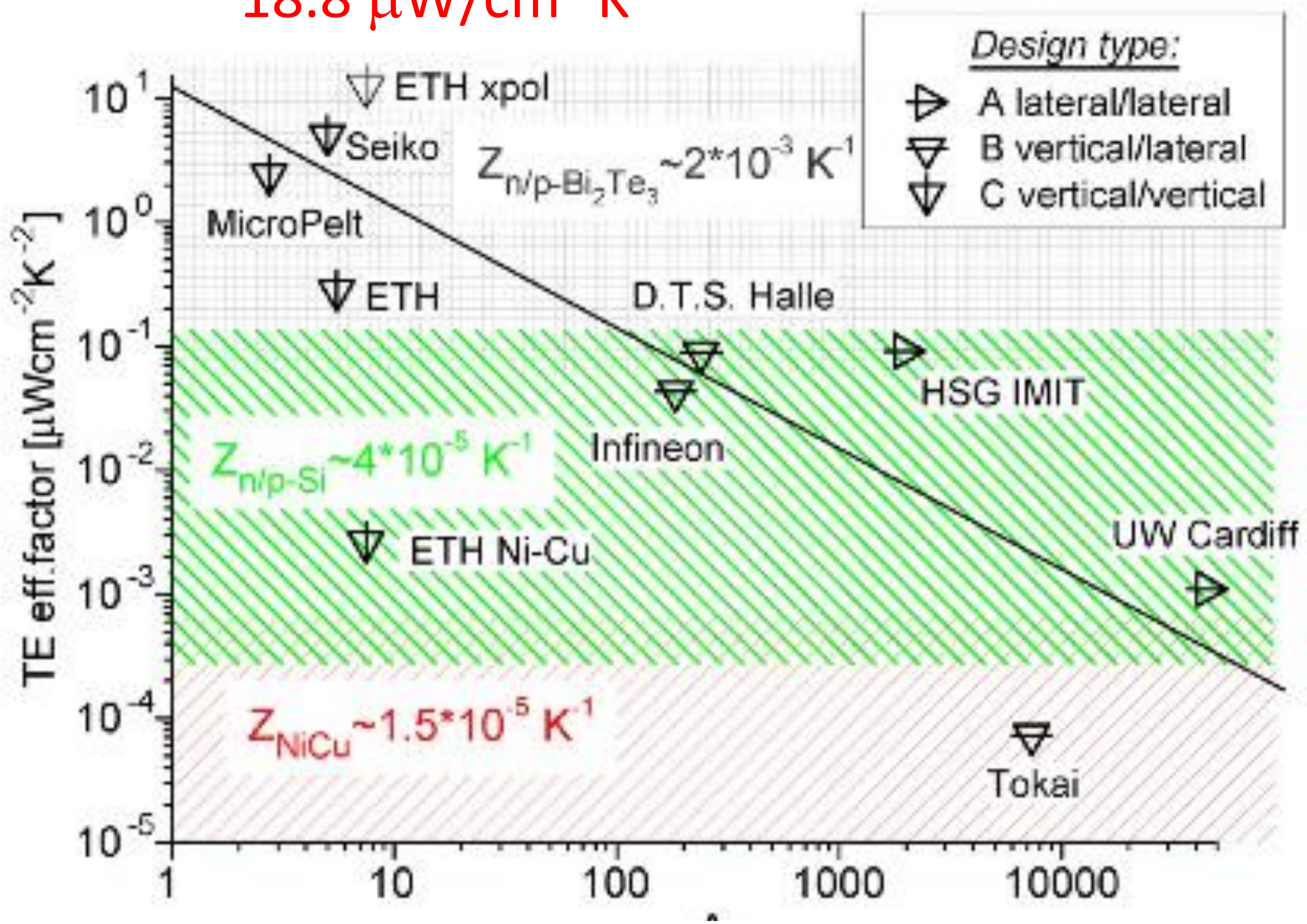
iMEC

This is a Very Difficult Problem to Address for Human Worn Devices!

- Thermal: Small ΔT from human to ambient
- Mechanical: Weak base excitations at low frequencies for human motion
- Indoor solar: 1 – 10 μW/cm^2 available
- RF scavenging: << 1 μW from ambient rf. Much higher powers can be achieved if directed rf is utilized.
- Inductive coupling: Tens mW available at close proximity

State of the Art Flexible Thermoelectric Generators

18.8 μW/cm² K²



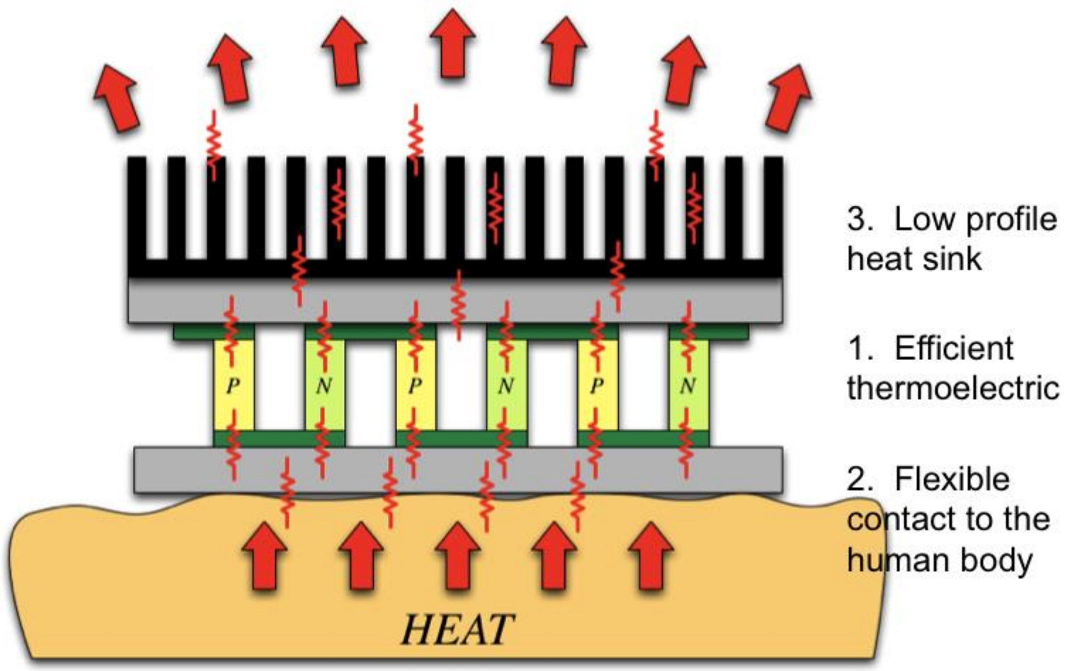
Insulation area/(active material area)

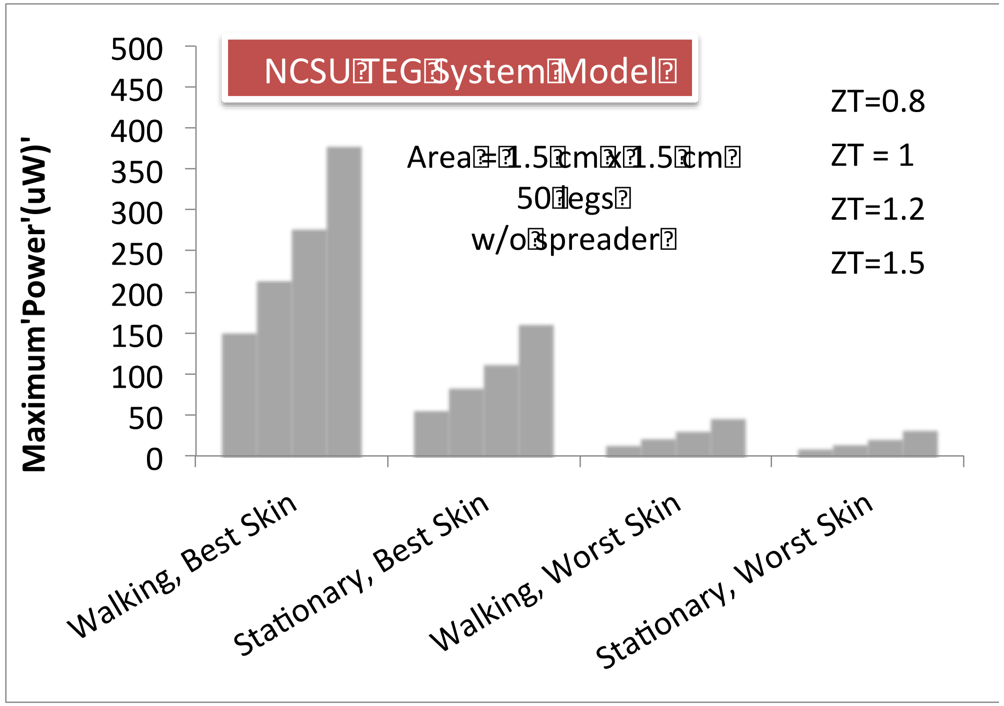
Needs for flexible thermoelectric generators

- Good materials (higher ZT)
- Longer length (100 – 300 μm) than typical film thickness for Bi_2Te_3
- Nanostructuring to decrease thermal conductivity
- Thermal resistance of harvester should be on order hundreds cm² K / W

Glatz et al., J MEMS 18, 763 (2009) Leonov, J. Micromech. Microeng. 21 (2011) 125013

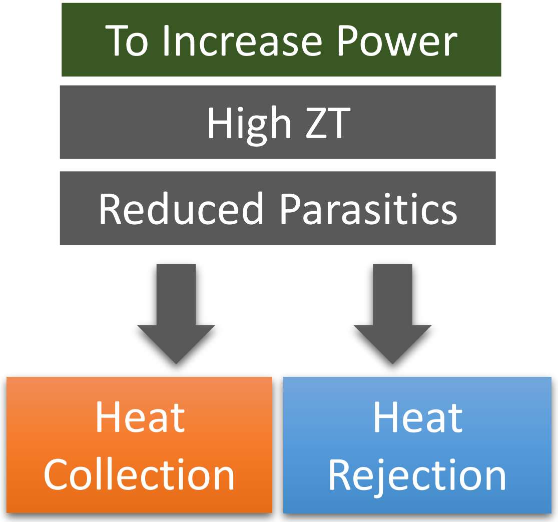
Flexible Thermoelectric Harvesters





Approach:

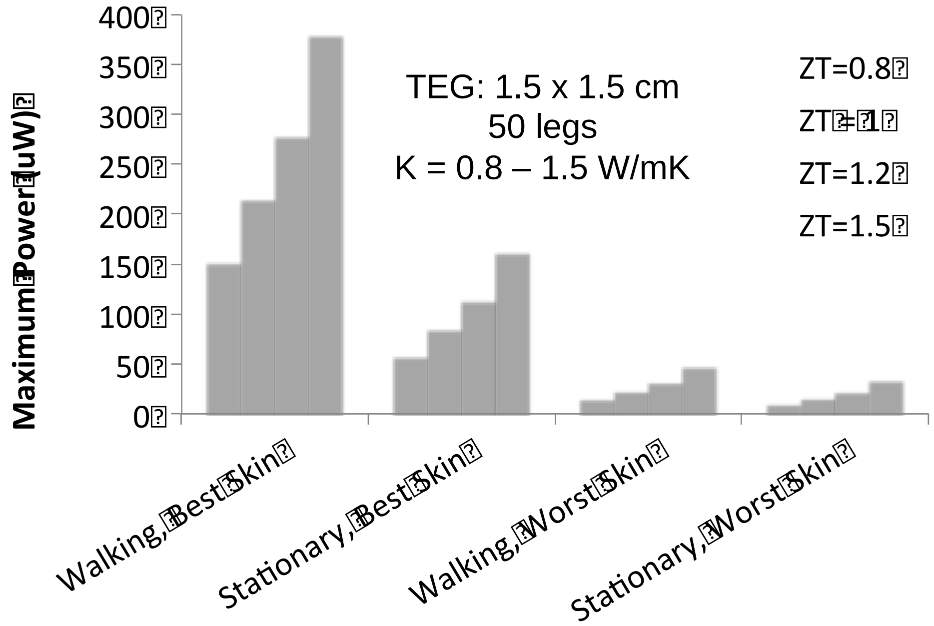
- Flexible, open-platform TEG package enabling integration of thermoelectrics with excellent performance from many sources
- Flexible, high performance heat sinks
- New material & process approaches

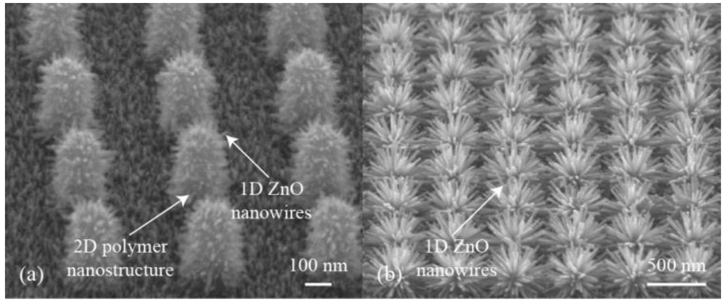


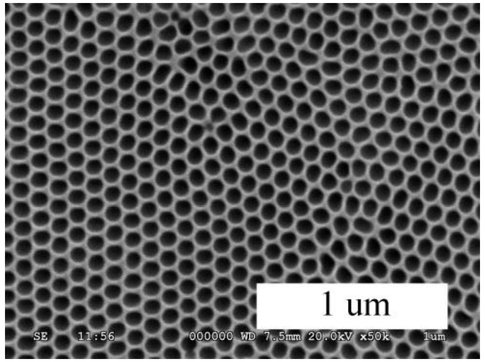
Barrier: Parasitics (esp. skin resistance) have a huge impact on TEG performance; output voltages ~ 5 – 30 mV

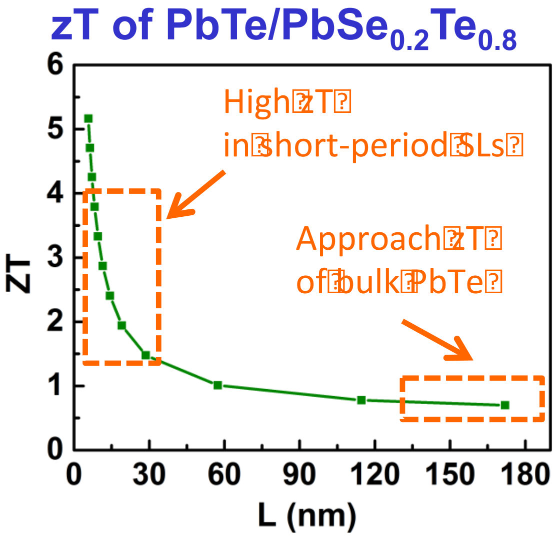
Thermoelectrics

- ~10 – 20 µW on a flexible hand-built package with COTS components
- Better Flexible package
- Reducing skin resistance is essential
- "Nano" in PbTe/PeTe$_{1-x}$Se$_x$ heterostructures, CNT-loaded polymers, ECD Bi_2Te_3 in alumina templates, hierarchical wicking structures



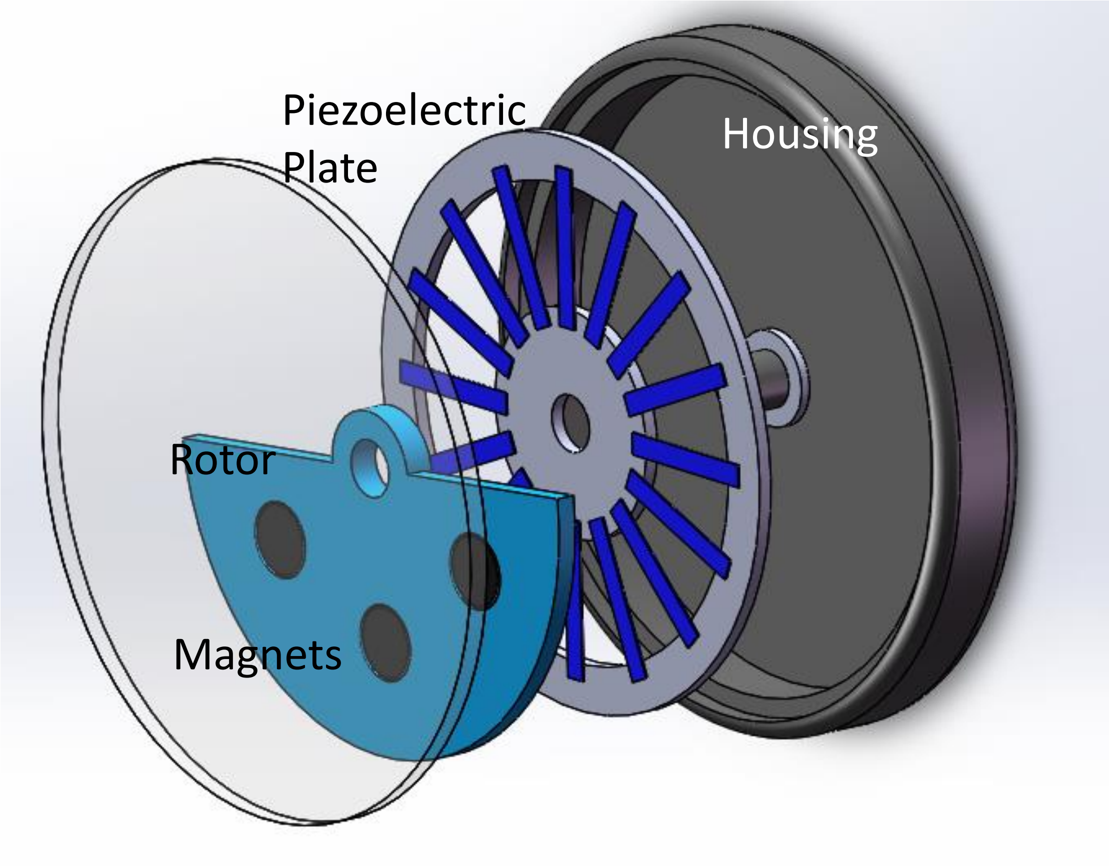






Non-Resonant Human Worn Harvesters

Measured prototype: 57 μW/cm^2 peak power exceeds that of end-loaded cantilever on Si by > 35 times

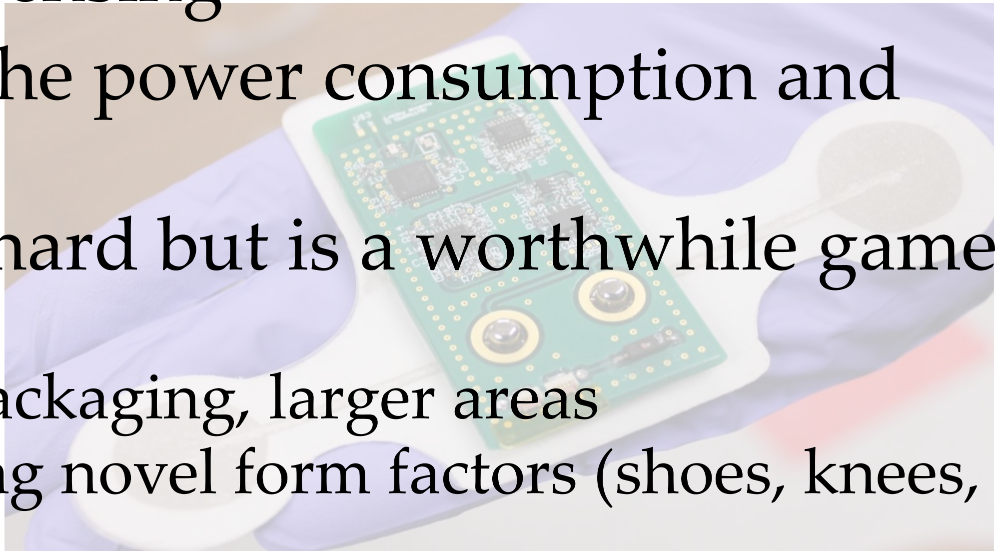


Shad Roundy

Activity	Walking	Jogging	Running
Power Available	95 μW	360 μW	700 μW
Power Density	10 μW/gram	37 μW/gram	74 μW/gram

Future Areas of Collaboration to Enable Self-Powered Miniaturized Sensors

- Ultra low power electronics can change the sensing paradigm by enabling long term and continuous sensing



- Sensors innovation lies in lowering the power consumption and biochemical sensing
- Energy harvesting from the body is hard but is a worthwhile game changing technology
  - Thermoelectrics: Higher ZT, Flexible packaging, larger areas
  - Mechanical: need new designs including novel form factors (shoes, knees, chest straps)
- Nano is creating advancements in sensor system components
- Samsung and KAIST (low power electronics, energy harvesting, sensors, flexible materials, manufacturing)

Thank you