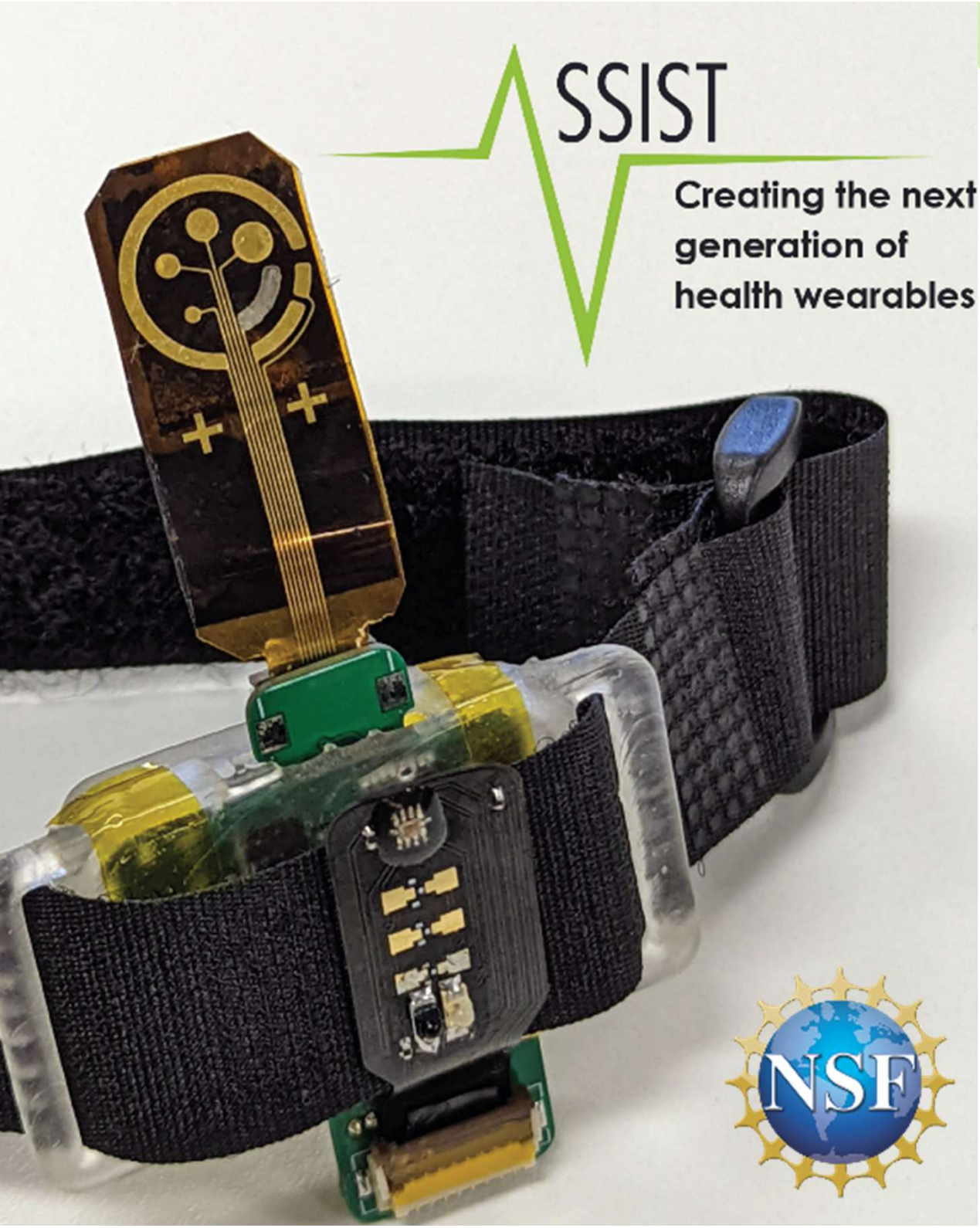


Center for **A**dvanced **S**elf-Powered **S**ystems of **I**ntegrated **S**ensors and **T**echnologies **(ASSIST)**

Designing for Energy Efficiency Advances in Wearable Sensing

Alper Bozkurt, Co-Director
McPherson Family Distinguished Professor
in Engineering Entrepreneurship
Dept of Electrical and Computer Engineering

NC STATE UNIVERSITY

UNC SCHOOL OF MEDICINE

PennState

FIU FLORIDA INTERNATIONAL UNIVERSITY

UNIVERSITY of VIRGINIA SCHOOL OF ENGINEERING

UNIVERSITY OF MICHIGAN

THE UNIVERSITY OF UTAH

ASSIST Center Summary

Visit us at assistcenter.org

NSF Nanoengineering Center focusing on self-powered wearable sensing

- established in 2012
- graduated from NSF ERC program in 2024
- $70M+ invested to-date through NSF, Industry and other funding agencies
- 700+ publications (H-index of 50)
- 90+ Inventions (50+ patents)
- 10+ startups
- Workforce Development:
  - 100+ PhDs, 30+ MS and 100+ UG
  - 120+ REUs (Research Experience for Undergraduates)
  - 40+ Capstone projects
  - 500+ K-12 participants in the wearable device challenge

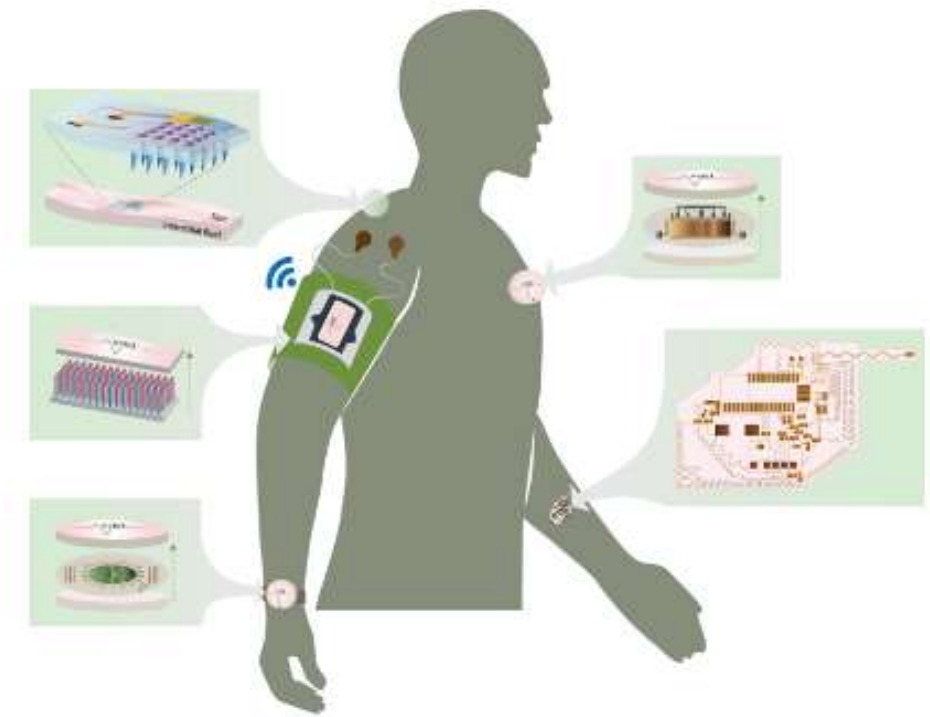
ASSIST Start-ups

VitalFlo, everactive, Zenomics, NEXT, FUNXION, DERMISENSE, CLEARSENS, OlfTech Solutions

ASSIST Workforce Development

Transformative Technologies for Personalized, Vigilant Health Monitoring

***Center Vision**: to create self-powered sensing, computing, and communication systems that enable data-driven insights for a smart and healthy world.*



- Self-powered wearables for correlated sensing of health and exposure
- Wireless and comfortable
- Physiological, biochemical, behavioral and environmental sensors
- Vigilant with continuous and real-time data
- Artificial Intelligence support for actionable decision

Use Case Inspired Systems Driven Research

Problem	Societal Challenge
Cardiovascular Diseases	>600k deaths annually
Asthma	1/12 people in US, majority children
Diet Management	36% of adults with risky BMI
Wound Healing	$15B/year
Mental Health	$300B avoidable costs

vertical integration & co-design

Self & Remote Powering
- Body heat & motion
- Ultrasound
- Biochemical
- Wireless (Ambient / Directed RF)

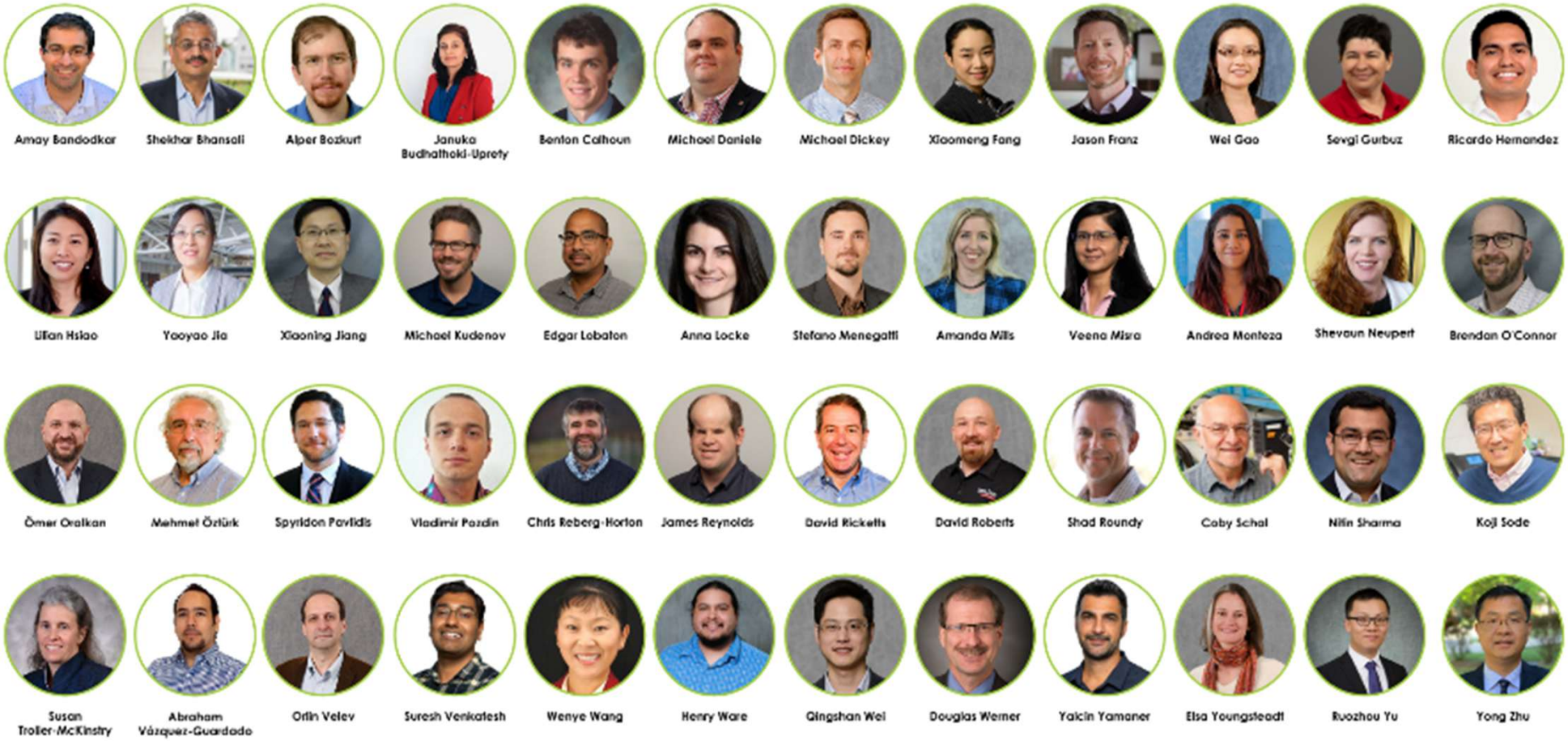
Low Power Sensing
- Physiological
- Biochemical
- Environmental

Low Power Systems-on-Chip
- Low power electronics
- Low power radios
- Body optimized antennas

E-Textiles / Flexible Materials
- Sensor integration
- Performance
- Manufacturability

Engineered Systems
- Hard / soft wearables
- Textiles
- Implantables
- Artificial Intelligence

Interdisciplinary Community of ASSIST Faculty



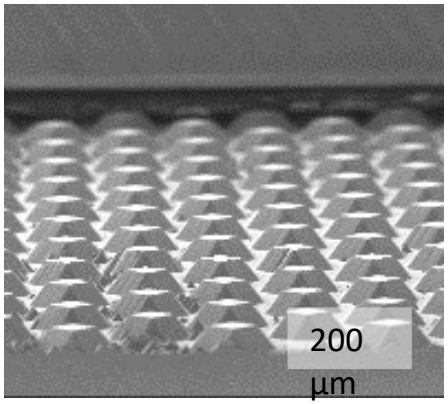
materials, devices, circuits, antennas, textiles, biomedical sensing, data analytics, system integration

FIU Florida International University · UNC School of Medicine · PennState · University of Virginia School of Engineering · University of Michigan · Texas · The University of Utah

Wearable Energy Harvesting

energy available around the body: thermal, mechanical, electromagnetic, electrochemical, ~~solar~~ investigating a wide-breadth of interdisciplinary technologies

Body Heat	Body Motion	Ambient RF	Biofuels	Energy Storage
• Flexible thermoelectrics	• Piezoelectrics • Flexoelectrics • Liquid metal	• Ambient Wi-Fi • Novel antennas on textiles	• Passive sweat collection • Novel enzymes for lactate and glucose conversion	• Li ion capacitors • High Energy Density • Low leakage

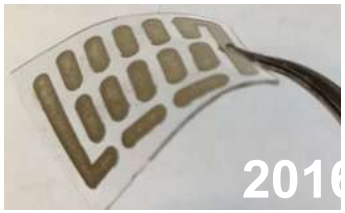


The right source depends on where the device is worn, what the person is doing, and how much power the application needs.

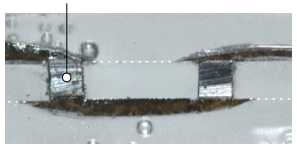
Timeline on ASSIST Flexible Thermoelectrics

human body is continuously producing heat.
conventional thermoelectric devices are rigid, while the body is curved, soft, and constantly moving.

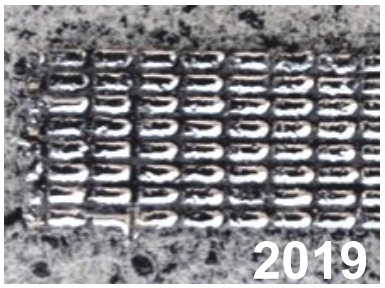
Dual Polyimide Substrates
- Excellent thermal design
- Challenging fabrication
- Poor Flexibility



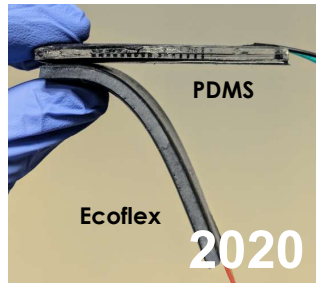
Silicone substrate with Ag Nanowire Interconnects
- Challenging Fabrication
- High resistance



Silicone substrate with EGaIn Liquid Metal Interconnects
- Negligible Interconnect Resistance
- Excellent Selectivity

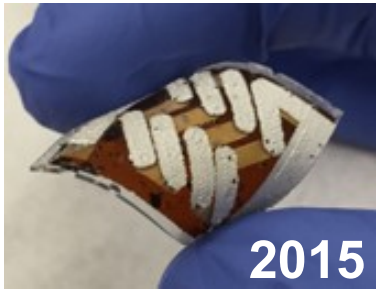


Low Thermal Conductivity Aerogel Doped Filler
- Reduced Heat Leakage
- 4.2X Higher Power Density

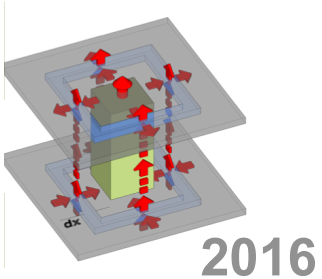


ASSIST TEGs at Consumer Electronics Show

Inclusion of Metabolic Rate in TEG Model

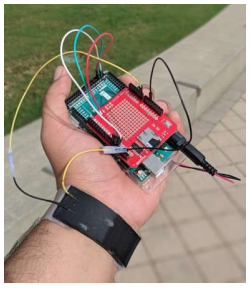


Single Polyimide Substrate
- Printed interconnects
- Improved Flexibility
- High resistance
- Poor lifetime



Quasi 3-D Model
- Thermal/Electrical Model
- Highly Efficient & Accurate

High Thermal Conductivity EGaIn Encapsulation
- Reduced Thermal Series Resistance
- Heat Spreading
- Improved Robustness
- 2.4X Higher Power Density

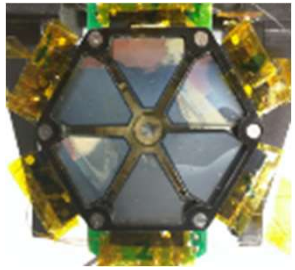


On-Body Characterization
- Data Acquisition
- Impact of Activity Level

moving a basic device concept to conform to the human body
improved materials, mechanical architecture, thermal design, interconnects, and manufacturability

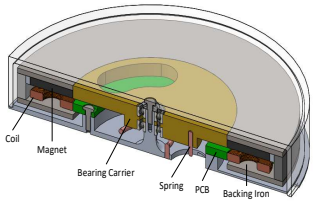
Wearable Mechanical Harvesters

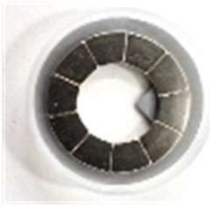
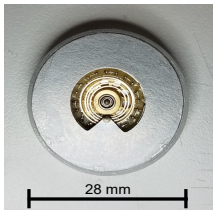
Piezo Wrist-worn Harvesters



- Series of prototypes
- Produces:
  - 100-140 mW at +/- 30 deg., 1 Hz excitation
- Strengths: Power, high voltages
- Weaknesses: Mechanical robustness

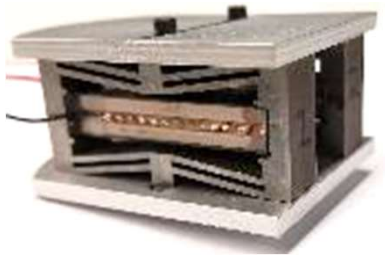
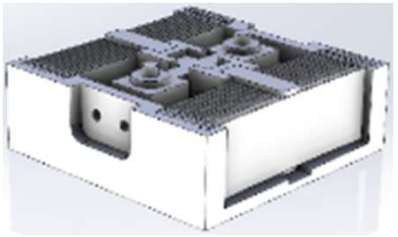
Electromagnetic Wrist-worn Harvesters



- Series of prototypes
- Produces:
  - 60 mW wrist – walking
  - 500 mW wrist – jogging
  - 200 mW ankle – walking
- Strengths: Power, robustness
- Weaknesses: Low voltage output (but can be rectified)

Shoe Insole Based Harvester

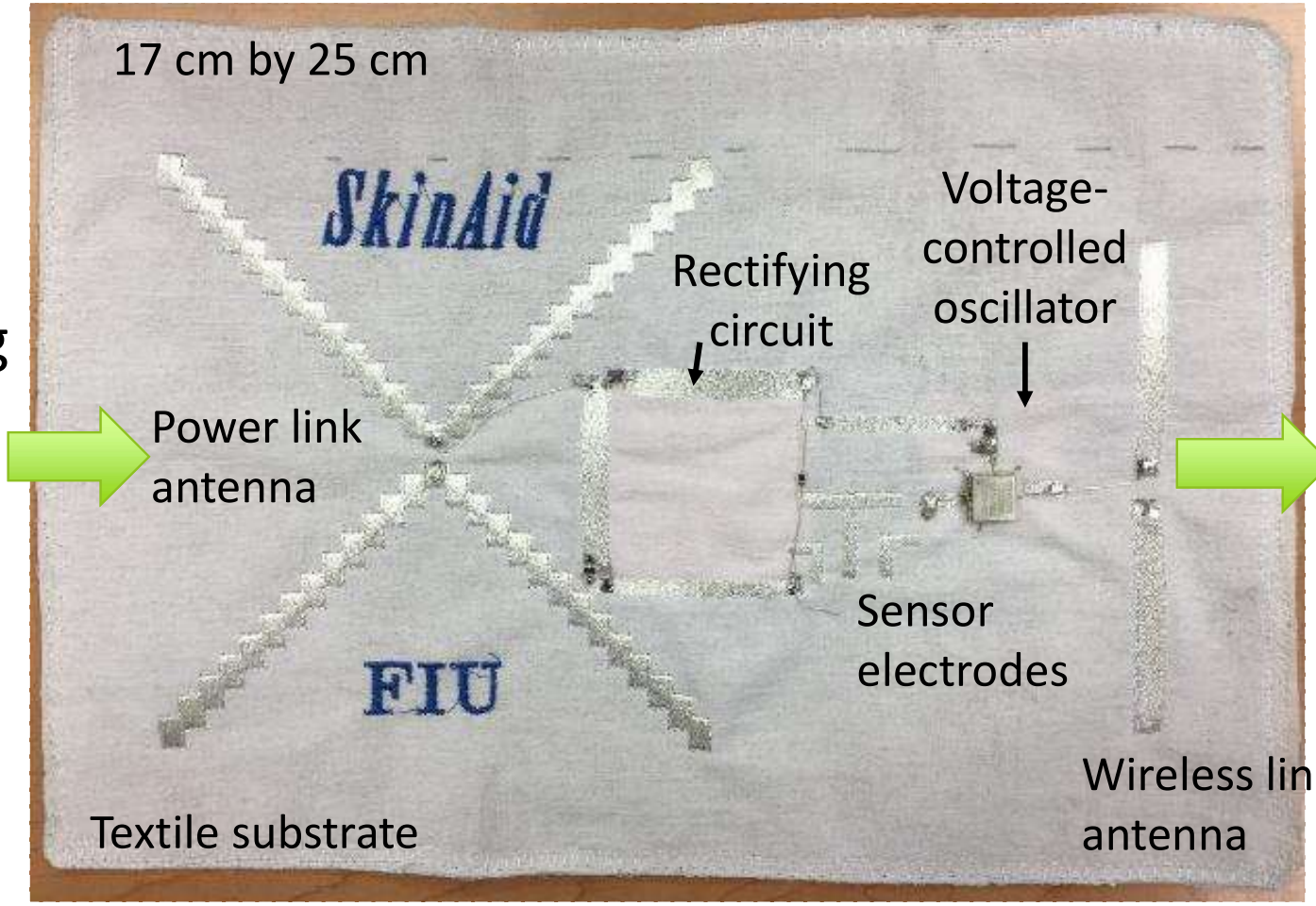
- Much high power density available at the foot
  - 10's of mW compared to ~ 100 mW
- Compelling applications such as early fall detection among elderly or those with Parkinson's disease

tradeoff between power, voltage, some greater robustness

Battery Free Wireless Sensing Patch

RF energy available, external to body

Remote wireless powering



Modulated signal with pH/Uric Acid sensor data

ASSIST Power Generation

portfolio of energy technologies matched to the appropriate use case and power budget

Modality	Use Case	What Makes ASSIST systems unique	Power Levels
Flexible Thermoelectric	For vigilant ECG	Use of state-of-the-art bulk thermoelectric legs in a highly flexible matrix optimized for low thermal conductivity and liquid metal interconnects. Superior performance and manufacturability	20 $\mu W/cm^2$ (no air flow - natural convection) 80 $\mu W/cm^2$ (1.2 m/s air flow, walking)
Mechanical Harvesting	Self-powered Gait Monitoring	Integrated system for self-powering gait monitoring co-designed for comfort and power output; potential to be high sensitivity and more robust than state of the art; Flexoelectric harvesters using silicon are unique.	10 mW
RF Harvesting	Wound Healing	Flexible and fabric based wound monitoring patch, with RF power harvesting and data com links on the same patch. The sensing modality is compatible with different electrochemical sensors, e.g. Uric Acid, pH.	10 mW at 2 ft distance from a 1W RF source
Biochemical Harvesting	Sweat Sensing	Harvesting energy from lactate based innovative bioelectrochemical device, BioCapacitor, using direct electron transfer type engineered super stable lactate dehydrogenase covering dynamic range of sweat lactate concentration.	1 mW (lactate/glucose enzyme fuel cell)

Low Power Multi-Modal Sensors

Reducing power is equally important on the consumption side..

Bioelectric	Biophotonic	Inertial	Biochemical	Environmental
• Low power ECG • Low power EDA • EMG • Dry electrodes	• Low power PPG • Multi-wavelength LEDs • Heart rate, respiratory rate, blood oxygen, sleep, blood pressure	• Activity • Coughing	• New enzymes for lactate, glucose, and uric acid • Passive sweat/ interstitial fluid collection	• Gases for air quality and breath • VOCs for air quality and breath • Particulate matter

Multimodal sensors and their correlation

finding correlations across modalities that give us information a single sensor cannot provide

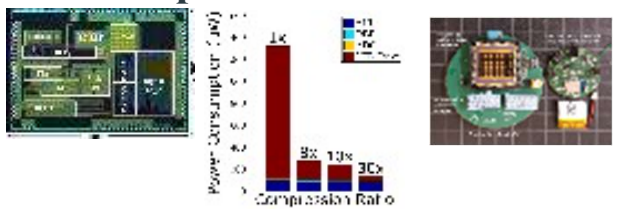
Application Specific Ultra-Low Power Asthma Sensors

Asthma related sensing

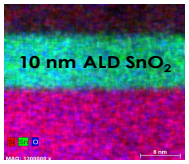
- hr/hrv/ptt via ECG/PPG
- activity and air exposure tracking
- correlation between health, environment and behavior

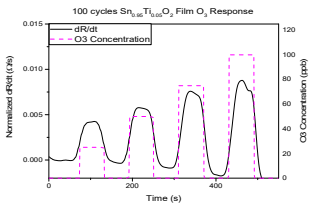
Sensors	Power (uW)	Range
Ozone	150	10ppb-1ppm
VoC	10	50ppb-20ppm
PPG	172	n/a

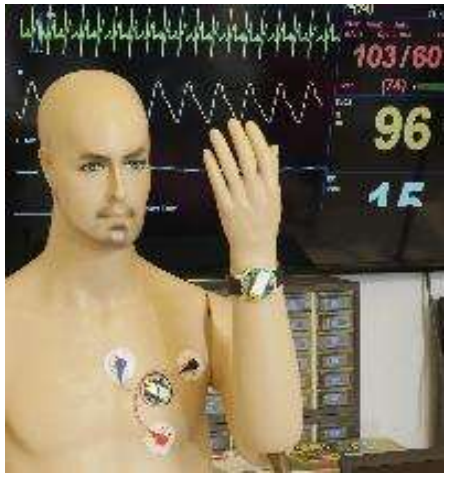
Low power PPG



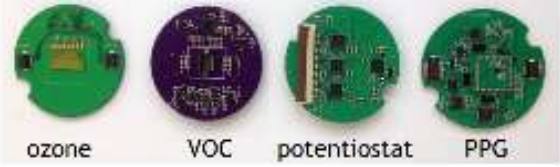
Low Power Ozone



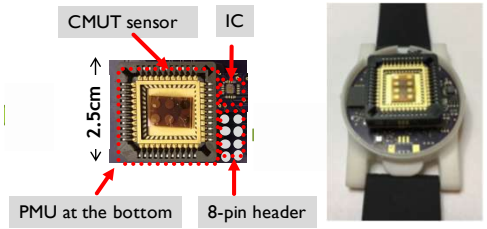




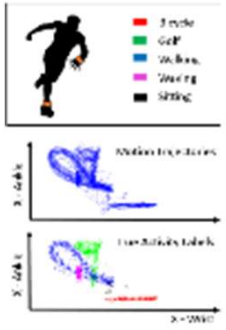
Daughterboards
Front-end for Thrust 3 sensors

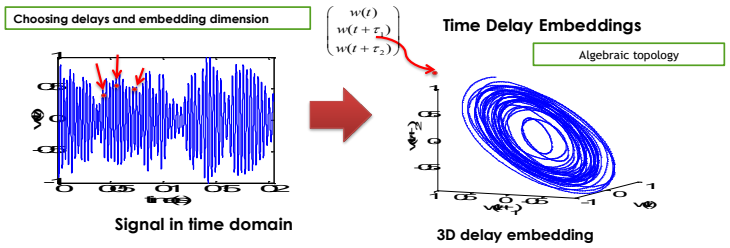


Low Power VOC



Edge-Computing IMU and Microphone



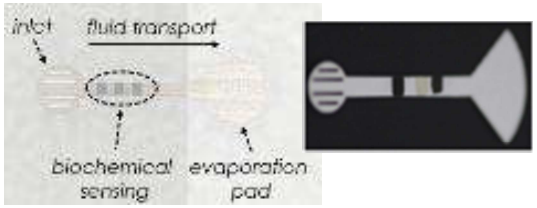


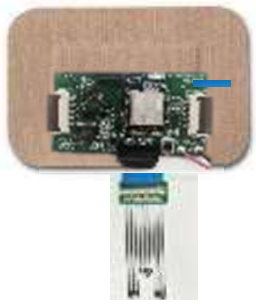
Ultra-Low Power Diabetics and Wound Monitoring Sensors

Diabetics related sensing
- Sweat-ISF-Wound Fluid
- Multi-analyte – multiplexed sensing
- Electrochemical analysis

Sensors	Power (uW)	Range
Glucose	40	1uM-1mM
Lactate	40	20mM-60mM
Uric acid	20	20uM-1mM

Multi-Analyte, Low Power Potentiostat (watch or patch form factor)

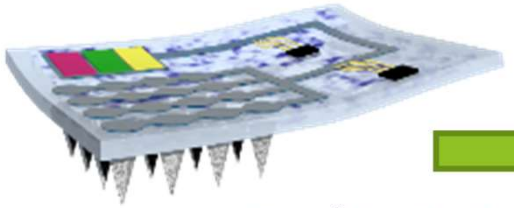


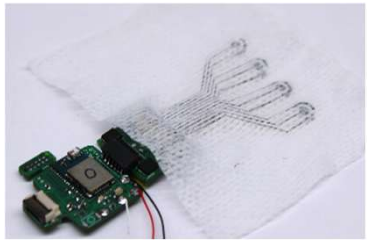


Zero Power Osmotic Pumping

Nanocellulose Patch

HET Gen 2

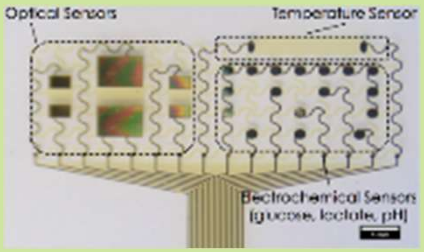




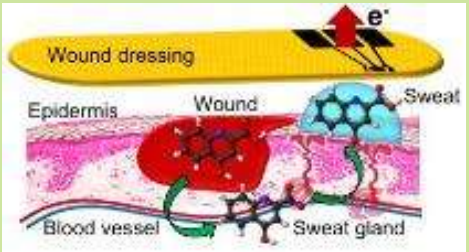
Diet Management Use Case

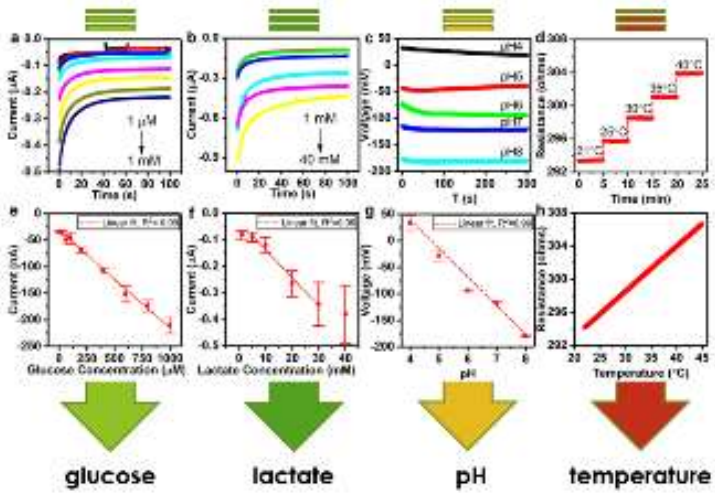
Wound Care Use Case

Glucose & Lactate Sensing



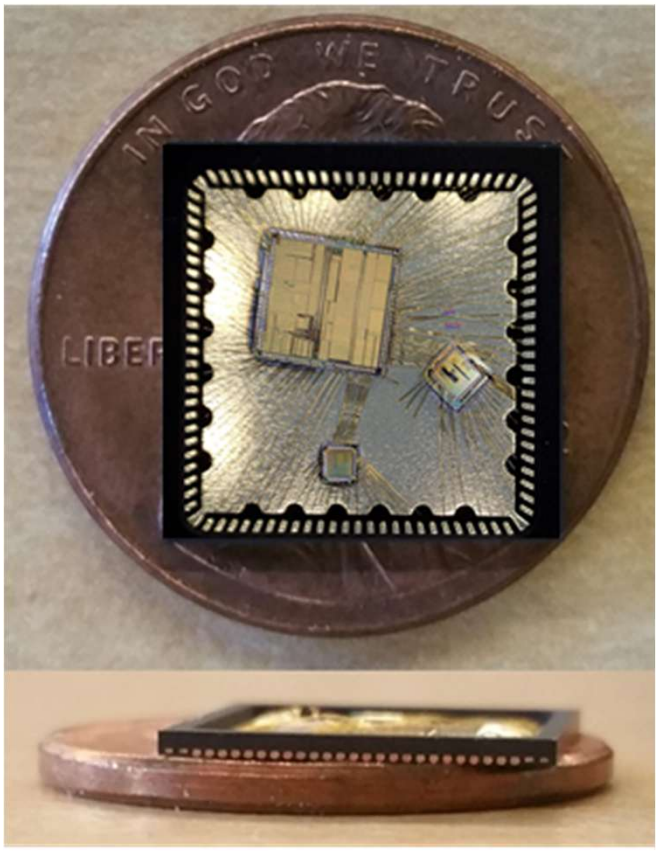
Uric Acid Sensing





Low Power Electronics : Multi-Chip Solution

optimizing the electronics power budget at the chip level, application specific co-design
analog front end, system-on-chip computation, energy harvesting management, wireless communication



System on Chip

- 566 nW total power
- RISC-V

Energy Management Chip

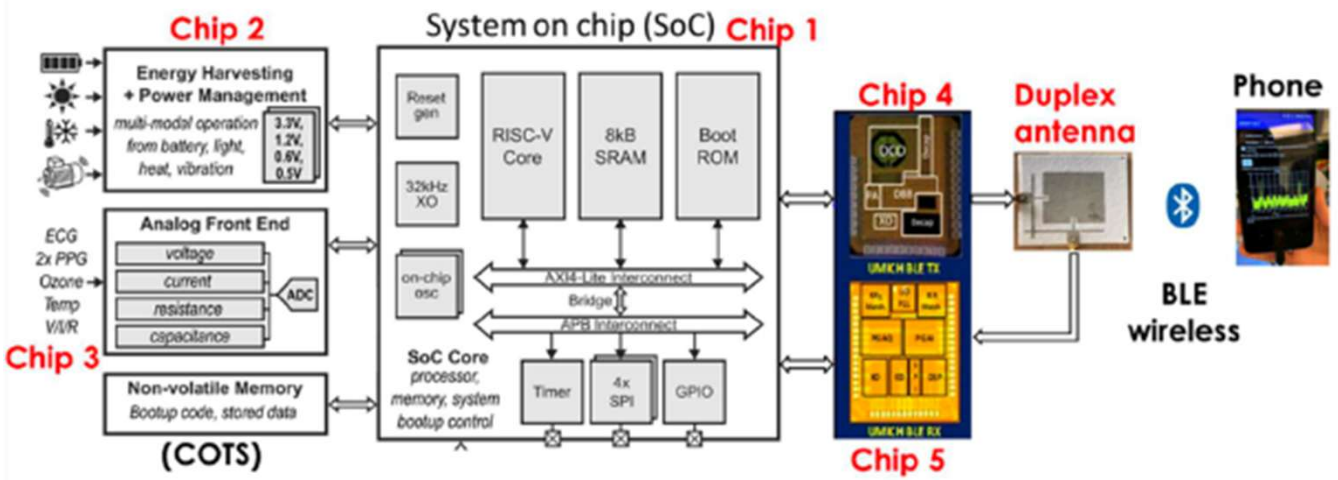
- Multi-modal: TEG/PV/Piezo
- Four custom voltages outputs

Analog Front End Chip

- ECG, PPG, RR, Ozone
- Respiration and ECG always on
- RR triggers PPG/Ozone

Custom Radio Chip

- BLE 4.0 Compliant
- 300 uW total power
- -69dBm sensitivity and 500Kb/s



hierarchical or event-driven operation:

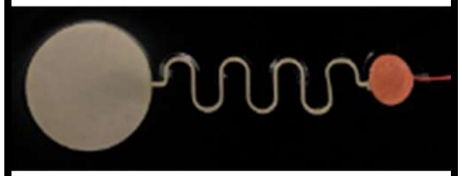
- keep only the cheapest sensor always on
- wake higher-power sensing when something interesting happens

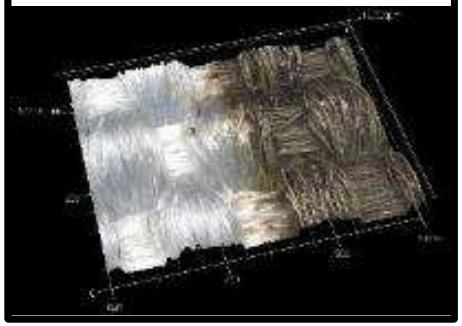
Flexible and Wearable Technologies

ergonomic mechanical interface with the body
comfort, flexibility, manufacturability, electrical performance, and energy efficiency

Smart textiles

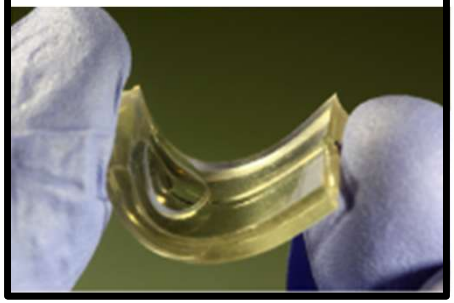
- Printed electrodes
- Smart textile designs





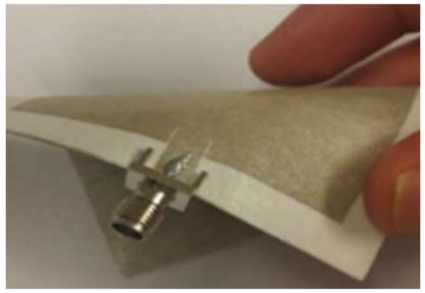
Liquid metal interconnect

- Stretchable conductors
- TEGs, antenna, and



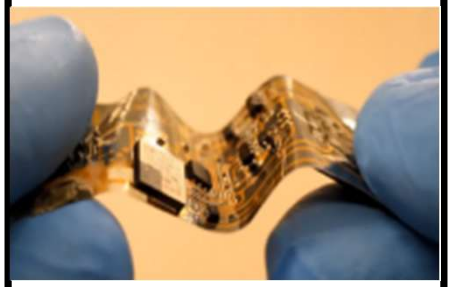
Fabric antennas

- Wearable and high efficiency



Stretchable substrate PCBs

- Thin conformable profile providing comfort and flexibility



ASSIST Industry Members and Partners To Date

IAB and members:

- semiconductors, medical devices, pharmaceuticals, materials, textiles, communications, healthcare, defense
- identify what is scientifically interesting, manufacturable, useful, and commercially relevant

Research Portfolio

ASSIST is breakthrough not through one particular sensor, harvester, chip, or textile but learning to co-design the entire wearable system around an extremely constrained energy budget, driving innovations from materials and devices through circuits, communication, AI, and human-centered system design (available in online portfolio).

Health & Exposure Tracker Wrist Worn & Chest Patch

Reconfigurable for various applications

• Asthma • Mental Health • Aging • Behavior Tracking • Cardiovascular Health

Multimodal sensing (wrist worn)

- Electrodermal activity (EDA)
- Gas sensing (environmental & skin vapor)
- Heart rate/Photoplethysmography
- Activity tracking
- Caloric burn rate
- Skin temperature
- Ambient temperature/humidity

Multimodal sensing (chest patch)

- ECG
- PPG
- Cough detection
- Activity tracking
- Ambient sound

Implantables/Injectables

- Multimodal sensing
- Bioresorbable
- Subcutaneous temperature
- Ultrasound energy transfer
- PPG
- Activity tracking

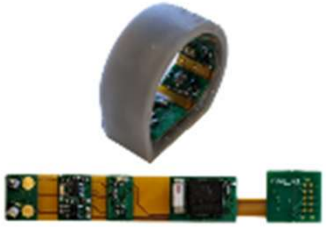
ECG Shirt

- Always-on operation
- Body-powered (heat)
- Dry electrodes
- Low-power radio
- Low-power circuits
- Wearable antenna

ECG Armband

- Comfortable, real-time ECG
- Ergonomic design with dry electrodes
- Optimized for motion artifacts
- Onboard IMU for contextual sampling
- Self-powered capability

Biophotonic Ring



- 12 Wavelength PPG
- Skin temperature
- Heart rate
- Total hemoglobin
- Hematocrit

Metabolic Tracker

- Sweat or interstitial fluid
- Biochemical markers including glucose, lactate, uric acid, pH
- Activity tracking
- Self-powered capability

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