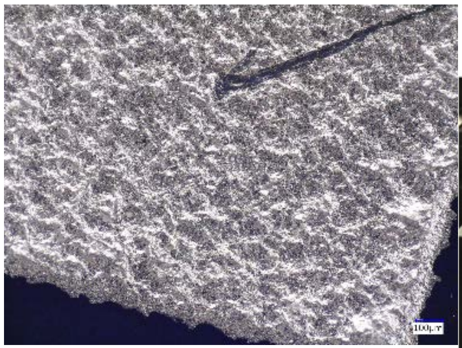
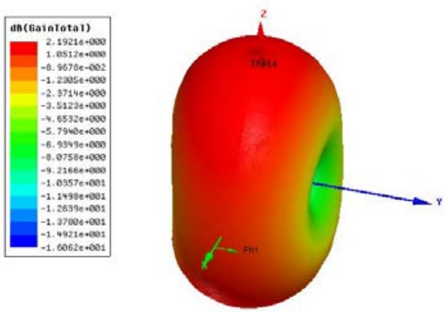
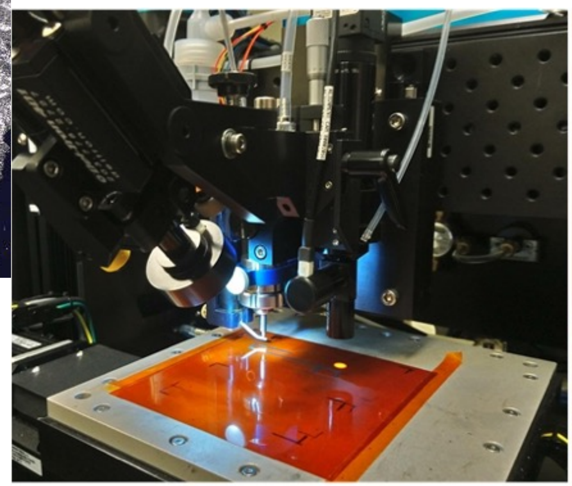
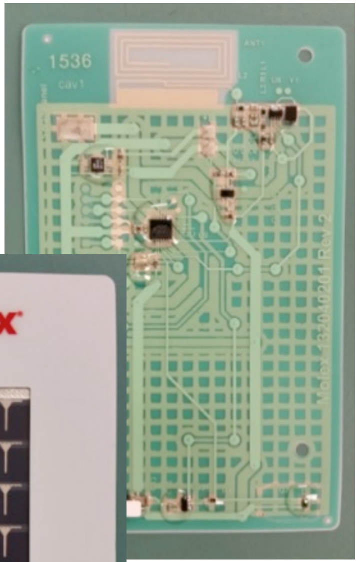
U.S. DEPARTMENT OF
ENERGY
Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

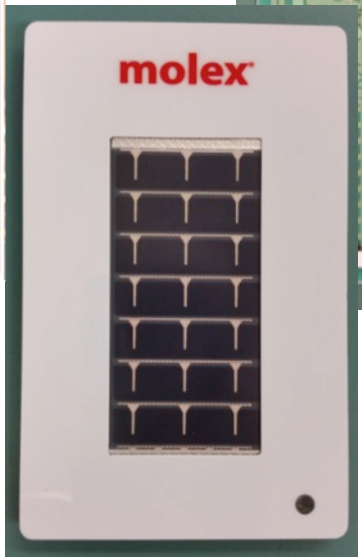
Energy-harvesting, Self-calibrating Wireless Sensors for Improving Energy Efficiency in Buildings











Oak Ridge National Laboratory, PARC, Molex
Teja Kuruganti
kurugantipv@ornl.gov

Project Summary

Timeline:

Start date: 10/1/2016

Planned end date: 9/30/2018

Key Milestones

1. Ten fabricated prototype sensor circuits demonstrate target performance; 3/31/2018
2. Communication network demonstrates targeted performance of process gain >10dB, range > 200ft, and receiver sensitivity > -110dBm; 6/30/2018

Budget:

Total Project $ to Date:

- DOE: $1,000,000
- Cost Share: $130,000

Total Project $:

- DOE: $1,000,000
- Cost Share: $130,000

Key Partners:

Palo Alto Research Center (PARC)
Molex

Project Outcome:

- System-level architecture for a plug-and-play, multi-sensor, wireless platform to realize ≤ $10/node to meet building monitoring requirements
  - Low-cost, multi-modal sensor platforms
  - Improve the operational lifetime of the sensor node by exploiting innovations in energy harvesting and storage
  - Self-calibration of the multi-sensor platform to reduce drift and variability

Team

- **Project Lead – Oak Ridge National Laboratory (ORNL)**
  - **Teja Kuruganti, Pooran Joshi, Stephen Killough, Christopher Winstead**
  - Systems integration to develop high degree of coordination between novel communication technology, sensors, energy harvesting
  - Low-power, low-data rate communication technology driven by innovation in spread spectrum techniques.
  - Innovative thermal annealing techniques, such as pulse thermal processing (PTP)
- **Manufacturing Partner - Molex**
  - **Rob Irwin, Mike Wilzbacher, Steve Fulton, Dave English, Chris Ray, Mike Deppe**
  - 45 design, development and manufacturing centers in 17 countries.
  - Variety of printing systems used for fabricating electronic circuits and devices and includes a state-of-the-art nine station roll-to-roll printing system with rotary screen and flexographic capability as well as a variety of curing modules and multiple flatbed screen printing systems
- **Printed Electronics Materials and Processing – PARC**
  - **David Schwartz, Bob Street, Sean Doris, Adrien Pierre, Rahul Pandey**
  - Materials science, modeling, materials deposition and patterning, metrology, and device analysis Wide range of printing and coating techniques including ink jet, screen, extrusion, aerosol jet, gravure, spin casting, slot dye coating, doctor blading, and more.

Challenge

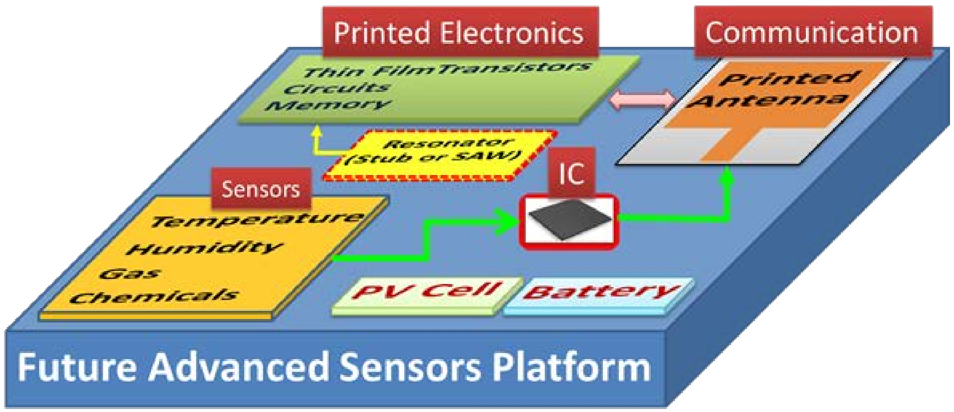
Problem Definition: Sensors that monitor building parameters can enable fault detection and diagnosis (FDD) of building equipment and provide input to whole-building control strategies, which will result in improved energy efficiency of buildings. Energy harvesting-based wireless sensors for building monitoring that are low-cost (initial and maintenance) can provide the required monitoring. However, current manufacturing techniques, algorithms, and signal processing techniques are not readily equipped to solve. An integrated multi-disciplinary project to investigate to balance tradeoffs and achieve required performance is needed.

Advice: Self-powered "peel-and-stick", low-cost, plug-and-play multi-sensor wireless platforms that are ≤ $10/node can monitor building conditions and enable optimal control of energy usage resulting in the following savings:

- low-cost, multi-modal sensor platforms (number of sensed variables ≥1) and data fusion techniques for accurately measuring real-time building environmental parameters
- Improve the operational lifetime of the sensor node by exploiting innovations in energy harvesting and storage with mean time between replacement of batteries ≥10 years and mean time between charging ≥72 hours
- Self-calibration of the multi-sensor platform using novel manufacturing techniques to reduce drift and variability, algorithms for estimating sensor drift during operation, and self-calibration capability with a calibration lifetime ≥5 years

Approach – Multifunctional Wireless Sensors

Multifunctional Sensor Platform



Four Key Elements of Technology	
1	Low-power Wireless Communication
2	Energy-Harvesting and Storage
3	Integrated System Design
4	Innovative low-cost manufacturing

Key Technology Improvements

→ Low-power wireless

→ Multifunctional sensor

→ Advanced materials

Approach – Path to Success

Design, system-level architecture, requirements definition

- Requirement and design definition
- Architecture development

Energy-efficient, scalable, low-power communication network

- Communication architecture and design
- Deploy and test communication network

Synergistic energy harvesting and storage

- Evaluate technologies
- Performance evaluation

Low-cost, reliable sensor technology for building monitoring

- Temperature sensor performance
- Humidity sensor performance
- Performance evaluation

Scalable manufacturing techniques

- *Integration*
- *Manufacturing*
- *Fabrication*
- *Testing*

Technology to Manufacturing Plan

Building Monitoring System Development

In Partnership with Molex and PARC

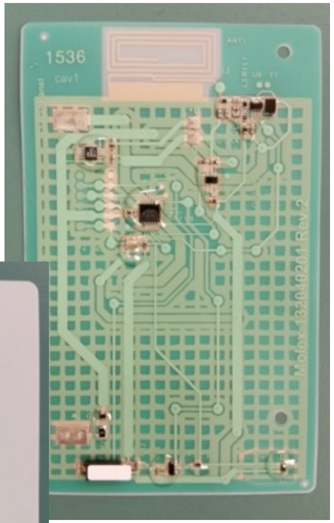
- Develop wireless sensor system to enable increased building energy efficiency
- Provide information for optimal control of energy consuming systems: HVAC, Lighting
- Self-powered “peel & stick” for easy upgrades in existing buildings

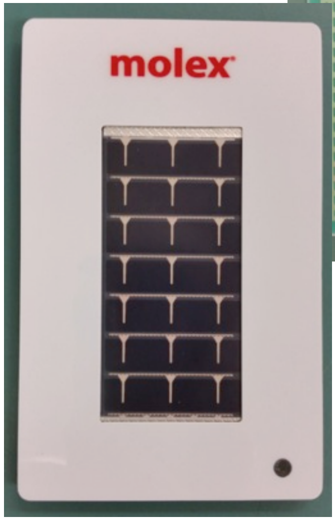
Approach

- **Ultra-low power wireless communication:**
  - Printed Antenna, Spread Spectrum Communication
- **Energy harvesting:**
  - Thin Rechargeable Battery, Flexible PV
- **Multiple sensors:**
  - Temperature, humidity and light sensors
- **Thin, light form factor:**
  - Base circuit printed on PET film
  - Low temperature solder based component attach

Success Criteria: Synergy among PV-Battery-Antenna-Sensor components to meet cost/performance objectives for Buildings Applications

Oak Ridge National Laboratory





molex

parc A Xerox Company

Impact

Target Market and Audience:

- All residential and commercial buildings.
  - **Small and medium commercial buildings** – improved control of energy with **6-8 quads** of energy savings potential
  - **Large commercial buildings** – improved control of energy use optimization, and diagnostics of large equipment with **8-9 quads** of energy savings potential
- Building automation system and equipment manufacturers for OEM integration
- Technology adaptable to various sectors: *Health, Manufacturing, Vehicles, Energy*

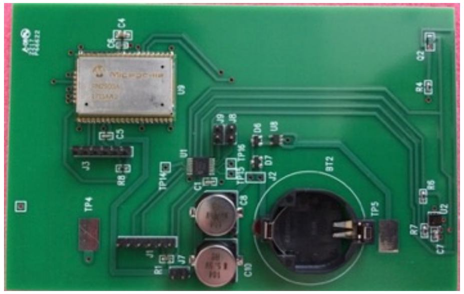
Impact of Project: The project envisions reducing the cost barriers to deploying advanced sensors to enable optimization of energy usage. The project will develop and demonstrate low-cost wireless sensors along with path towards roll-to-roll manufacturing techniques.

- Achieve BTO goal of multi-functional wireless sensor networks leading to 17% savings for HVAC and 35% savings for lighting by 2030 in both residential and commercial buildings
- Demonstrate end-to-end technology and identify path towards low-cost manufacturing through industrial partnerships
- Identify building equipment and automation manufacturing partner(s) for commercialization and deployment tailored to specific building applications

Impact on Buildings Technology: Advanced sensor, control technology brings big growth to building energy management market: $2.14 billion industry by 2020 (Lux Research)

Wireless Technology

- Devices in the network are asynchronous and transmit when they have data available to send
  - Adaptive sizing to reduce consumption
- Data transmitted by an end-node device is received by multiple gateways, which forward the data packets to a centralized network server
  - End-to-end architecture with ability to integrate BAS protocols
- The network server filters duplicate packets, performs security checks, and manages the network
- Data is then forwarded to application servers
  - Open-source “LoRaServer” used as the application server
- Improved energy performance to meet > 72 hours between charging



Prototype

kTagLoRaPowerT Revised: Tuesday, January 30, 2018
Revision: 2

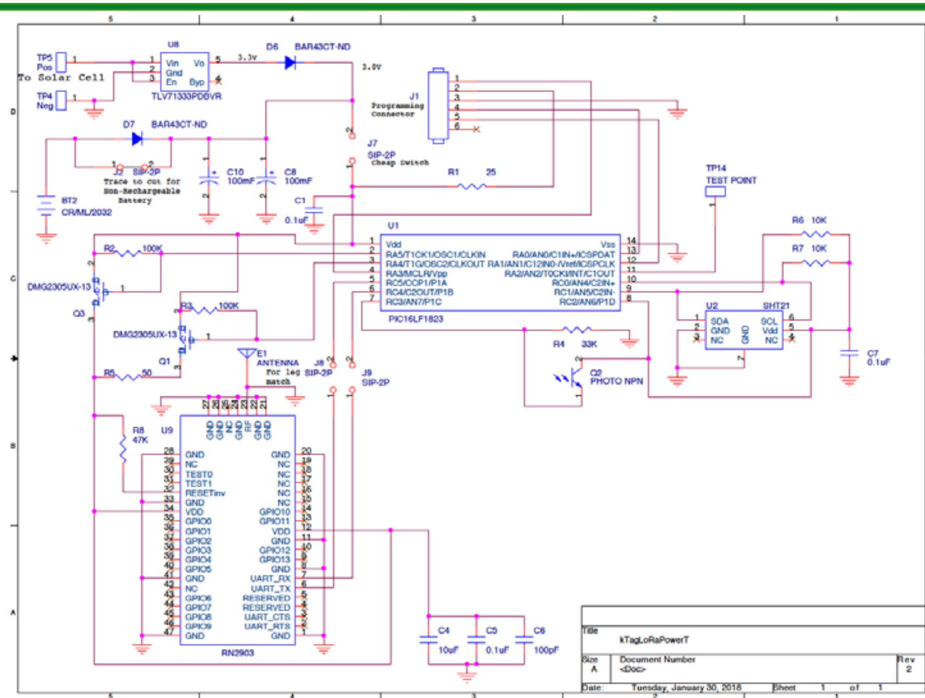
Bill Of Materials January 30,2018 7:38:58 Page1

Item	Quantity	Reference	Part	Footprint	Part# (Digikey?)
1	1	BT2	CR/ML/2032	CR2032holder	BC2032-E2-ND
2	3	C1,C5,C7	0.1uF	0603	PCC2277CT-ND
3	1	C4	10uF	0805	490-1718-6-ND
4	1	C6	100pF	0402	PCC101CQCT-ND
5	2	C10,C8	100mF	SUPERCAP	399-10939-6-ND
6	2	D6,D7	BAR43CT-ND	SOT23	BAR43CT-ND
7	1	E1	ANTENNA	SIP-1P	
8	1	J1	HEADER 6	SIP-6P	Newark 67R8281
9	1	J2	SIP-2P	SIP-2P	
10	3	J7,J8,J9	SIP-2P	SIP-2P	
11	2	Q1,Q3	DMG2305UX-13	SOT23	DMG2305UX-13DITR-ND
12	1	Q2	PHOTO NPN	0805	751-1056-1-ND
13	1	R1	25	0603	P22GCT-ND
14	2	R3,R2	100K	0603	RMCF0603FT100KCT-ND
15	1	R4	33K	0603	P33.0KHCT-ND
16	1	R5	47	0603	P47GCT-ND
17	2	R6,R7	10K	0603	P10.0KHCT-ND
18	1	R8	47K	0603	P47.0KHCT-ND
19	1	TP4	Neg	solarpad	
20	1	TP5	Pos	solarpad	
21	1	TP14	TEST POINT	SIP-1P	
22	1	U1	PIC16LF1823	TSSOP14	PIC16LF1823-I/ST-ND
23	1	U2	SHT21	SHT2X	Mouser 403-SHT21
24	1	U8	TLV71333PDBVR	SOT-23-5	296-35591-1-ND
25	1	U9	RN2903	RN2903	RN2903A-I/RM098-ND

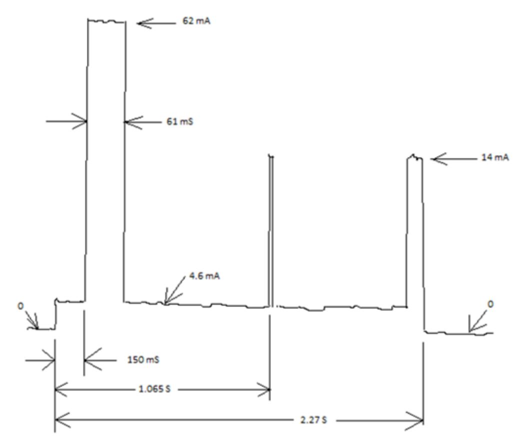
BOM

Prototype - Version 2

- Sleep current draw is **~3 µA**
- Transmission current draw is **~62mA**
- Soft start capability for RN-2903 to mitigate consumption

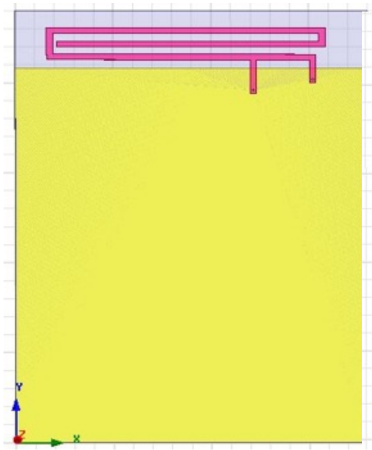


	Unit #00	Unit #28
Battery First Inserted	3.091 V	3.088 V
After 1 hour; Solar Charging; No transmissions	3.106 V	3.106 V
2 Hours Running in Light	3.082 V	3.089 V
1.5 Hours Running in Dark	3.044 V	3.057 V
0.5 Hours After Light Turned On	3.065 V	3.073 V
45 Additional Minutes in Light	3.068 V	3.077 V
1 Additional Hour in Light	3.068 V	3.079 V
Additional 24 Hours of Light	< 2 V	< 2 V

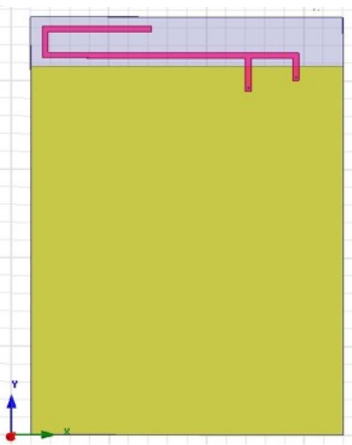


Antenna Characterization

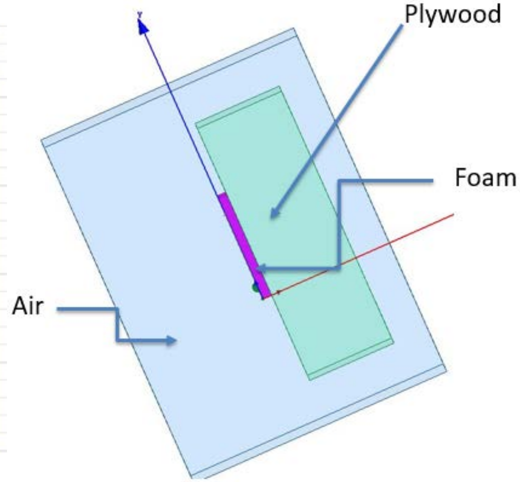
- Incorporating smaller dimension antenna to reduce the oversize of the tag and RF section
- Wider bandwidth
- Return Loss ~ - 17dB
- Awaiting Ink selection before finalization



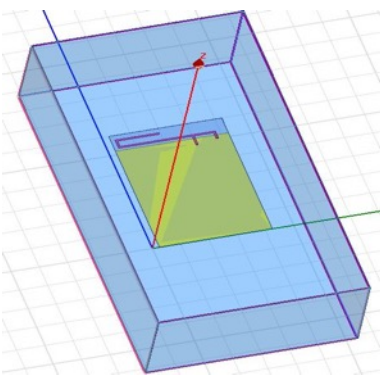
(a) 433 MHz



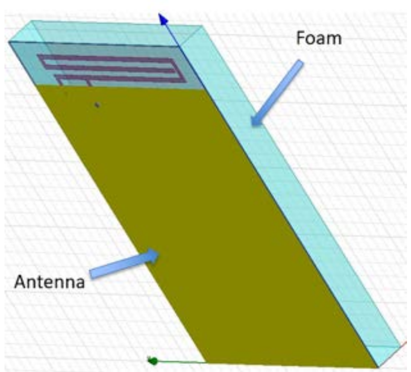
(b) 915 MHz



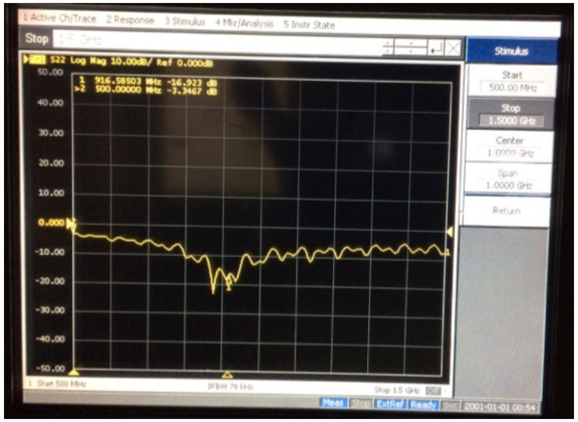
Antenna simulation with real world scenario

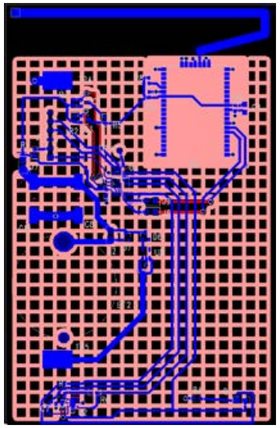


3D model in HFSS



Antenna model with foam



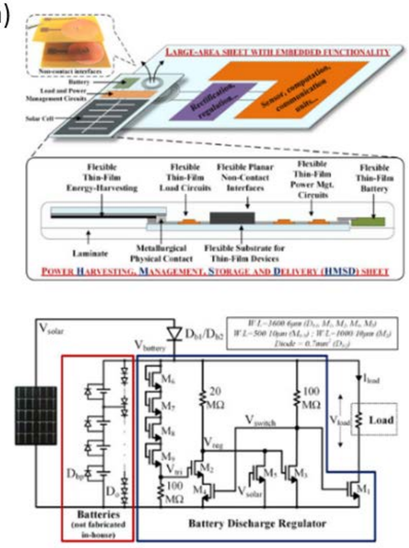


Flexible power systems

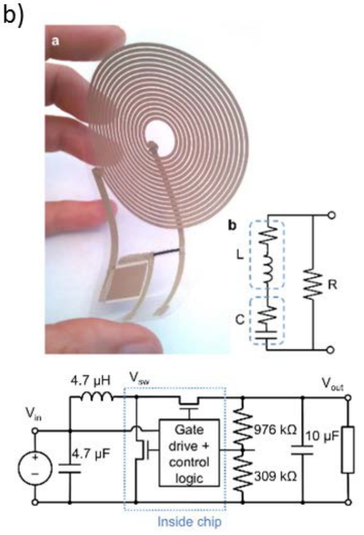
- Power conversion systems needed to:
  - Bias PV cells at maximum power point
  - Control flow of power to energy storage
  - Convert dc output of PV module to desired output
- Thin film actives (TFTs, diodes) and passives (capacitors, resistors) enable flexible planar power conversion systems
- Energy Storage
  - Thin-film batteries with capacity ~20mAh
    - Deep cycle for long-duration
  - Super capacitors ~ 100-200mF
    - High-current and reduce battery cycling

Storage Type	Number of Transmissions	Mean time between charging
SuperCapacitor 0.20 Farad 0.28 mA-hours	9 actual	2.25 hours
Rechargeable ML2032 62 mA-hours	2000 calculated	20 days
Primary CR2032 230 mA-hours	7000 calculated	70 days

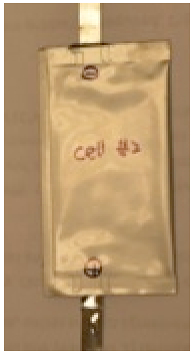
a)



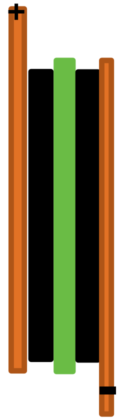
b)



Thin-film rechargeable batteries

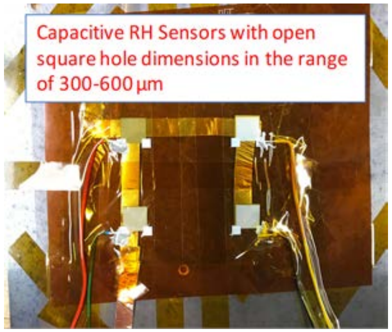


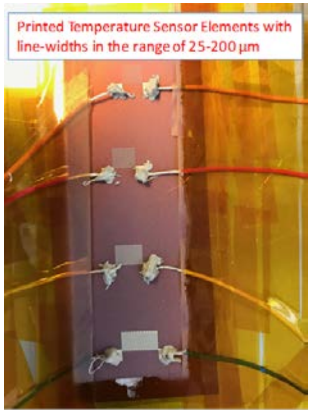
Flexible solid-state supercapacitor



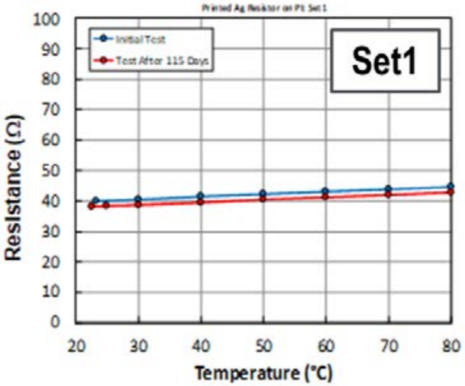
Printed RH and T Sensor Performance and Reliability

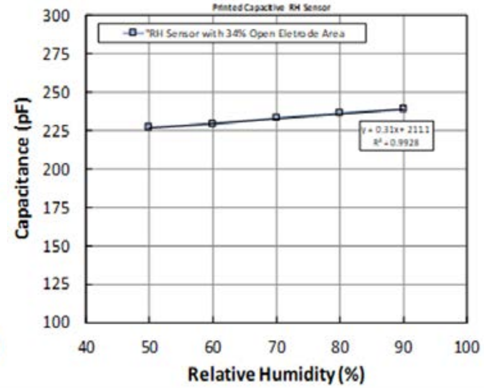
Printed Temperature and Humidity Sensors



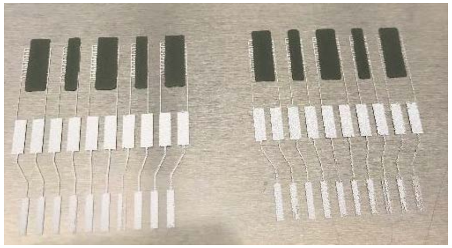


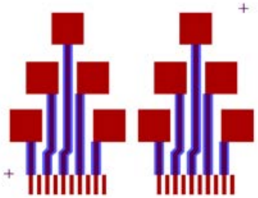
Direct-write Sensors



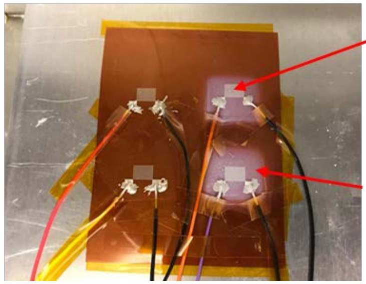


- Linear Response as a function of Temperature and Humidity





Multi-Sensor Printing



Printed Resistor

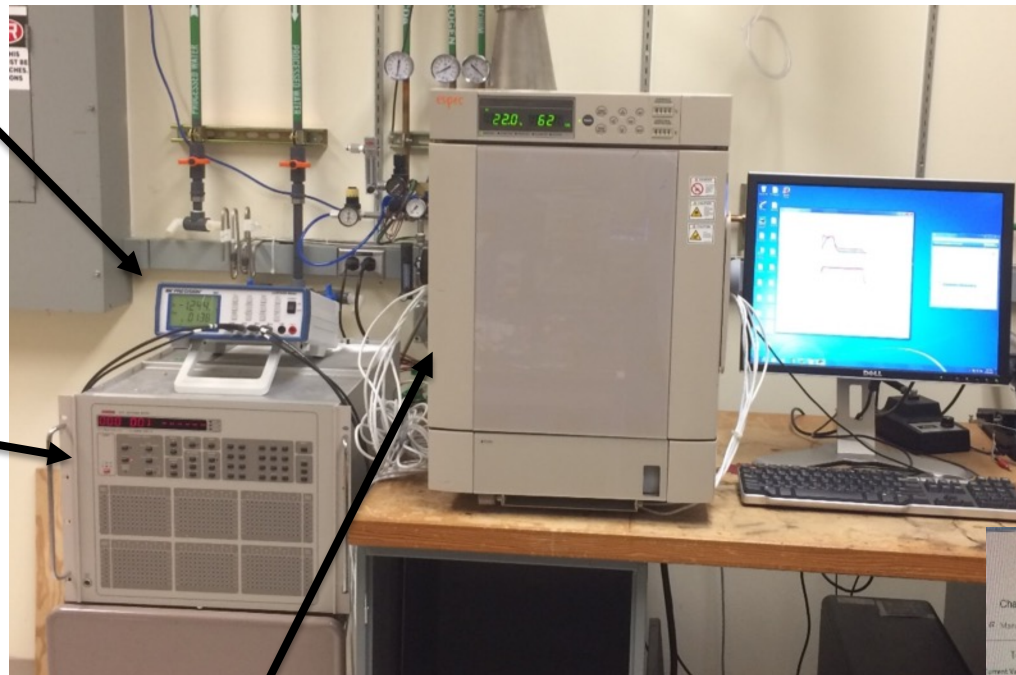
Super hydrophobic coating

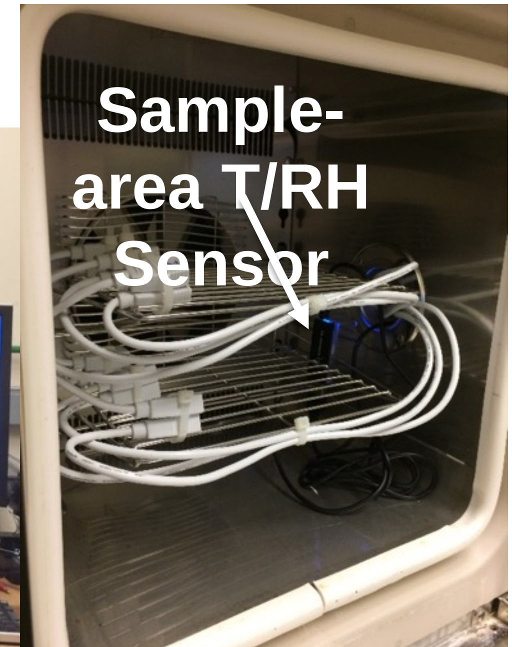
- Temperature – Ag and NiO
- Relative Humidity – Ag
- Surface Passivation Layers for Reliable Temperature Sensor Performance being investigated
- Rigorous testing for lifetime analysis

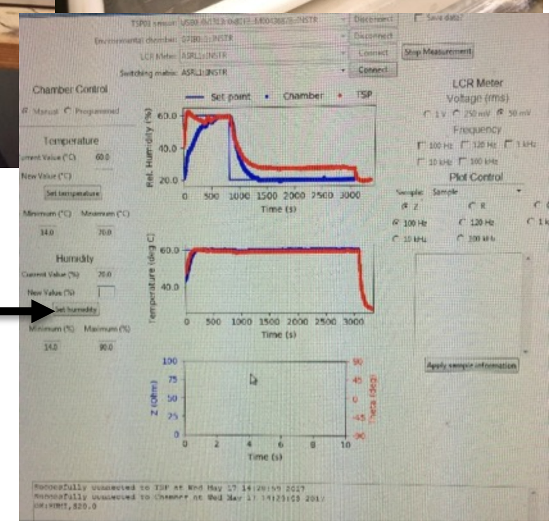
Accelerated lifetime testing

LCR Meter
Measures electrical characteristics of sensors

Switching Matrix
Allows 24 sensors to be measured concurrently







Environmental chamber
Controls temperature and relative humidity

Control Software
Enables automated testing

Manufacturing Process

molex

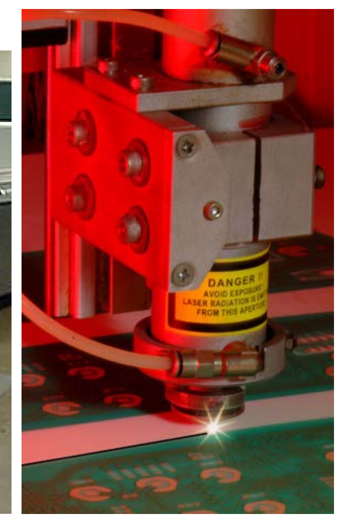
Print circuits → Attach surface mounted components → Attach printed sensors with eyelet press → Test electrical continuity → Laser cut features → Final assembly
- Solar panel
- Gasket
- Graphic mounting
- Graphic

→ Functional test

High-speed screen print

Surface-Mount Technology

Laser Cut



Progress and Accomplishments

Accomplishments:

- Successfully demonstrated commercially produced self-powered wireless sensors through manufacturing partner Molex
- Incorporated LoRa communication scheme to deliver required performance of >>72 hours of operation
- Using an indoor photovoltaic source and thin-film batteries that can operate successfully over several days with our light source
- Demonstrated thin-film sensors printed using inkjet printing of silver
- 2 Journal, 1 Conference, 2 Abstracts, 1 US patent; 3 publications under preperation
- Demonstrations to potential industrial partners and engaging in discussions tailored for building monitoring applications
- Multi-functional devices realized using additive, roll-to-roll manufacturing techniques.

Lessons Learned: Understanding of printed ink performance is required for high performance multi-sensor and antenna integration

Stakeholder Engagement & Remaining Project Work

- Stakeholder Engagement:
  - Molex is the manufacturing and commercialization partner
  - Engaging with OEMs on requirement definition and commercialization pathways
  - PARC developing IP in printed sensors in collaboration with ORNL
- Remaining Project Work
  - Integration of printed sensors in end-to-end manufacturing tool chain - Develop pick and palace methods for printed sensors
  - Calibration of printed sensors over time to evaluate accuracy and resolution over time
    - Complete study of printed sensors in chamber tests
    - Quantify stability of printed sensors to environmental stressors
  - Demonstrate low-power communication scheme interoperable with building automation systems - Quantify performance of the integrated systems design to meet target metrics

Thank You

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REFERENCE SLIDES

Project Budget

Project Budget: 465K (FY17), 535K(FY18)
Variances: None
Cost to Date: $753K
Additional Funding: None

Budget History			
FY 2017 (past)		FY 2018 (current)	
DOE	Cost-share	DOE	Cost-share
465K	53K	535K	77K

Project Plan and Schedule

Project Schedule												
Project Start:10/01/2016		Completed Work										
Projected End: 09/30/2018		Active Task (in progress work)										
		Milestone/Deliverable (Originally Planned) use for										
		Milestone/Deliverable (Actual) use when met on time										
	FY2017				FY2018				FY2019			
Task	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)	Q1 (Oct-Dec)	Q2 (Jan-Mar)	Q3 (Apr-Jun)	Q4 (Jul-Sep)
Past Work												
Complete design document for sensor platform												
Develop prototype of communication technology												
Preliminary printed sensor prototype an designs demonstrate seamless integration on the platform												
Calibration setup and preliminary results on the sensor reliability												
Current/Future Work												
Communication network demonstrates targeted performance												
Complete temperature and RH sensor development												