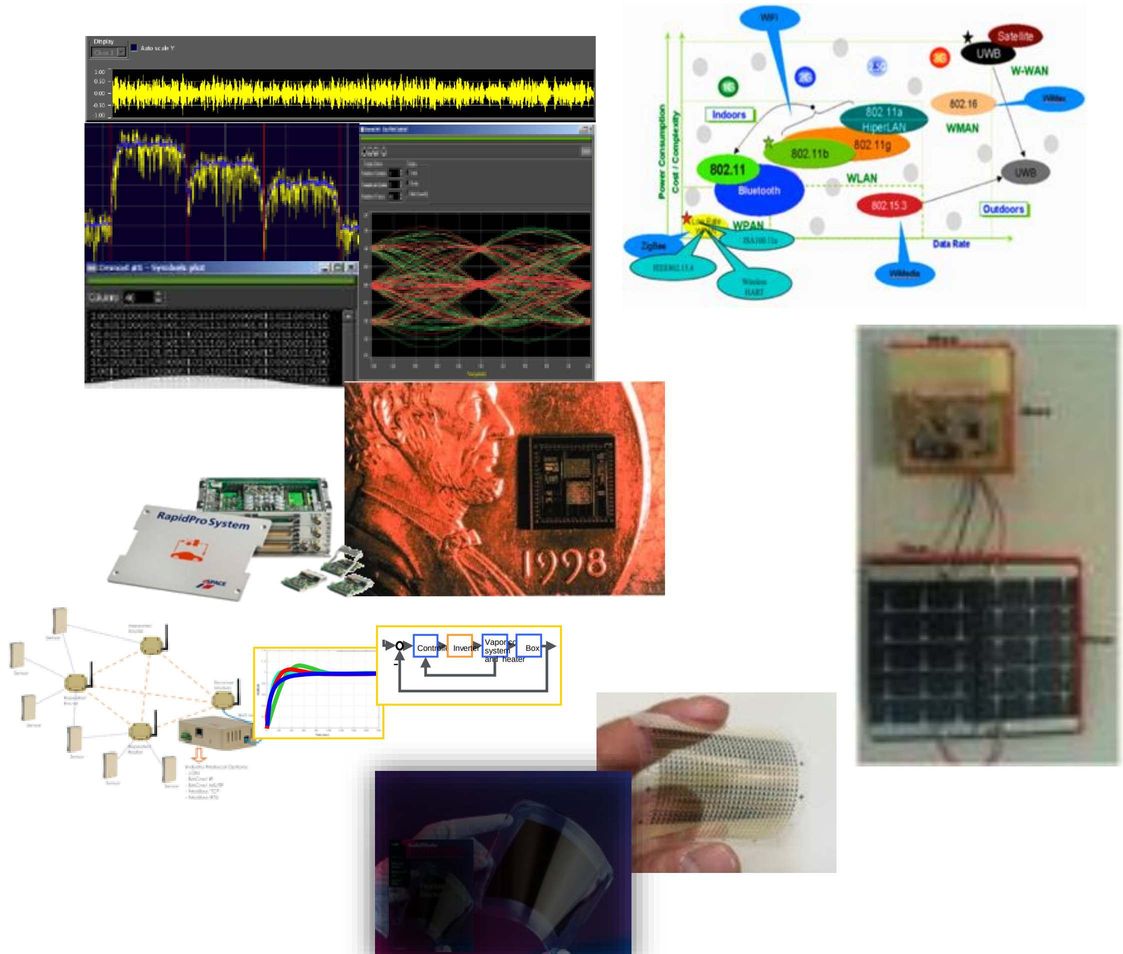
Low-cost Manufacturing of Wireless Sensors for Building Monitoring Applications

2016 Building Technologies Office Peer Review



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Oak Ridge National Laboratory

Project Summary

Timeline:

Start date: 10/01/2015

Planned end date: 09/30/2017

Key Milestones

1. Complete baseline testing and report results for Version 1 prototype ; 12/31/2015
2. Develop Version 2 prototype in collaboration with building equipment manufacturer; 09/30/2016

Budget

Total Project $ to Date:

- DOE: $ 269,596
- Cost Share: $ 300,000

Total Project $:

- DOE: $ 875,000
- Cost Share: $ 875,000

Key Partners:

Molex
Emerson Climate Technologies

Project Outcome:

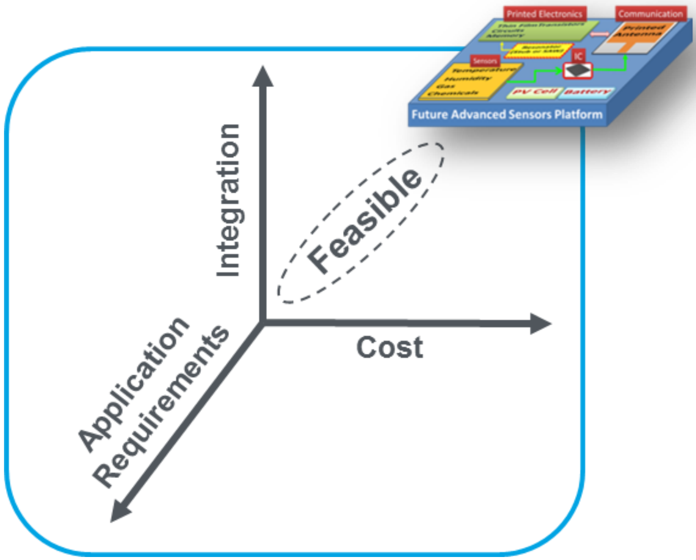
The outcome of project is to develop, manufacture, and demonstrate energy-harvesting-based self-powered wireless sensors for building monitoring applications.

The achieve this outcome the team is partnering with electronics manufacturer, Molex, to demonstrate a path towards low-cost manufacturing meet deployment requirements within buildings.

Purpose

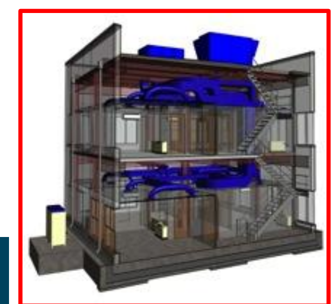
Problem Statement

- Buildings consume up to 40% of energy produced in the US
- Sensors and controls have demonstrated potential to reduce building energy consumption by 20-30%
- Savings can be realized only by retrofit solutions: 1-2 year payback to facilitate adoption



Non-Orthogonal Multi-dimensional requirements for Low-cost wireless sensors

- <u>Application Requirements</u>: Data Rate, Sensor Accuracy, Sampling Rate, Battery, RF communications
- <u>Integration Requirements</u>: Materials, Functionality, Device/Sensor Integration, Regulations
- <u>Cost</u>: Low-cost, Manufacturing Infrastructure



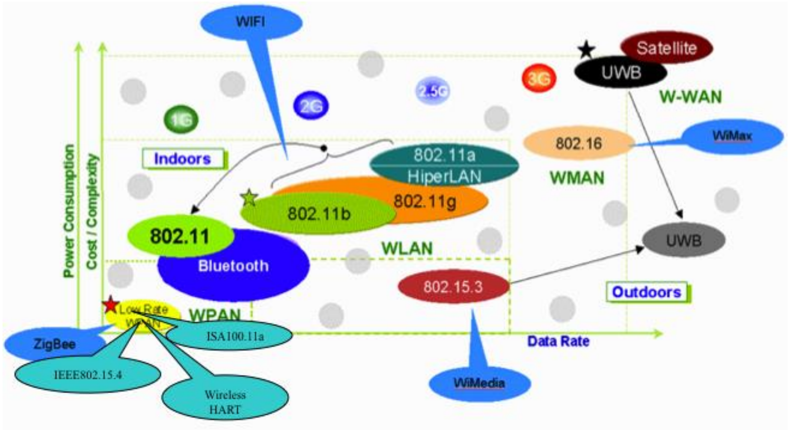
Project Focus: Develop Self-powered wireless sensor technology and System-level integration exploiting roll-to-roll manufacturing compatible technologies

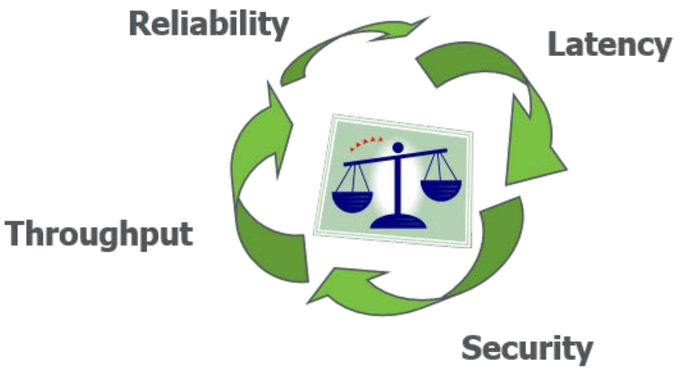
Objective

The objective of the project is to:

- Evaluate manufacturing requirements and design trade-offs for developing self-powered, and multi-sensor wireless platforms
- Manufacture prototypes, in collaboration with our partners, of wireless sensors using innovative manufacturing techniques;
- Evaluate performance of the prototypes and improve platform design to achieve cost-effective wireless sensors applicable to building requirements.

Advanced sensors and controls have the potential to save 20-30% energy consumed by buildings.





Target Market and Audience & Impact of the Project

Target Market and Audience:
- All residential and commercial buildings.
  - **Small and medium commercial buildings** – improved control of energy providing opportunity for 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.
- Near Term: Demonstrate end-to-end technology and identify path towards low-cost manufacturing through industrial partnerships
- Intermediate Term: Identify building equipment and automation manufacturing partner(s) for commercialization and deployment tailored to specific building applications
- Long Term: Demonstrate energy savings realized by widespread adoption of the low-cost sensors within buildings

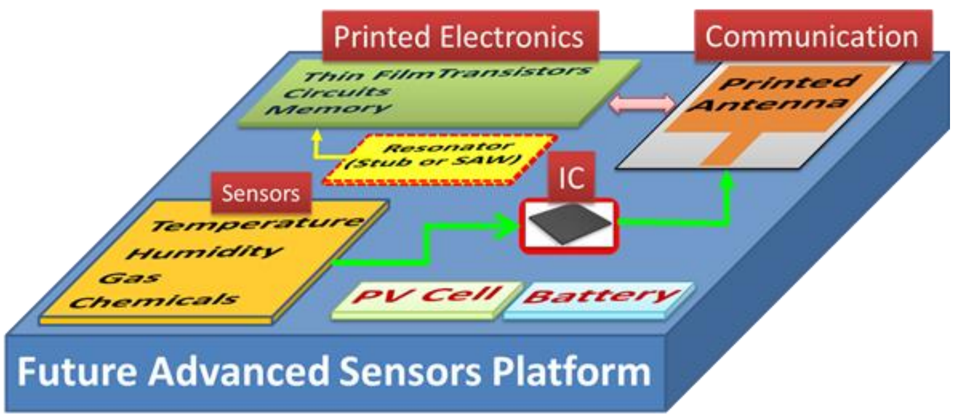
Impact on Buildings Technology: Advanced sensor, control technology brings big growth to building energy management market: $2.14 billion industry by 2020 (Lux Research)

Approach – Multifunctional Wireless Sensors

Multifunctional Sensor Platform

Current wireless sensor Platform: $150-$300/node

Proposed Advanced Sensors Platform: $1-$10/node



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**

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ORNL-Molex CRADA: Progress Path

FY14
- Laboratory Prototype Complete, **Patent Filed**
- **Identified CRADA Partner: Molex**

FY15
- **ORNL-Molex CRADA Negotiated**
- **Version 1 Prototype Manufactured by Partner**

FY16
- **Identify Requirements for Version 2 Prototype**
- Innovative Advances for Version 2 Prototype

FY17
- Develop Version 2 Prototype
- Partner with OEMs: Prototype Testing and Integration

Building Monitoring System Development

In Partnership with Molex

- 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

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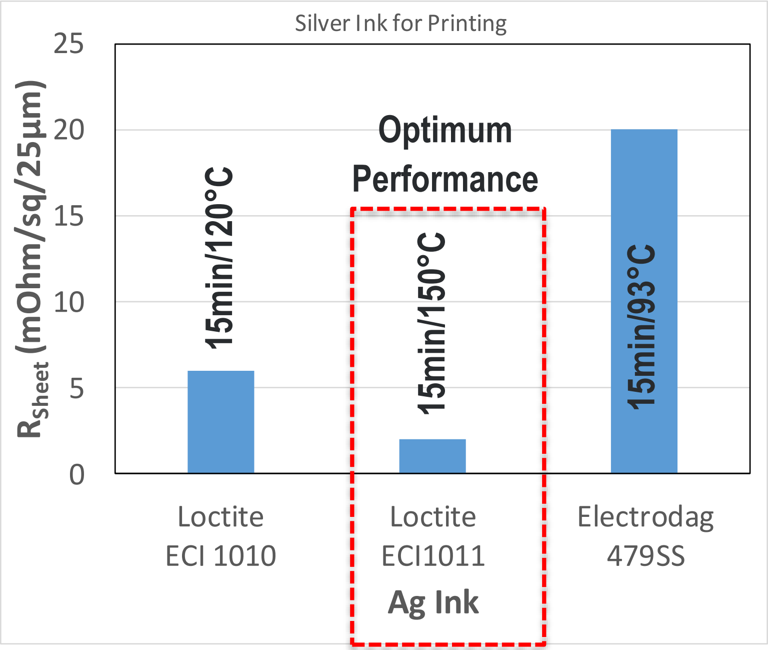
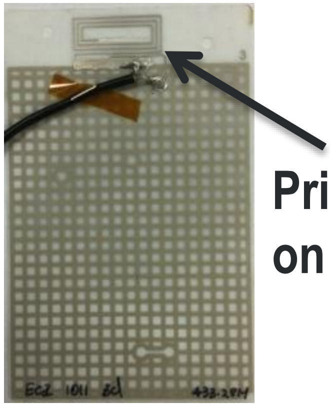
Printed Antenna: Ag DC Resistance Measurements

Performance Evaluation Matrix

- Terminal to Terminal (T-T) measurements
  (6 cavities x 4 samples x 3 inks)
- Terminal to End (T-E) of antenna measurements
  (2 cavities x 4 samples x 3 inks)
- The longest (cavity #1) and shortest (cavity #6) lengths measured



Ag Ink	T-T	T-E Longest Cavity	T-E Shortest Cavity
ECI 1011	1.1Ω	6.7Ω	3.3Ω
ECI 1010	2.6Ω	16.7Ω	9.3Ω
479SS	3.7Ω	25.4Ω	12.7Ω



Printed Antenna on PET Substrate

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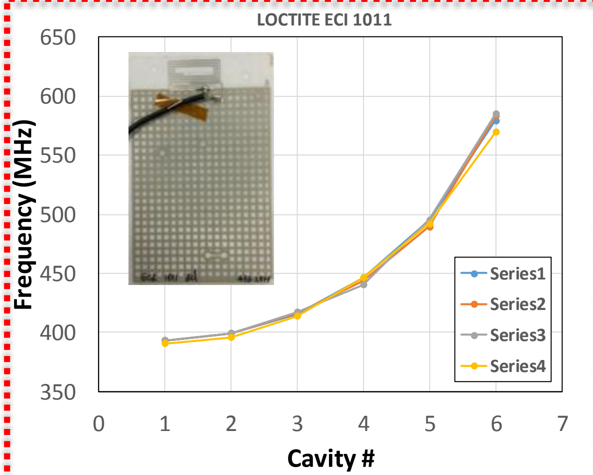
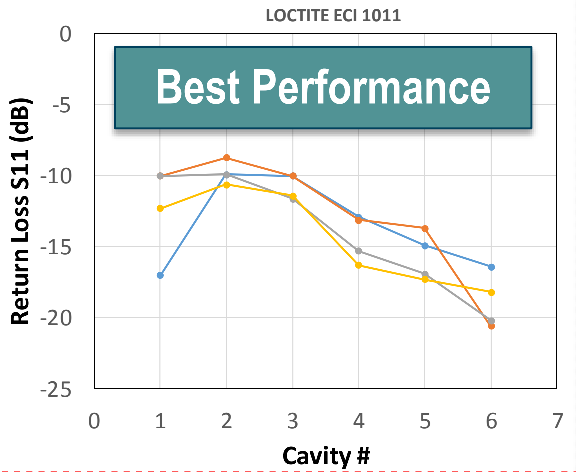
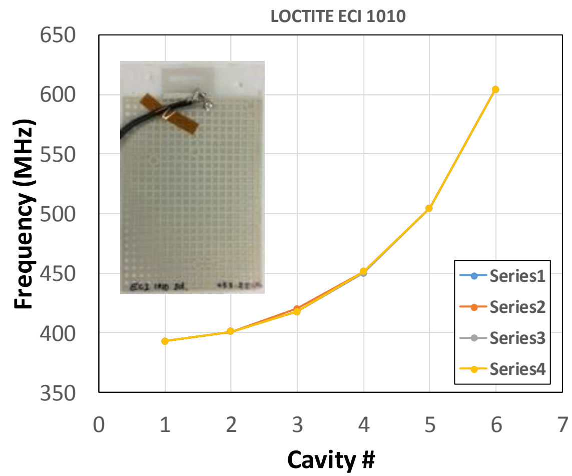
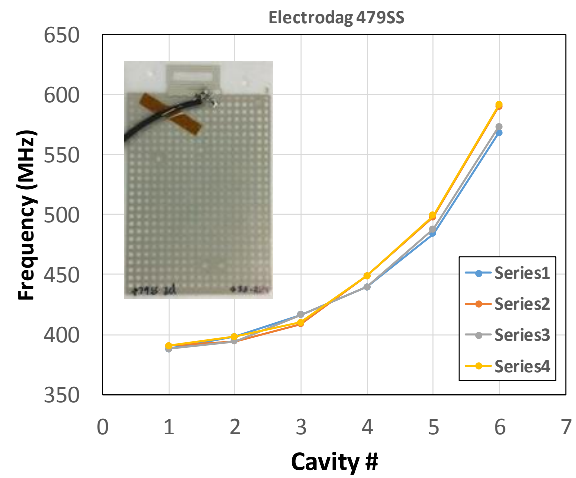
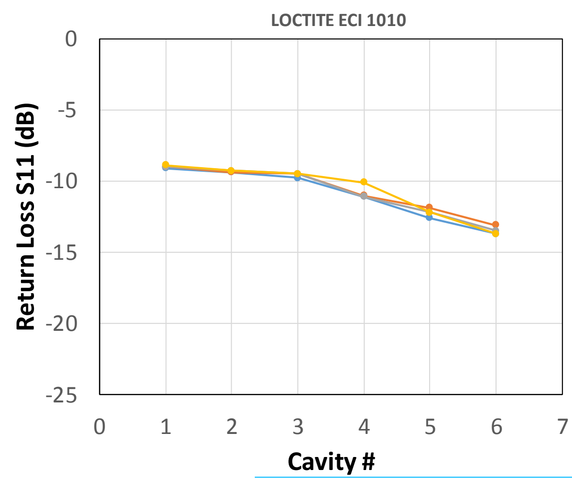
Printed Antenna: Resonant Frequency Measurement

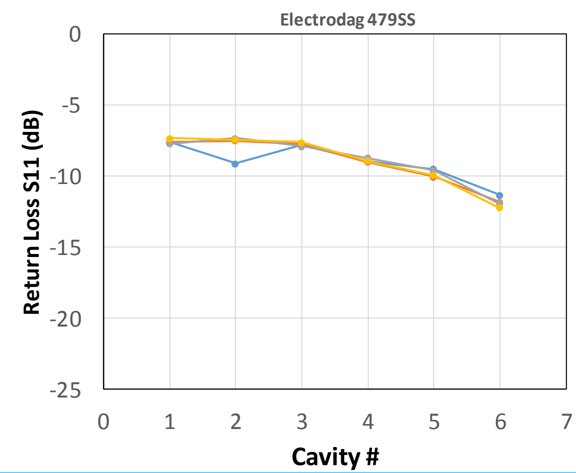












- For each antenna sample resonant frequency and return loss are measured
- The trim length is different for each ink –ink thickness, conductivity dependence

Based on Measurements: 3 samples trimmed (one for each ink) to resonate close to 433MHz

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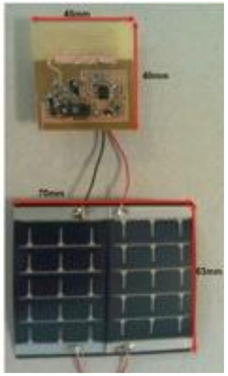
Building Monitoring System: Wireless Communication

COTS low-power wireless network	ORNL platform
~20-30mA per TX	~3-5mA per TX
2.4GHz, 10-100mW output power	433MHz, 1-5mW output power
Rx sensitivity: -95dBm	Rx sensitivity: -140dBm
Processing gain: ~9dB (16)	Processing gain: ~30dB (1023)
Range: 100-300m	Range: 1000-1500m
Bi-directional communication (TX-RX)	Uni-directional communication (TX)

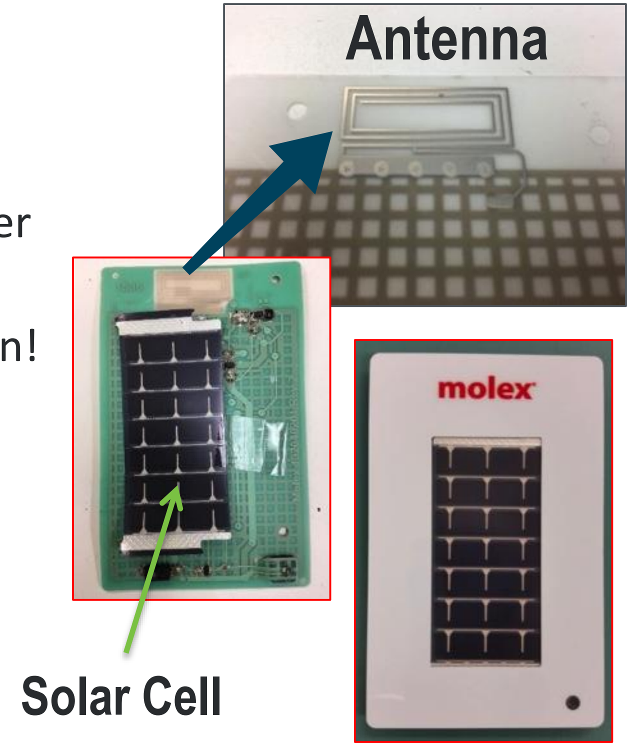
- Spread Spectrum length of 1023 bits to deliver the 20 bits (51:1 expansion) – 30dB Gain
- 1 W performance from a 1 mW transmitter: Smaller battery, low current operation
- Theoretically accommodates more than a million simultaneous transmitters: “orthogonal” shifted Gold codes
- CDMA techniques can allow simultaneous usage to recover most of the expanded bandwidth



Building Monitoring System

Distinctive Characteristics: Integrated System

- Operational after one hour of charge
- 3 days operation on a single charge broadcasting once per minute in the dark
- Broadcasting once every 15 minutes → 40 days operation!
- 9.5 hours to completely charge the battery
- Current consumption of Tx – 10 mA (time: 1 second)
- Light sensor configured for on/off reporting
- Ongoing work to test temperature and humidity sensors



Addressing Key Issues

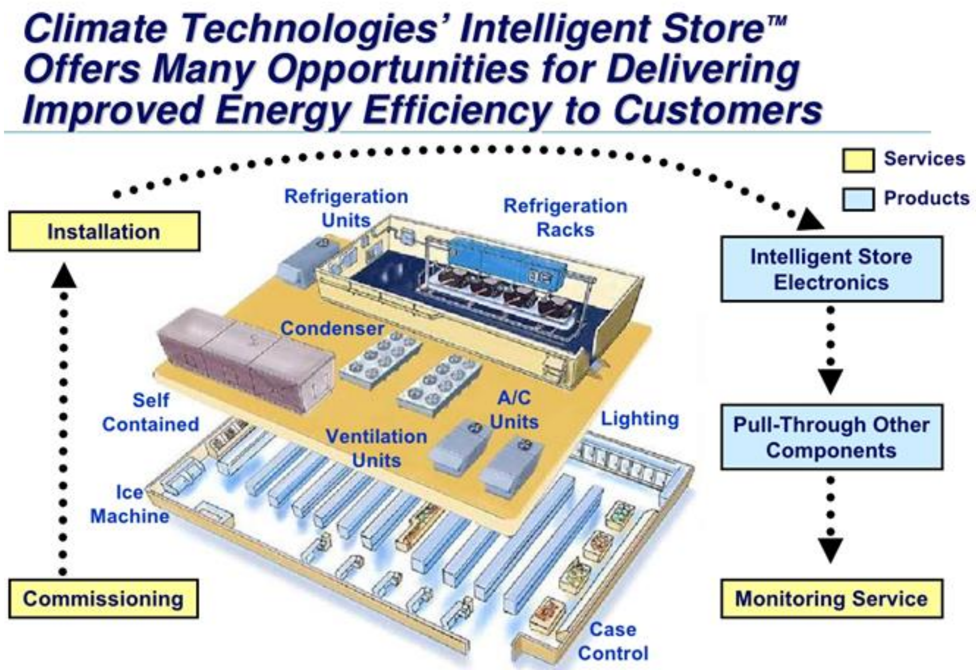
- Improve communication performance: reduce networking infrastructure, scalability.
- Increased co-integration: high-resolution printing approaches on flexible substrates.
- Investigate integration of other sensors of interest including indoor air quality sensors.
- Integration of energy harvesting and storage components.
- Working with building equipment and/or building automation manufacturer(s) to identify application specific requirements.

Working with Building Equipment Manufacturer

Emerson Climate Technologies interested in the wireless sensors

- Sensors for monitoring refrigeration equipment and ambient conditions
- Requirements have to drafted
  - High humidity levels
  - Temperature limitations
- Interest in beta testing in a store 8-10 months
- Reliability and ease of installation – high priority

Need a very simple and easy solution to monitor the temperature in a refrigeration case



Drivers for Success

Low initial cost

– $1 +/- per sensors which would be great (Including the gateway and any networking cost (Total: $10-15)

Lifecycle costs

– Past experience - battery life and availability were limiting (Specs: >1 Year, Lasted: 6-8 months)

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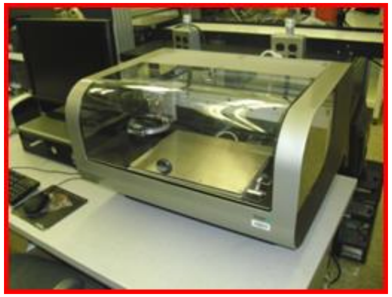
Printing and Low Temperature Curing

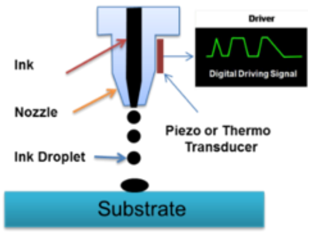
Inkjet Printing

Printing Challenges:
- Resolution
- Process tolerance
- Defect density
- Printing yield

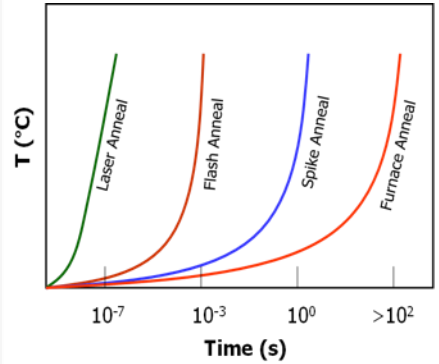
Line Width and Spacing Control
- **Our Target:** down to 100µm

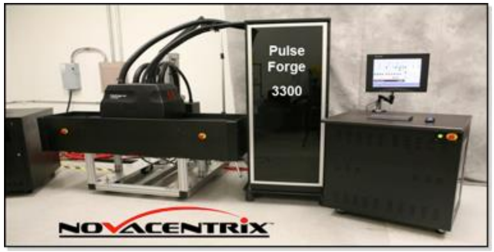
Piezoelectric Head





Curing: Pulse Thermal Processing



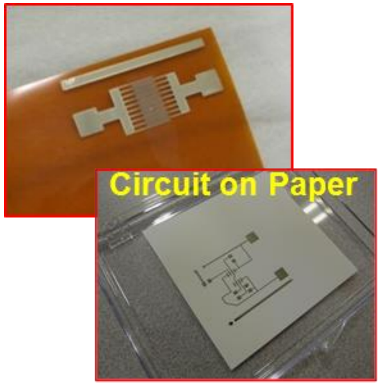


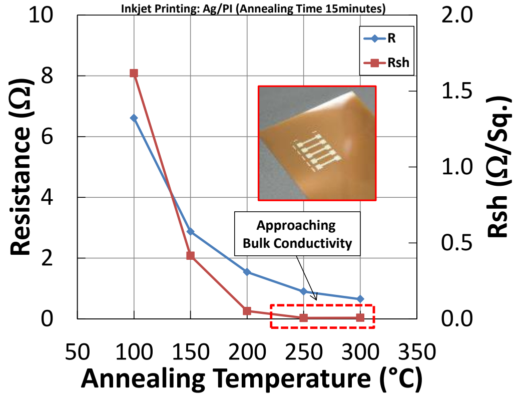
Power Density: $>20KW/cm^2$
Process Window: µs-milliseconds-continuous

Molex: Integrated Manufacturing

Naperville, Illinois, USA
- Mid range volume manufacturing
- Flat bed printing
- Local design support
- Final Assembly
- 60,000 sq ft
- ISO 9000, ISO14000

Printed Metal





Conductivity approaches the Bulk value

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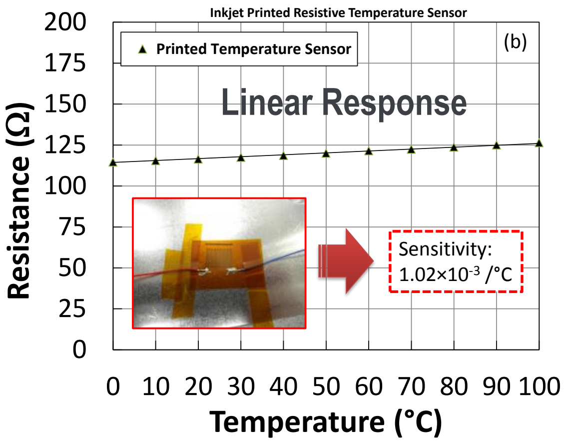
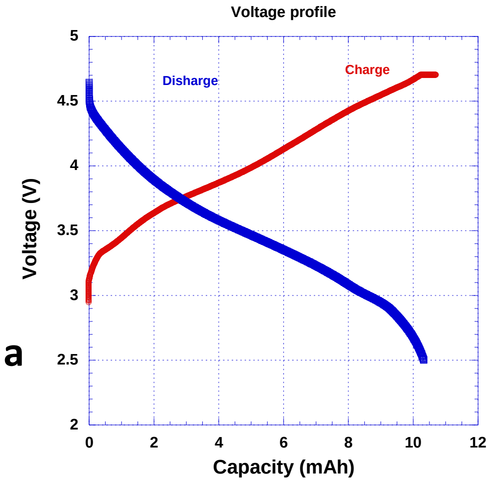
Flexible Electronics: Sensor and Device Development

Temperature Sensor



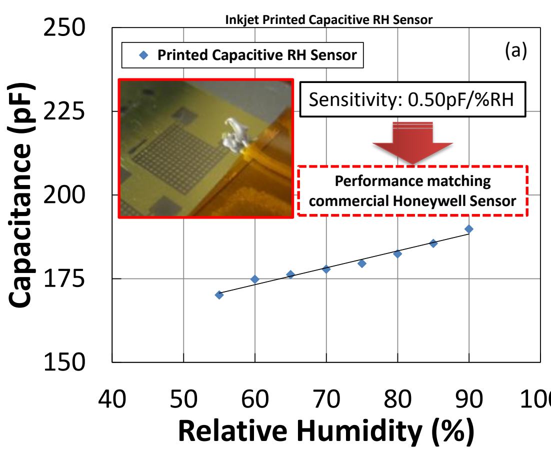
- **Resistance can be controlled by Line Definition control: No mask redesign step**

Small Form Factor Battery



- **The pouch cell offers a simple, flexible and lightweight solution to battery design.**

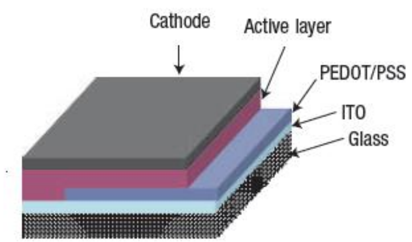
Humidity Sensor

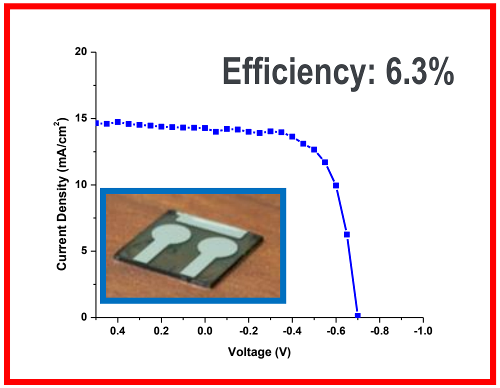


- **Mesh Electrode**: Additive Integration eliminates masking, photo, and etch steps

Organic Photovoltaic Device

Path towards peel-and-stick wireless sensors that are self-powered





- **Efficient energy harvesting solutions required**

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Progress and Accomplishments

Accomplishments:

- Successfully demonstrated commercially produced self-powered wireless sensors through manufacturing partner Molex
- 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
- Experimental data collected to demonstrate adequate performance for buildings applications
- Path towards integration of additional sensors (IAQ, Occupancy) into the platform

Market Impact:

- Reduce the cost barrier to deploying advanced sensors and controls to optimize energy usage (improve by 20-30%) with in buildings.
- 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.

Awards/Recognition: Patent pending.

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

Project Integration and Collaboration & Next Steps

Project Integration: The project is led by ORNL and the team includes experts from wireless networks, materials processing, battery manufacturing, and buildings technology. ORNL team is collaborating with Molex - flexible circuits manufacturer and Emerson – building equipment manufacturer

Partners, Subcontractors, and Collaborators: The project team is working with Molex, Inc. to manufacture low-cost wireless sensor platform using automated component placing and low-temperature soldering, co-integration of energy harvesting and storage components on flexible substrates. Emerson Climate Technologies has developed use cases with building requirements.

Communications: The work is presented at ISA, IEEE and AVS forums. Several publications are currently underway to disseminate the results

Next Steps and Future Plans: The next steps and future project activities include:

- Work with partner, Molex, on Version 2 prototypes tailored to building equipment manufacturer requirements
- Integrate super capacitors into energy storage solution to improve performance and reduce cost
- Improve communication design to improve sensitivity
- Integrated system design to reduce circuit complexity and manufacturing requirements
- Innovative flexible electronics manufacturing approaches to reduce cost

REFERENCE SLIDES

Project Budget

Project Budget: $250K (FY15), $380K (FY16), $245K (FY17)
Variances: None
Cost to Date: $165K
Additional Funding: None

Budget History					
FY 2015 (past)		FY 2016 (current)		FY 2017 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$250K	$300K	$380K	$300K	$245K	$275K

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Project Plan and Schedule

Project Schedule												
Project Start: 10/1/2015		Completed Work										
Projected End: 9/30/2017		Active Task (in progress work)										
		Milestone/Deliverable (Originally Planned) use for missed milestones										
		Milestone/Deliverable (Actual) use when met on time										
	FY2016				FY2017				FY2018			
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												
Q1 Milestone: Complete baseline testing and report results. The testing will include communication performance (receiver sensitivity, signal to noise ratio, and packet error rate) and sensor accuracy (temperature, relative humidity, and light level)												
Q2 Milestone: Complete design description document for Version 2. The document details the technical and manufacturing decisions to achieve the required performance specification as described in Task 2.												
Current/Future Work												
Q4 Milestone: Integrate requirements from commercial partner for a specific buildings application. Discussions are held with two major equipment manufacturers who have expressed interest and will be pursued in FY16.												
Q1 Milestone: Draft description of design tradeoffs for Version 2												