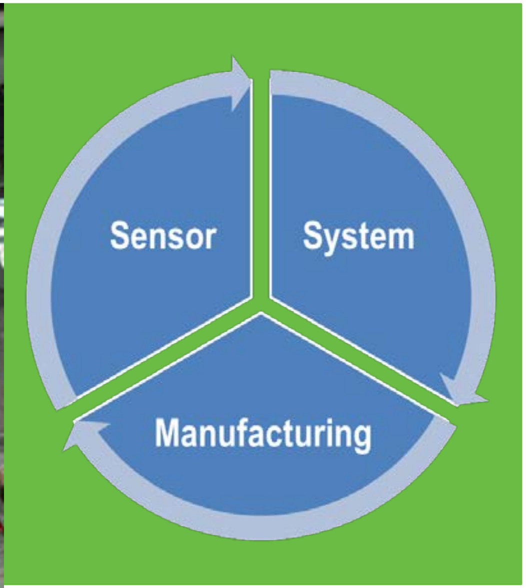
U.S. DEPARTMENT OF
ENERGY
Office of
ENERGY EFFICIENCY &
RENEWABLE ENERGY

Peel & Stick Sensor for Refrigerant Leak Detection



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Project Summary

Timeline:

Start date: 10/01/2017

Planned end date: 09/30/2018

Key Milestones

1. Develop metal oxide and 2D/3D nanomaterial coatings on flexible substrates; 03/31/2018
2. Evaluate sensing characteristics for flammable refrigerants; 09/30/2018

Budget:

Total Project $ to Date:

- DOE: $36,409

Total Project $:

- DOE: $100,000

Key Partners:

Danfoss

Project Outcome:

The project aims to develop a low-cost refrigerant sensor through a combination of direct-write printing and pulse thermal photonic processing to overcome thermal barriers for plastic integration

Direct-write printing of low-cost refrigerant senosrs employing high throughput, roll-to-roll manufacturing techniques will define a path towards direct and continuous monitoring of refrigerant leakage.

Team

Dr. Pooran Joshi: Focus on development of direct-write sensors, and low-temperature material and device integration on low-cost substrates. Over 20 years of R&D experience on advanced thin films, sensors and devices.

Dr. Vishaldeep Sharma: Current research focus is in the area of commercial refrigeration, with a primary focus on the design and evaluation of carbon dioxide refrigeration systems. Research interests include commercial air-conditioning and refrigeration, energy audits and green roofs.

Dr. Brian Fricke: Over nearly eight years of active involvement in the assessment and evaluation of low global warming potential (GWP) refrigerants in commercial refrigeration systems.

Dr. Ayyoub Momen: Extensive experience and expertise in thermal fluid sciences, magnetocaloric refrigeration, energy storage, and high-temperature thermochemical conversion.

Dr. Teja Kuruganti: Over 14 years of experience in wireless communications and sensor development and deployment. He manages ORNL's buildings-related sensors, controls, and transactive energy research.

Challenge

Problem Statement

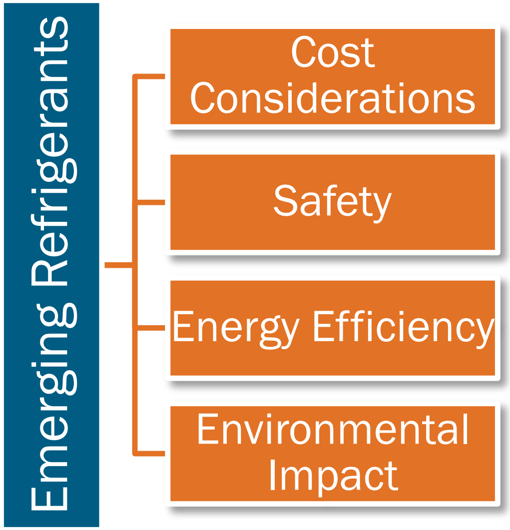
Chlorine free refrigerants

- **F-Based, HC refrigerants**
  - Non-toxic, but highly flammable (2-10% in air)
  - R134a: ODP=0, GWP=1430
  - Projected global warming impact: 7.9% (2050)
- **Ammonia as refrigerant**
  - Environmentally friendly: ODP=0, GWP <1
  - Toxic: Poisonous in high concentration (>100ppm)
  - Flammable between 16-25% by volume

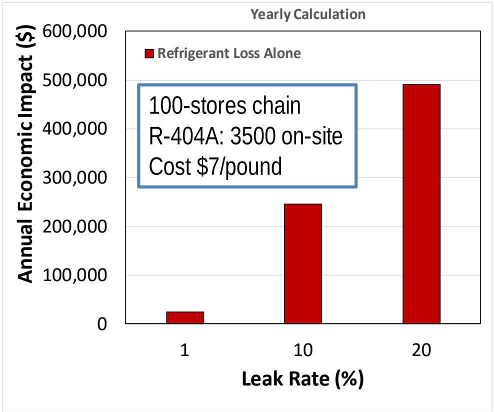
Anthropogenic activity

- Refrigerant leakage is the most frequent fault in a refrigeration system.
- Annual leakage in commercial refrigeration systems can vary from an average of 11% up to 30% in some cases.

Refrigerant Gas Detection



Early Detection: Crucial



Advanced sensors and controls critical to addressing the issue

Path to Success

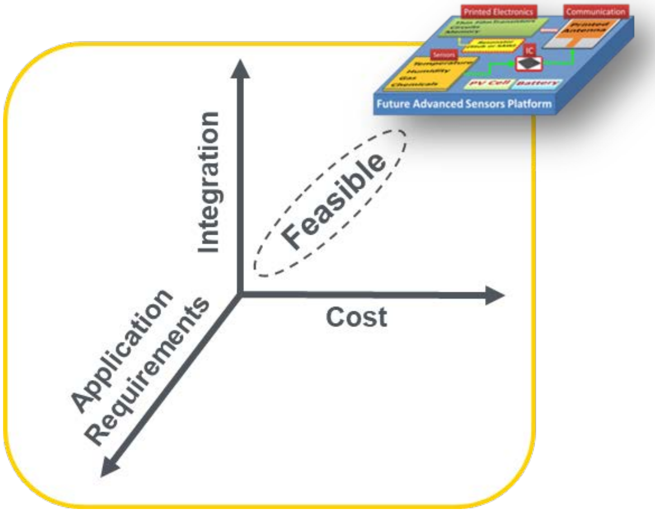
Address Refrigerant Leak Detection Issue:

Both commercial and residential applications

- Inertia in use of energy efficient toxic and/or flammable refrigerants.
- Currently, sensors used to prevent a potential combustible event.

Refrigerant Sensor Development

- Sensitivity/selectivity
- Response time
- Reliability
- System integration
- Cost



Low-cost sensors required to address health, safety, environmental, and financial issues associated with current and emerging environmentally friendly refrigerants.

Technology Space

Sensor Technologies for Refrigerant Applications

Sensor	Range (ppm)	Response Time (s)	Operating T (°C)	Lifetime (years)	Cost
Infrared (PIR/NDIR)	0 -10,000	5 - 300	-40 - 75	5 - 15	$300-$12,000
Electrochemical Cell	0 – 1,000	<90	-20 - 50	1 - 3	$250 - $1,600
Metal-oxide-semciconductor	20 – 10,000	15 - 90	-34 - 170	3 - 5	$500 - $1,300
Catalytic	0 – 1,000	20 - 30	40 - 150	2 - 5	$700 - $1,500
Heated Diode	<0.1 – 6.6oz/yr	0.5 – 1	-20 - 50	2 - 3	$100 - $500
Virtual Sensor	Indirect estimation based on algorithm; No leak measurement				

* AHTRI Report No. 9009

Opportunity

- Conducting polymers show promise for electrochemical detection of ammonia.
- Low-cost, small-footprint MOS sensors suitable for refrigerant monitoring in residential environment.

Approach

Direct-write printed sensor development

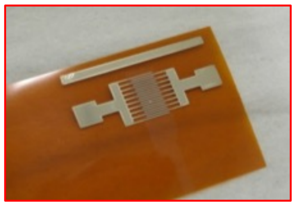
- Develop process for conductive polyaniline nanoparticle (PANI) printing.
- Evaluate coating quality and material characteristics.
- Develop process and evaluate the impact of 2D materials (CNT and RGO) on sensor performance.
  - Main focus: Ammonia sensitivity, selectivity, and reliability characteristics.

Metal oxide sensor development

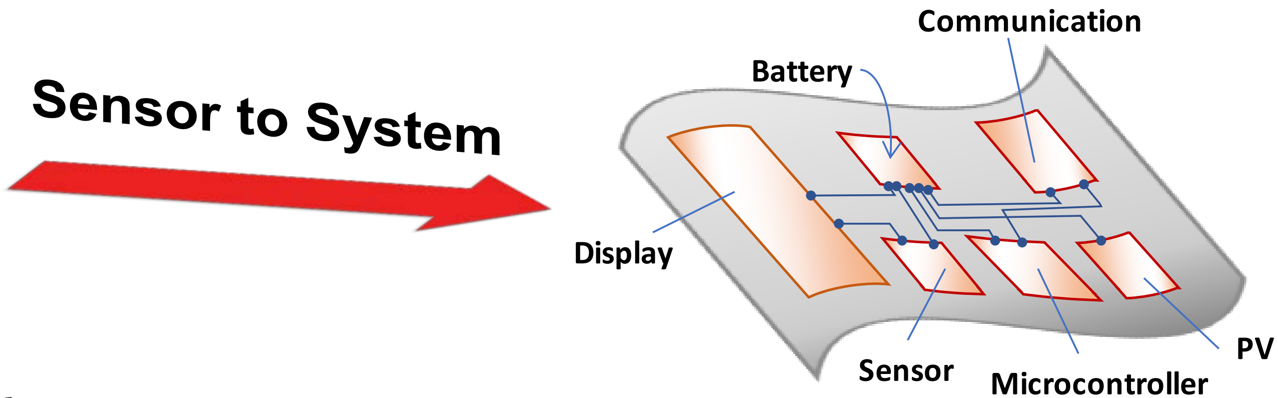
- Low-temperature pulse thermal processing of thin film on low-cost plastic substrate.
- IDE development for resistive sensor configuration.
- Binary metal oxide printing: Focus on metal oxide (ZnO).
  - Main focus: Evaluate material performance for F-sensor applications.

Impact

Sensor → Signal → Control → Actuation



Focus



Low-cost refrigerant sensor

- Enable high penetration of environmentally friendly refrigerants.
- Sensitivity, selectivity, and power consumption will dictate synergistic integration on multifunctional sensor platform.
- Low-cost critical for widespread deployment sensor in areas where refrigerant from a leak will concentrate.
- Low-power operation critical for sensor connectivity with low-cost, low-power IoT platform.

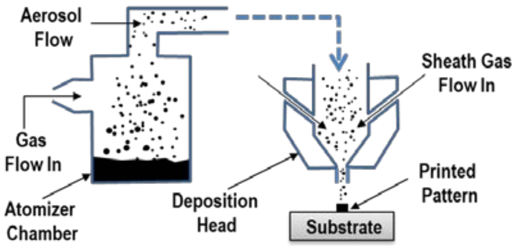
Enabling Capabilities

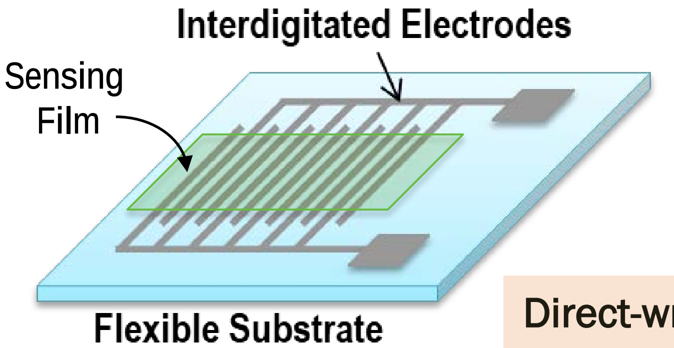
Direct-write Inkjet Printing

Printing challenges:
- resolution
- process tolerance
- defect density
- printing yield

Line width/spacing control
- Down to 10μm

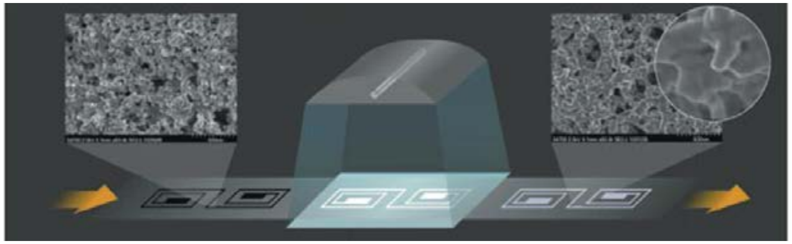
Aerosol Jet Printing



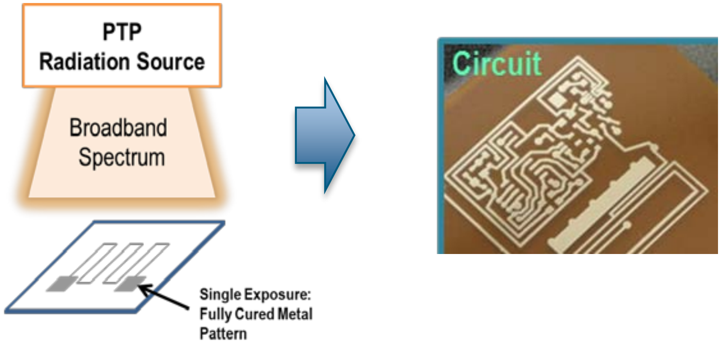


Direct-write printing of sensing and contact layers

R2R compatible thermal processing curing: Pulse thermal processing



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



- Additive integration on paper, plastic, ceramic, and rubber.

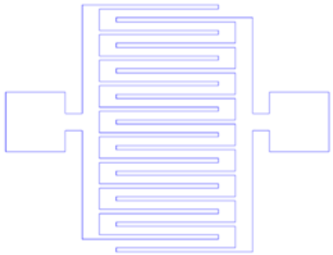
Preliminary Results

Project phase: Early stage research

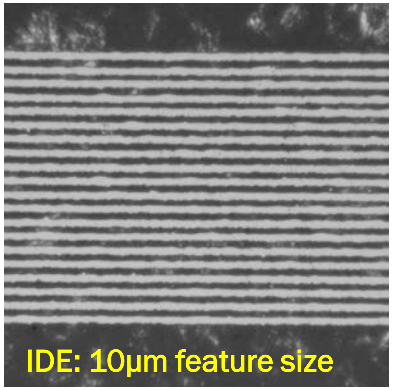
Printing of IDE and resistive element

Ag Ink Source	Loading (wt.%)
MicroPE PG-007	> 60
Clariant PRELECT TPS 50	> 60

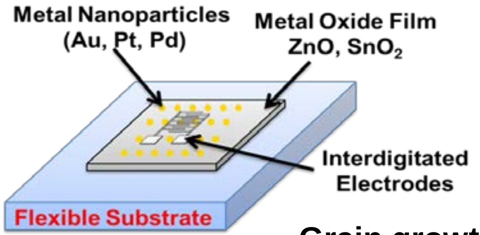
AutoCAD Design

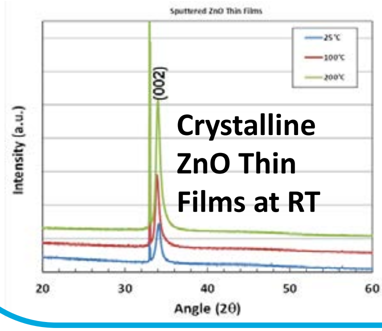


Printed Ag metal line

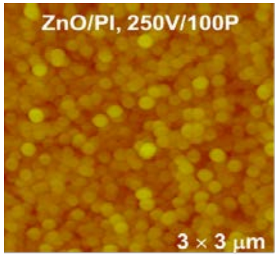


Metal oxide films on flex

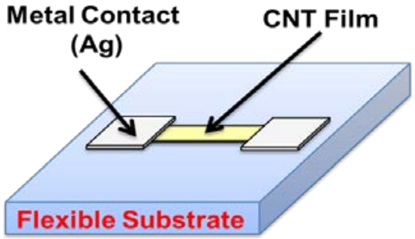


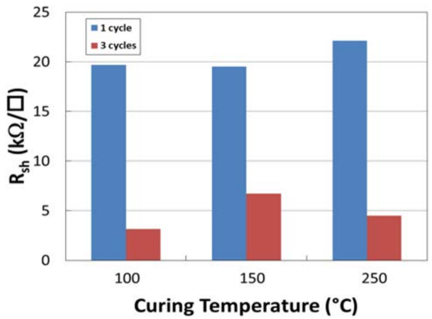


Grain growth by photonic curing



CNT Printing





Stakeholder Engagement

Danfoss has shown interest in working with ORNL on refrigerant sensors.

Air-Conditioning, Heating and Refrigeration Technology Institute, Inc. (AHRTI) interested in the project.

– AHRTI has identified refrigerant sensors as one of their top research priorities.

Remaining Project Work

- Evaluate sensor, materials, substrate, and process space
- Develop PANI ink
- Direct-write metal oxide
- Evaluate sensor sensitivity/selectivity
- Impact of 2D materials

Oct	Nov	Dec	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep

- Develop metal oxide and 2D/3D nanomaterial coatings on flexible substrates.
- Evaluate sensing characteristics for flammable refrigerants.

Thank You

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REFERENCE SLIDES

Project Budget

Project Budget: $100K
Variances:
Cost to Date: $2K
Additional Funding:

Budget History					
FY 2017 (past)		FY 2018 (current)		FY 2019 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
		$36K			

Project Plan and Schedule

Project Schedule		
Project Start: 10/01/2017	(light blue)	Completed Work
Projected End: 09/30/2018	(dark blue)	Active Task (in progress work)
	◆ (red)	Milestone/Deliverable (Originally Planned) use for missed
	◆ (black)	Milestone/Deliverable (Actual) use when met on time

	FY2018				FY2019				FY2020			
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)
Current/Future Work												
Q2 Milestone: Develop metal oxide and nanomaterial coatings on flexible substrates	Completed	Completed ◆										
Q4 Milestone: Evaluate sensor characteristics for flammable refrigerants			Active	Active ◆								