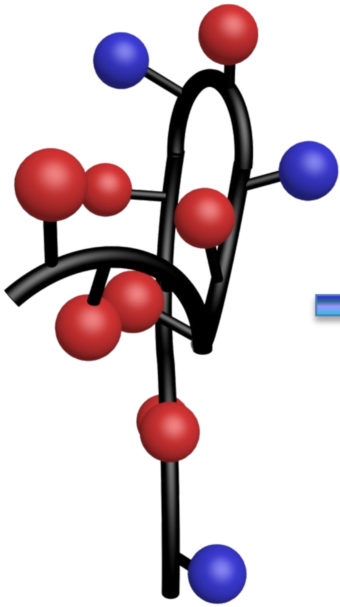
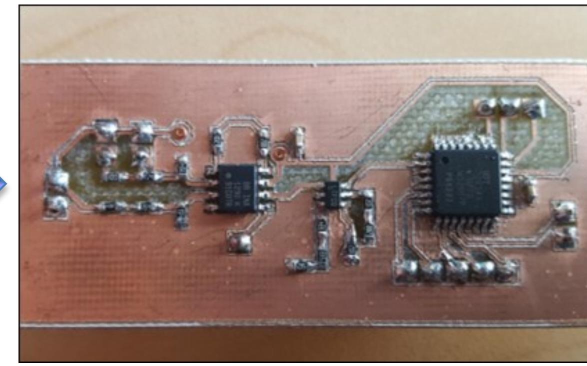
Low-Power, Low-cost Gas Sensors with Highly Specific Chemical Responses





Bryan W. Boudouris

Davidson School of Chemical Engineering and Department of Chemistry

Purdue University

2020 Fall P2SAC Virtual Conference

General Process Safety and Assurance

Monday, December 7, 2020

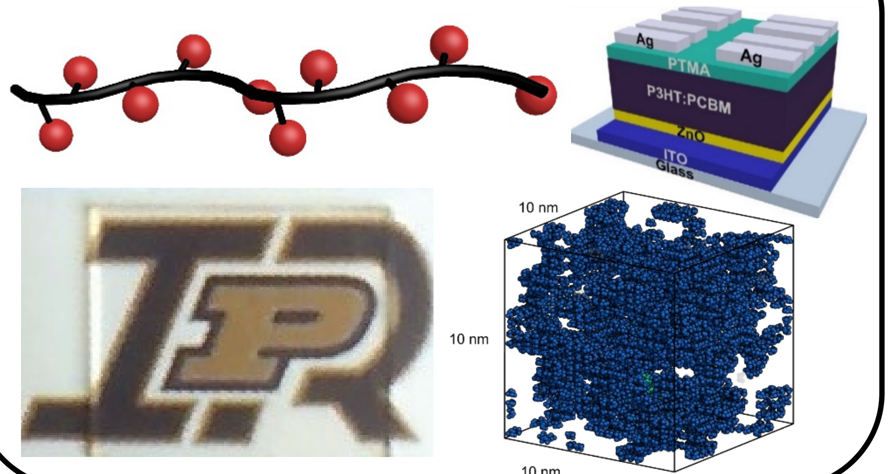
Email: boudouris@purdue.edu; Twitter: @Boudouris_Group

PURDUE ENGINEERING

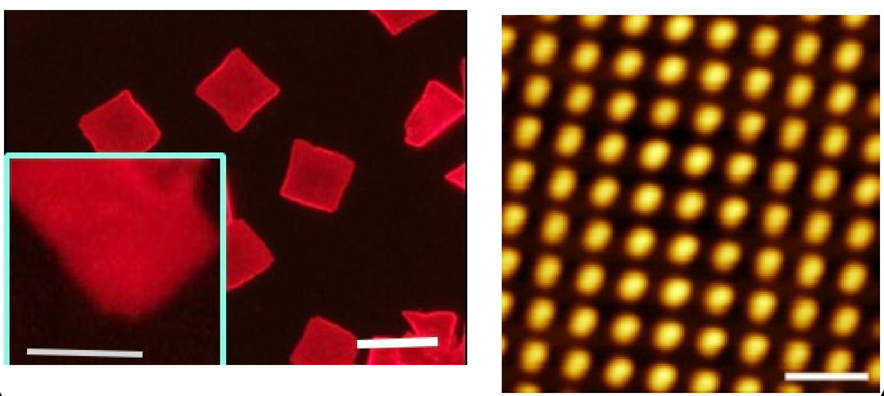
Functional Polymers for Energy, Water, and Electronic Solutions

Electronically-active Polymers

Transparent, Conducting Polymers



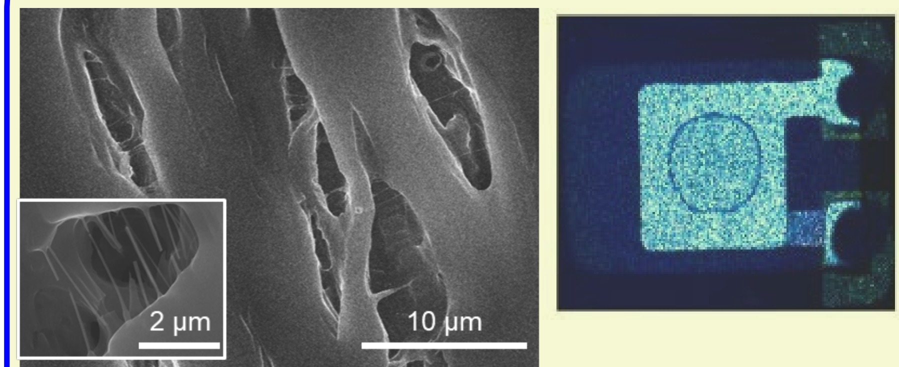
Thermoelectric and Ferroelectric Devices And 2D Hybrid Materials



Interfacial Control is Key to Device Performance

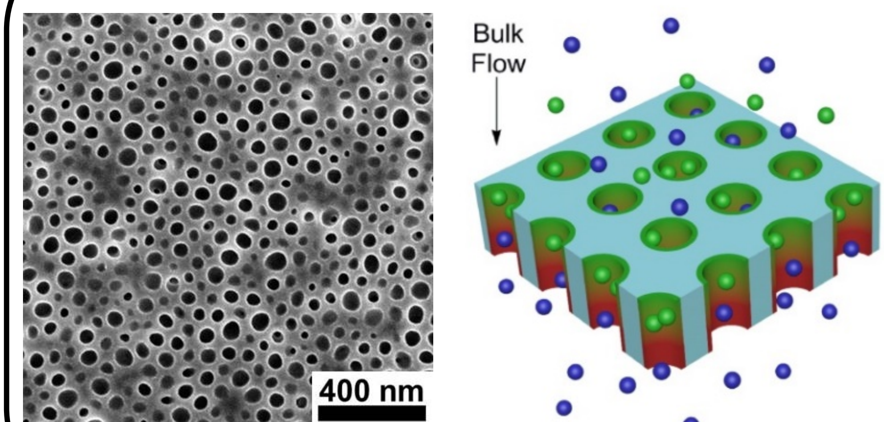
Interfacial Interactions in Soft Materials

Printable Functional Polymer Blends



Development of Polymers and Polymer Blends for High Sensitivity Air Quality Monitors

Water Purification Membranes

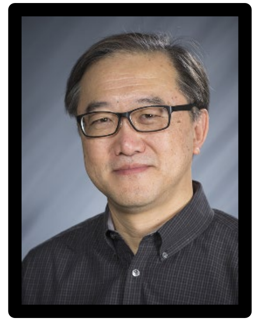


Size ***AND*** Chemical Selection Criteria

Multi-disciplinary Team with Complementary Expertise

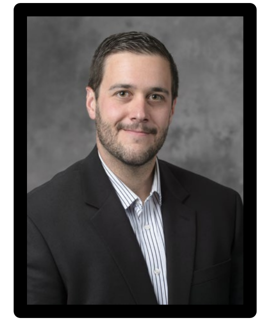
- Jim Braun
  - Building Systems

- Jeff Rhoads
  - Sensor Development



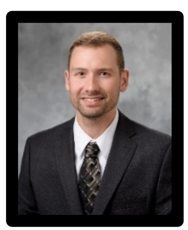
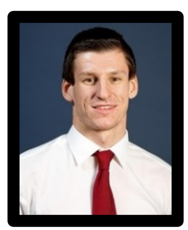
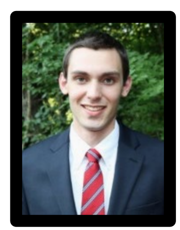
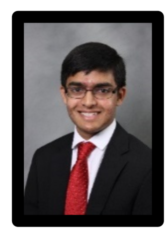
- George Chiu
  - Mechatronics and Hardware Integration

- Bryan Boudouris
  - Functional Chemistries



- Will Buchanan
  - T2M Support and Business Development



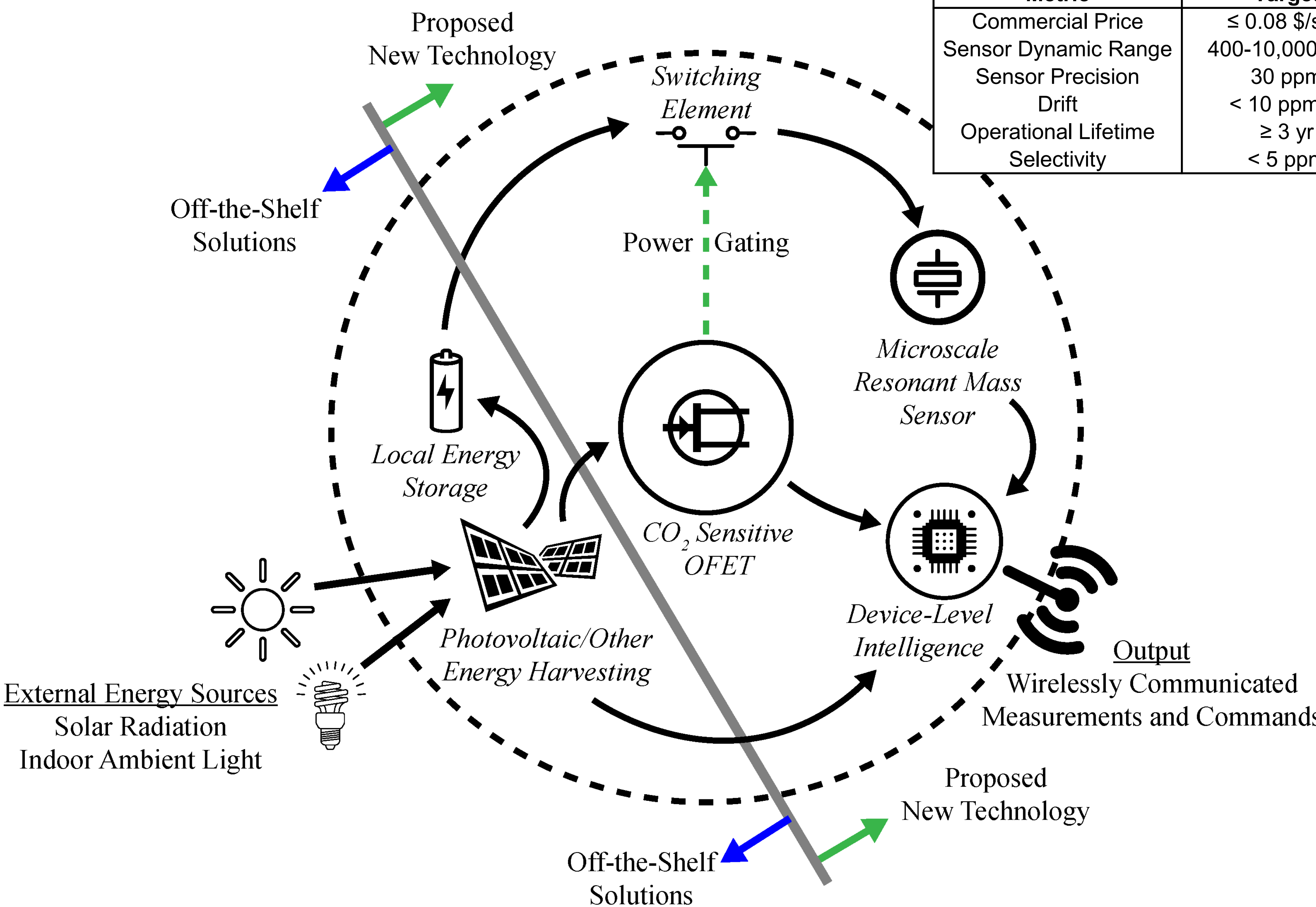








Post-Doctoral Research Associate: Xikang (Po) Zhao (ChemE); Nikhil Bajaj (ME); *Allison Murray (ME)*
Graduate Students: **Zachary Siefker (ME)**; *Allison Murray (ME)*; **John Hodul (Chem); Joe Meseke (ME); Nikhil Carneiro (ME)**
Undergraduate Research Assistant: **Abhi Boyina (ME)**; **<u>Eugenio Frias Miranda (ME)</u>**; Nikhil Carneiro (ME); Katie Mao (ME); Joshua Jenkins (ME)

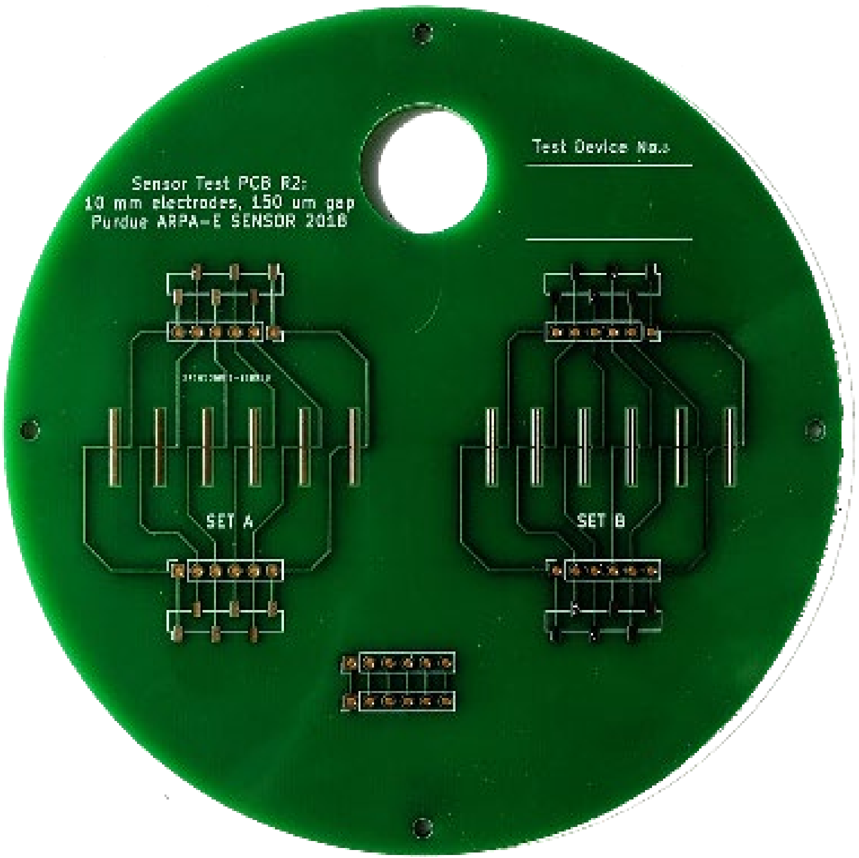
Our Approach: Dual-Hierarchical Sensing

Metric	Target
Commercial Price	≤ 0.08 $/sqft
Sensor Dynamic Range	400-10,000 ppm
Sensor Precision	30 ppm
Drift	< 10 ppm/yr
Operational Lifetime	≥ 3 yr
Selectivity	< 5 ppm

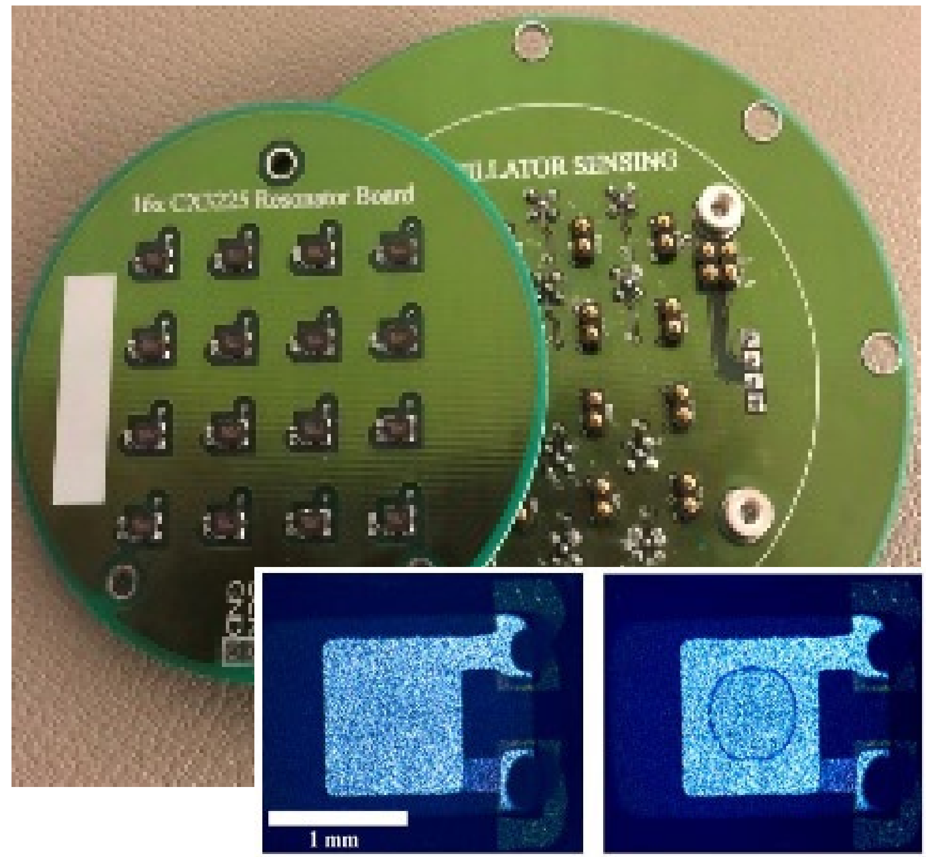


Both Sensors Use Small Amounts of Polymer Blend Inks

Low-Power Chemiresistive Sensor



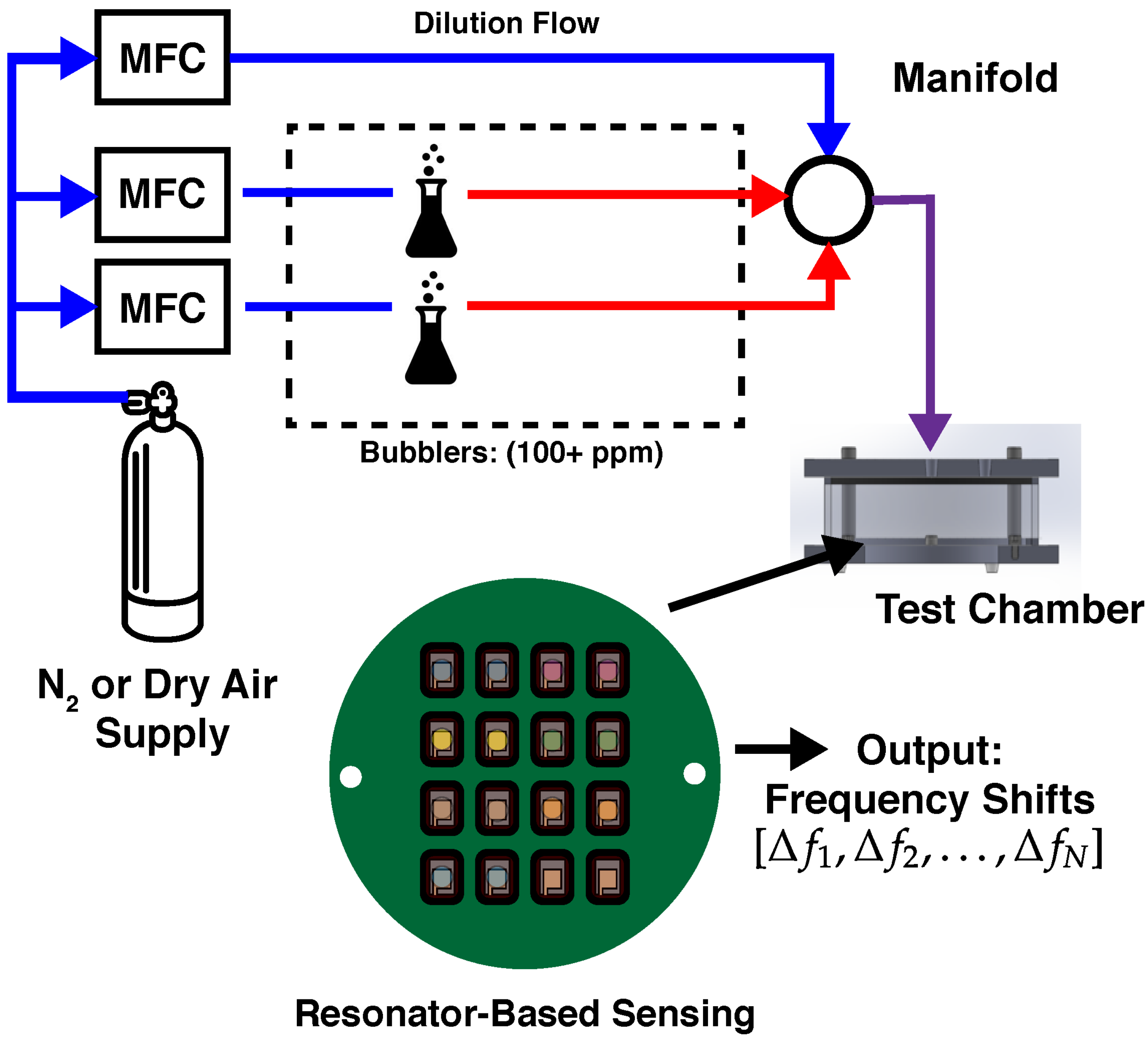
High-Resolution MEMS Sensor



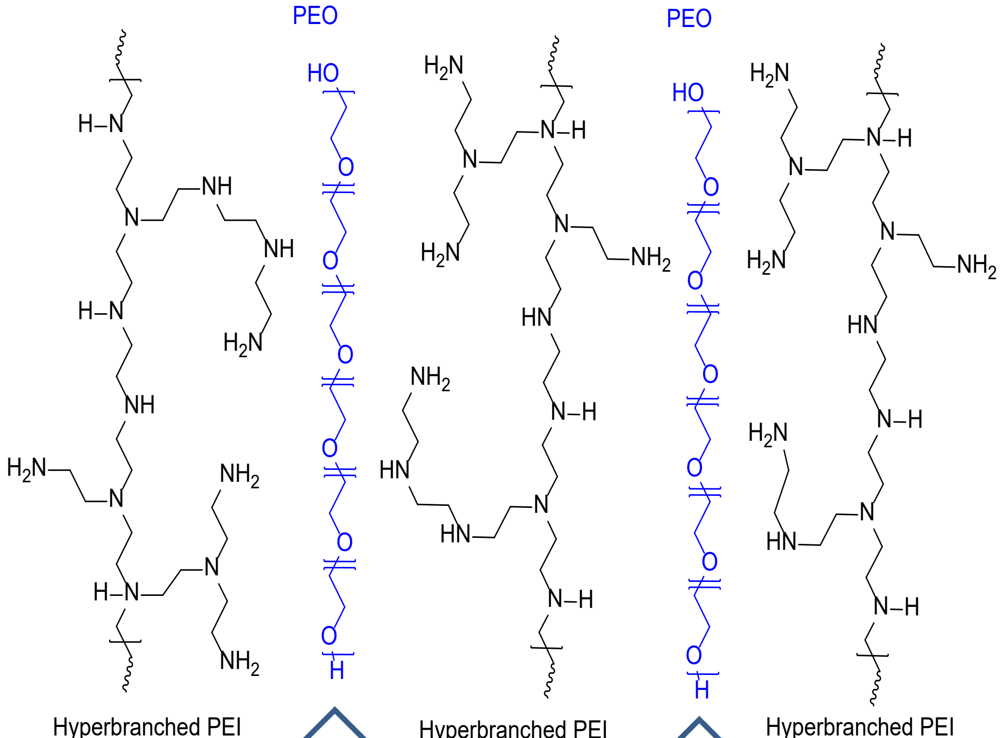
- Both sensors functionalized with the same polymer blend such that CO_2 uptake is the same between the two modalities.

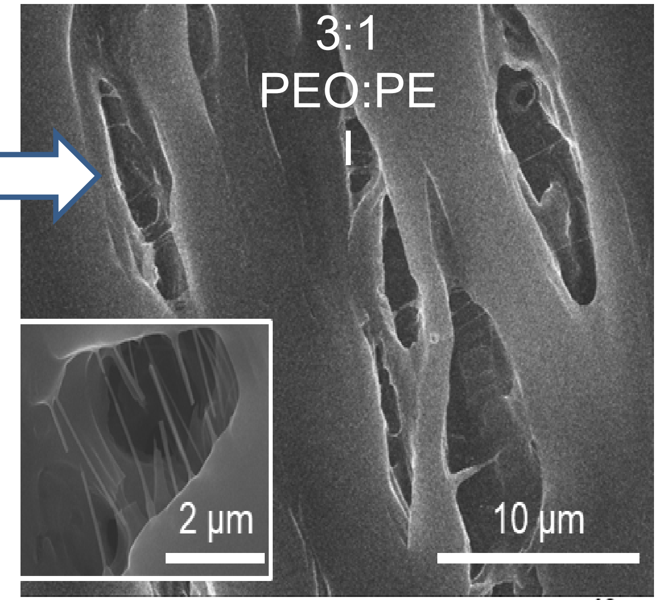
- The chemiresistive sensor has carbon nanotubes in the composite for electrical readout.

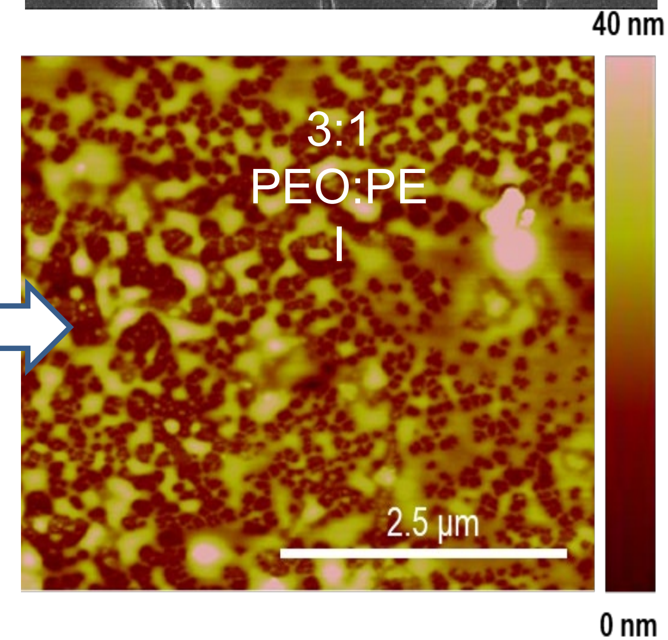
Our Approach: Dual-Hierarchical Sensing



PEO Macromolecular Structure Allows for PEI to Adsorb CO_2





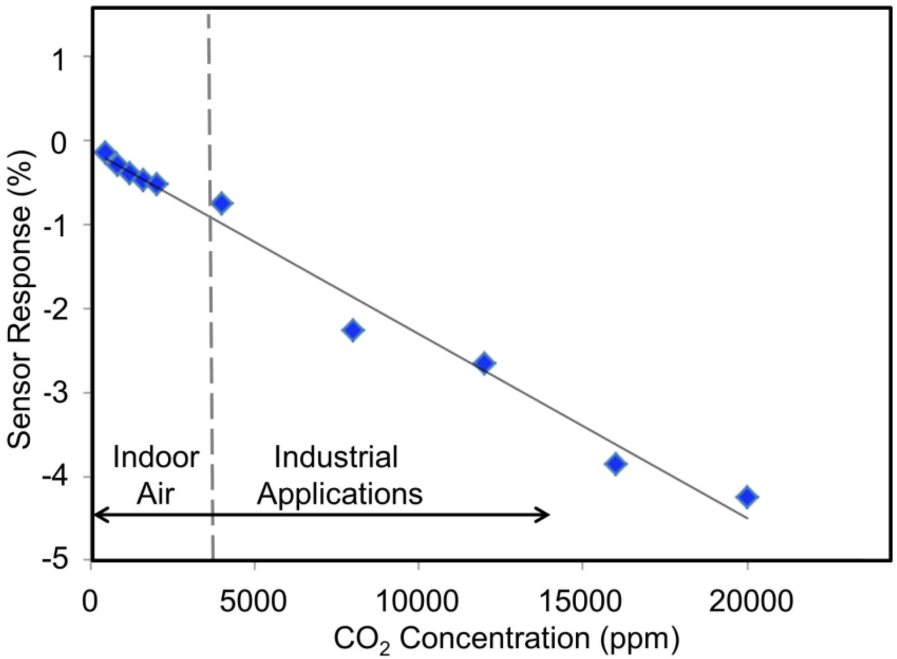


- Semicrystalline PEO when blended in amorphous hyperbranched PEI allows for more overall order in the polymer matrix.

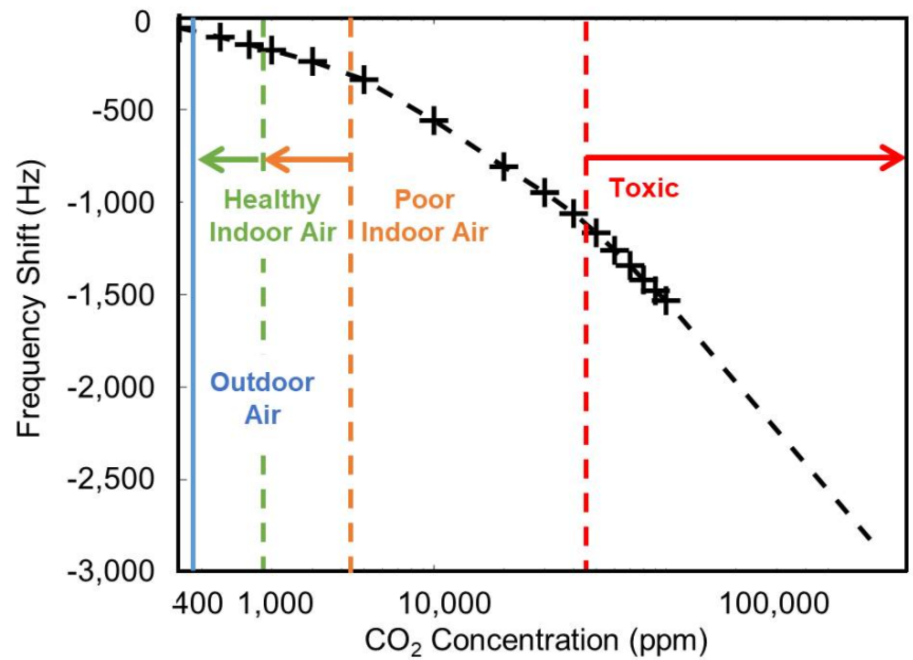
- Less hyperbranched amines = More amines to interact with CO_2 and More pockets for CO_2 to adsorb into the material

Both Sensors Show Clear Response Across a Wide Range

Low-Power Chemiresistive Sensor



High-Resolution MEMS Sensor

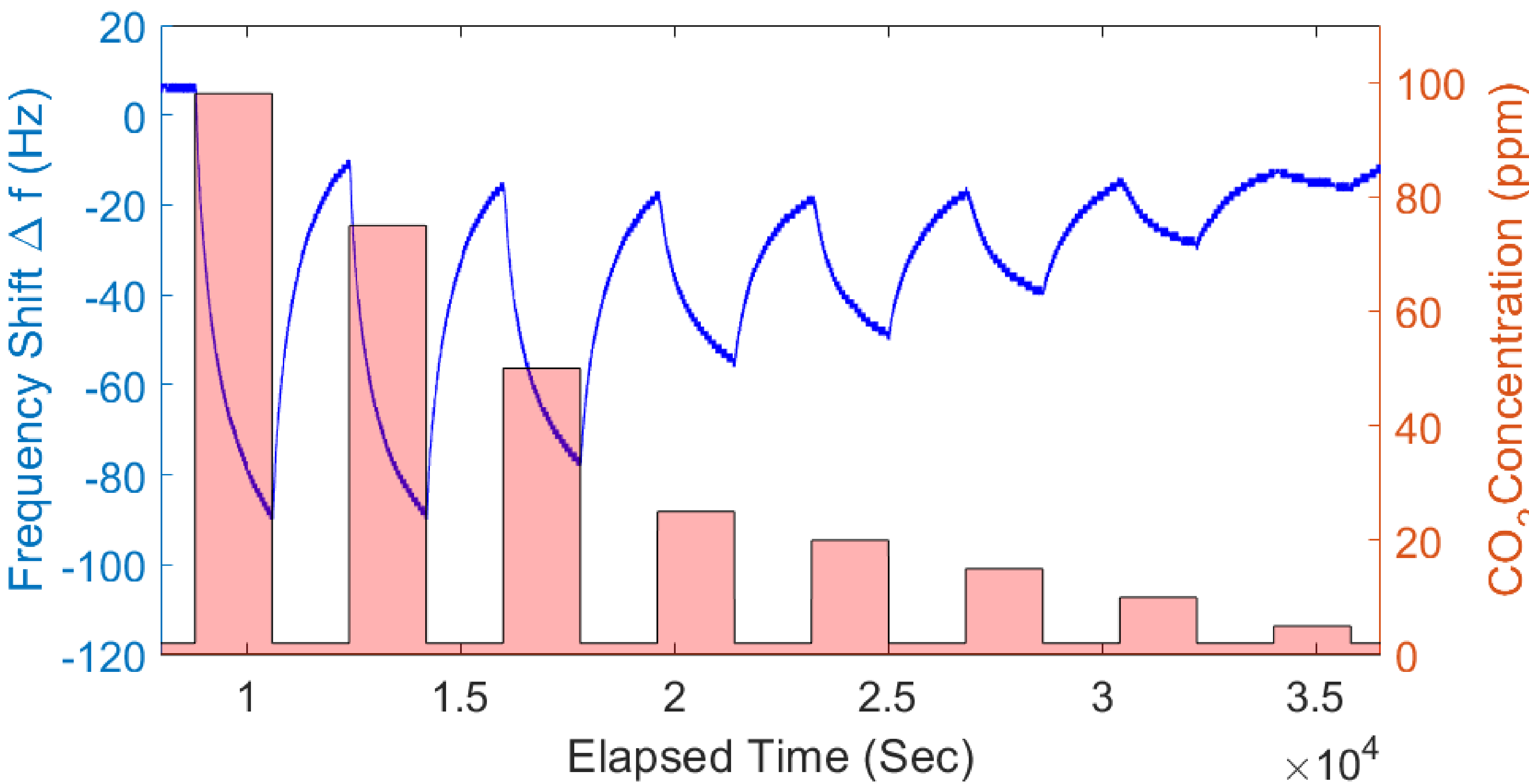


- Both sensors have relatively high resolution in the range of healthy-to-poor indoor air quality and well into the range utilized in industrial applications.

- The chemiresistive sensor provides a raw electrical readout (i.e., a change in the resistance is measured as a function of time) while the MEMS sensor provides a change in frequency shift as the added adsorbed CO_2 mass dampens the MEMS resonant frequency.

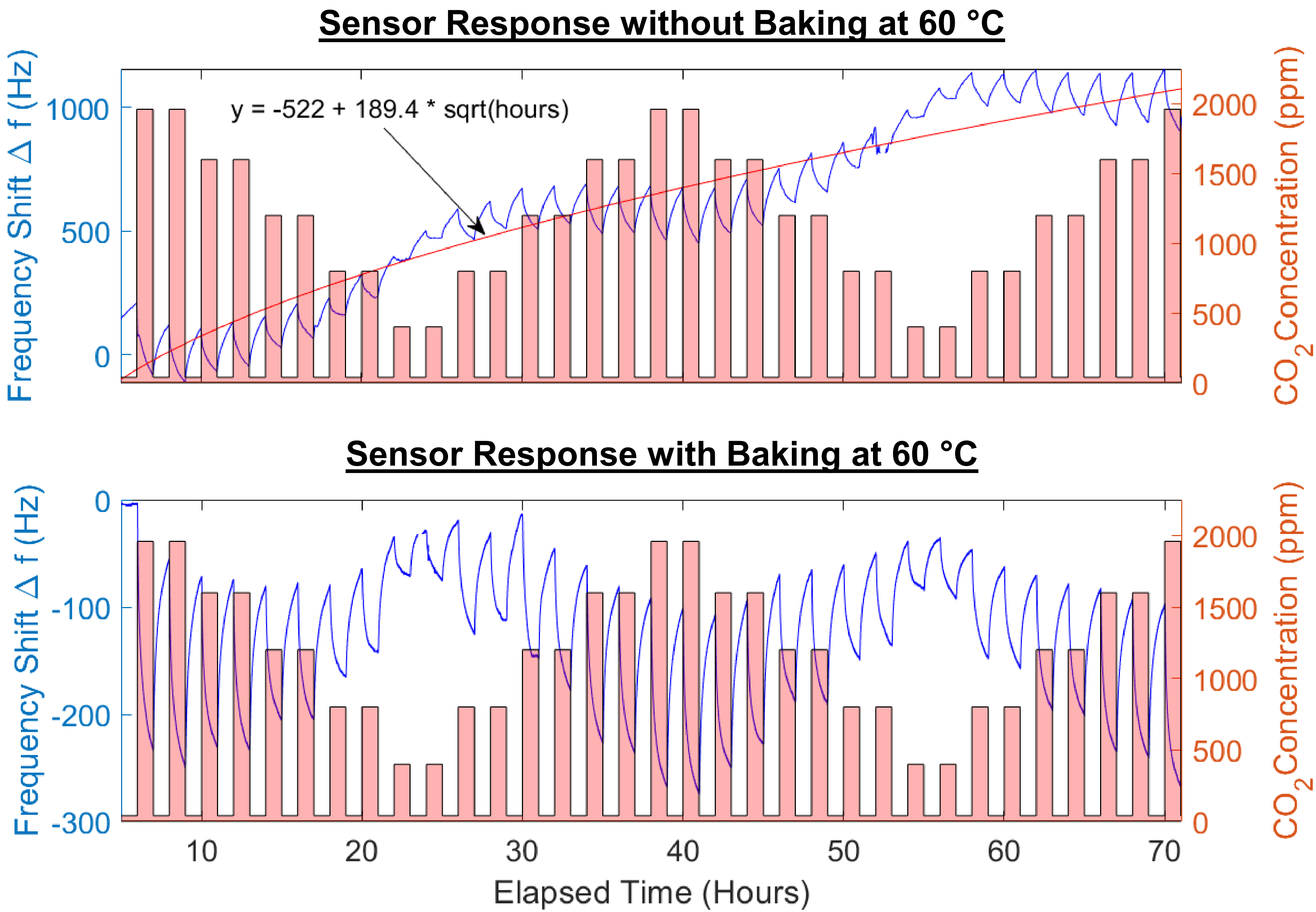
Manuscript Under Review

Shows Clear CO_2 Response Down to 5 ppm



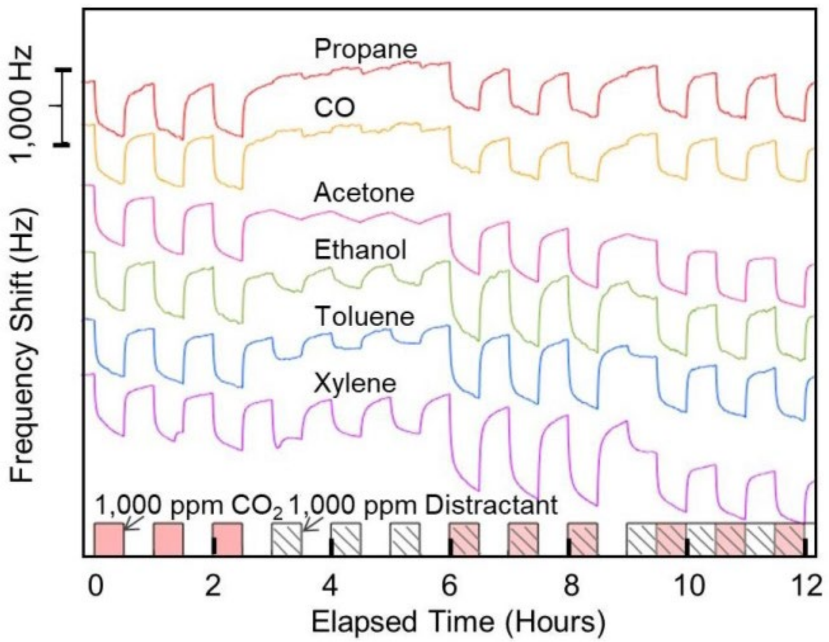
- Response time is on the order of 60 seconds in our testing chamber.
- In practice, the response time for a given application (e.g., room occupancy sensing) will depend on the ability of the gas handling system to deliver the analyte to the sensor.
- With COTS filters, dust/particulates do not seem to be an issue in our initial practical studies.

Simple Baking After Printing Removes Device Drift

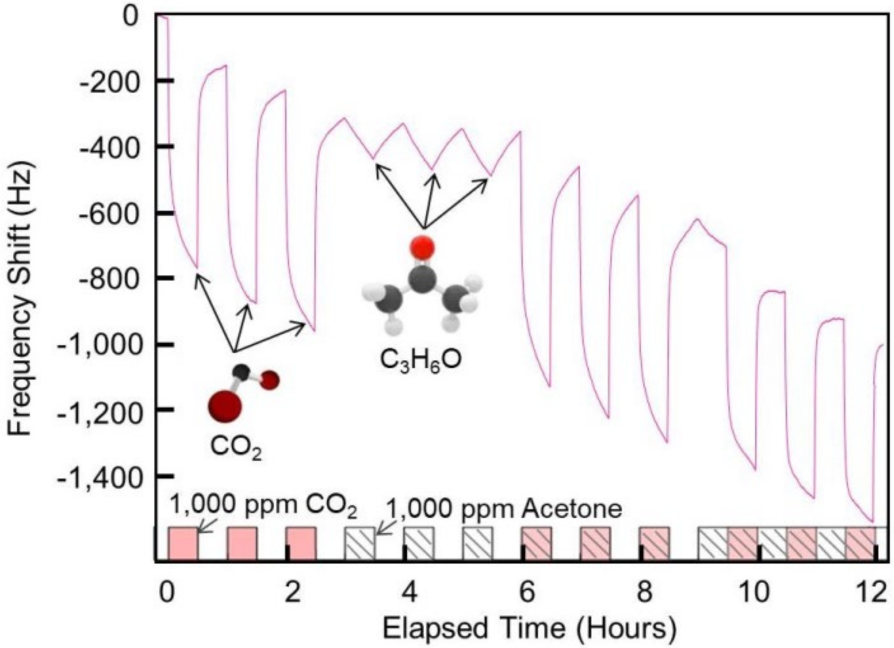


Selective Chemistries Mean No Interference from Distractant Gases

PEI-PEO Chemistry is Inert to Distractant Gases



Example Showing Almost No Response to Acetone Vapor

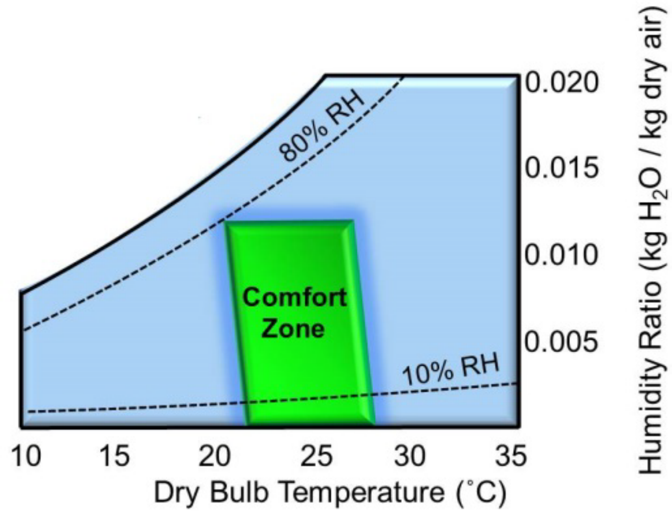


- The distractant gases utilized spanned the spectrum from low molecular weight alkanes (e.g., propane) through higher molecular weight aromatic materials, and they were selected due to their potential presence in IAQ monitoring scenarios.

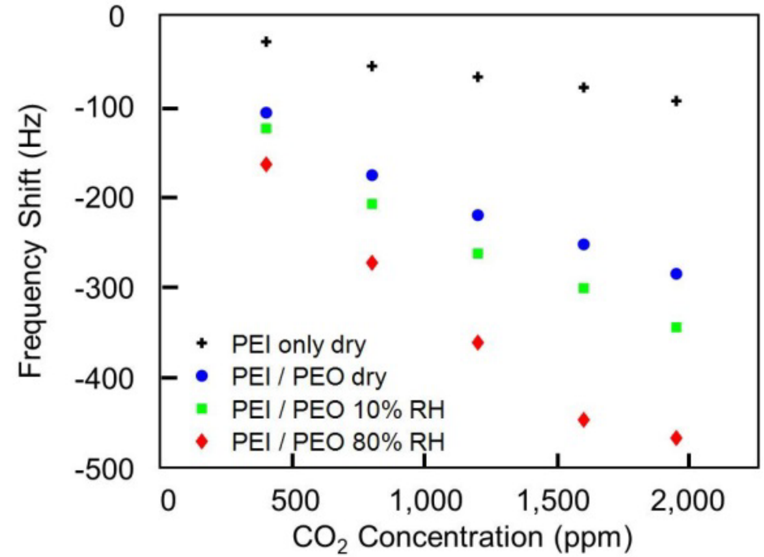
- **The concentrations of distractant gases utilized here as interfering species were <u>significantly higher than what would be present in any realistic scenario.</u>**

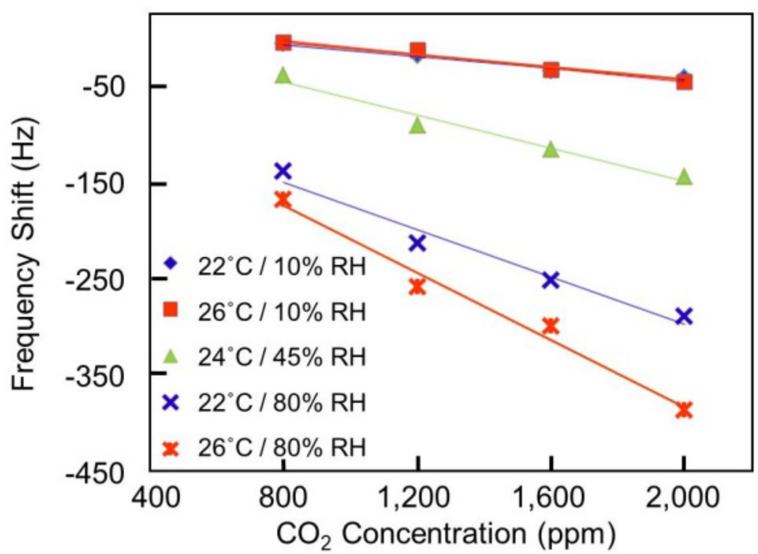
CO_2 Sensors Work Well Across Common IAQ Conditions

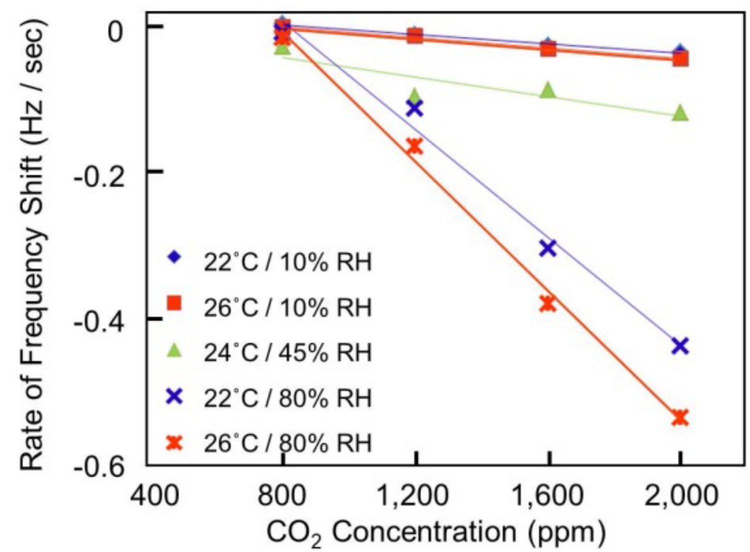
ASHRAE-Defined Comfort Zone



Response at Different RH Values







Center for High Performance Buildings at Purdue

CENTER FOR HIGH PERFORMANCE BUILDINGS

A CENTER DEDICATED TO PARTNERING WITH INDUSTRY IN THE DEVELOPMENT, DEMONSTRATION, EVALUATION, AND DEPLOYMENT OF NEW TECHNOLOGIES AND ANALYSIS TOOLS FOR HIGH PERFORMANCE BUILDINGS.

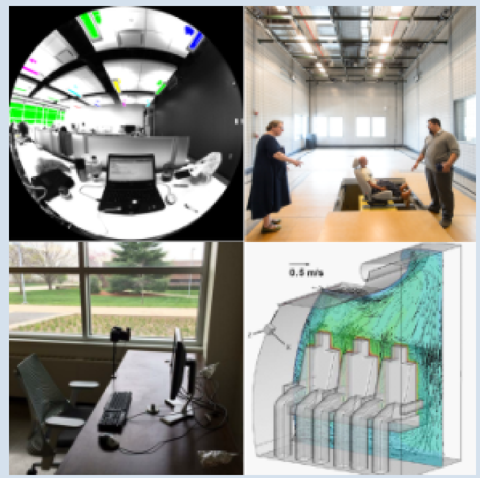
BUILDING TECHNOLOGY & SYSTEMS

This focus area addresses the development, evaluation, and integration of building technologies that can improve occupant comfort and reduce energy usage and operating costs. General research interest of this area are:

- Building Envelopes
- Lighting & Daylighting
- Interior Finishes
- Comfort Delivery
- Modeling, Design Tools
- Smart Buildings
- Renewable Energy
- System Optimization
- Diagnostics Tools

Read more>

INDOOR ENVIRONMENT & HUMAN PERCEPTION



Understanding and modeling the interaction between occupants and their indoor environments is a major focus area for the CHPB. Research interest of the faculty members are:

- Comfort, Productivity, Human Health
- Indoor Air Quality & Human Exposure
- Prediction Models
- Personalized Control
- Interfaces
- Indoor Bioaerosols & Airborne Nanoparticles

Read more>

HIGH PERFORMANCE EQUIPMENT

Read more about High Per

Faculty within the CHPB have a long history of research related to primary and secondary HVAC&R; equipment used in buildings. Research focus of faculty are:

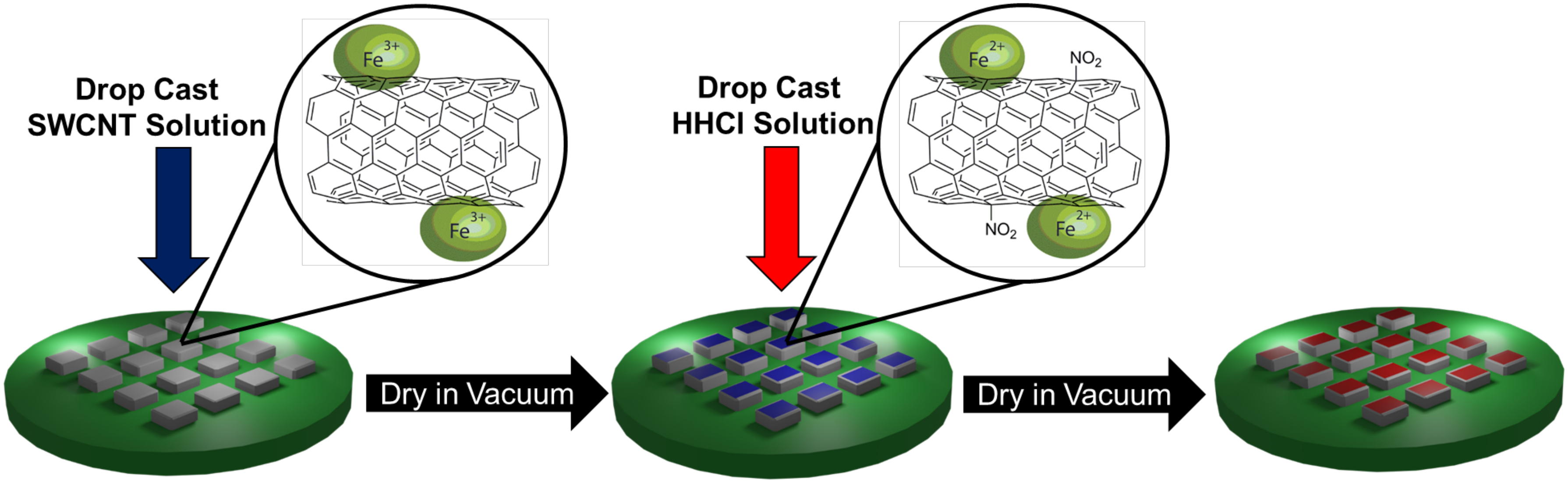
- Compressors
- Heat Pumps
- Refrigerants
- Combined Heat Power [CHP]
- Geothermal Technology
- Modeling and Testing
- Appliances

Read more>

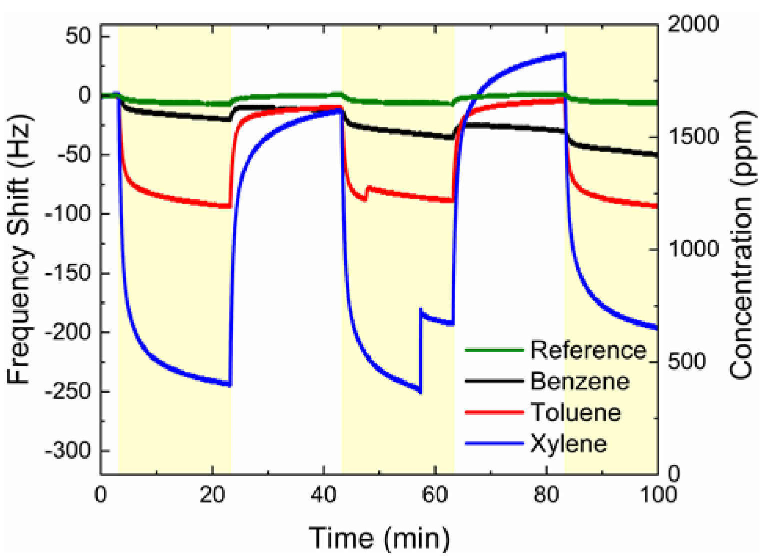
https://engineering.purdue.edu/CHPB

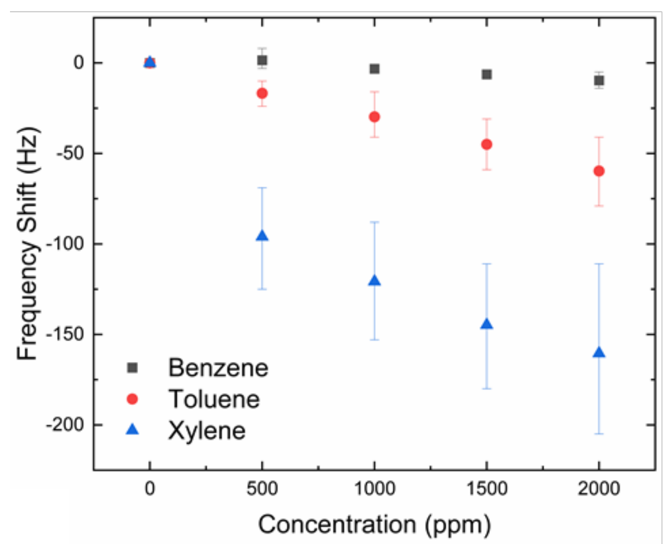
First Target – Sensing Aromatic Hydrocarbon Gases

MEMS Devices Functionalized with Treated SWCNTs Give Specific Uptake



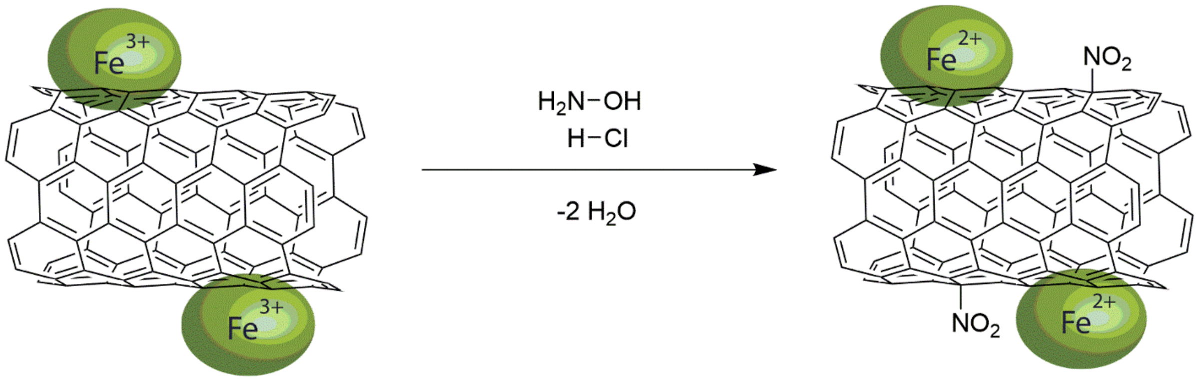
Different Aromatic Hydrocarbons Showed Different Respones



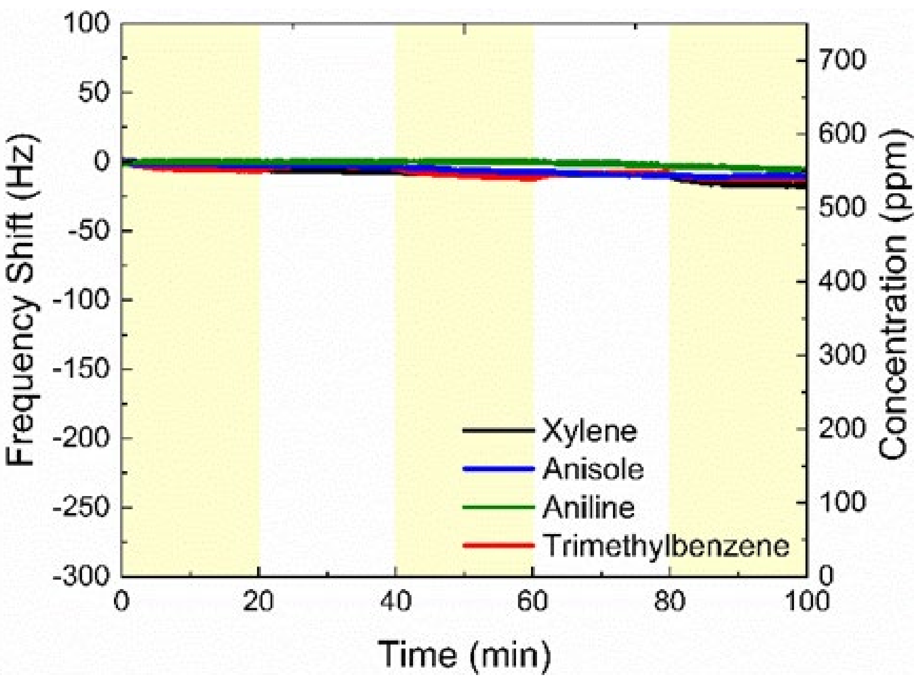


Electron-Donating Character of Analyte Dominates Response

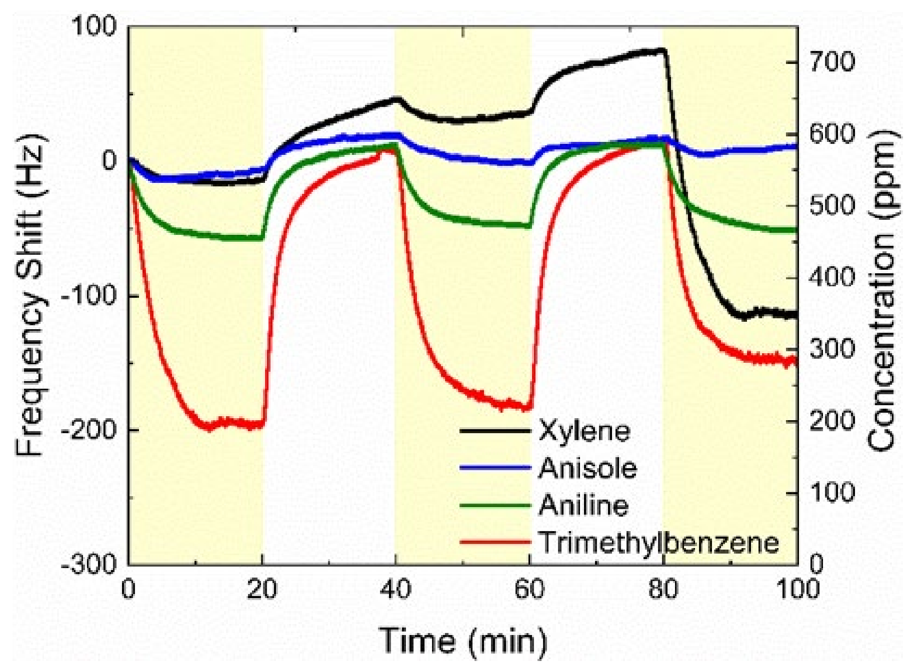
Residual Impurity from the SWCNT Synthesis Dopes the Nanotubes



Bare MEMS Resonators



Resonators with SWCNTs

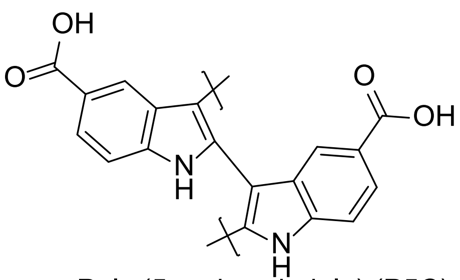


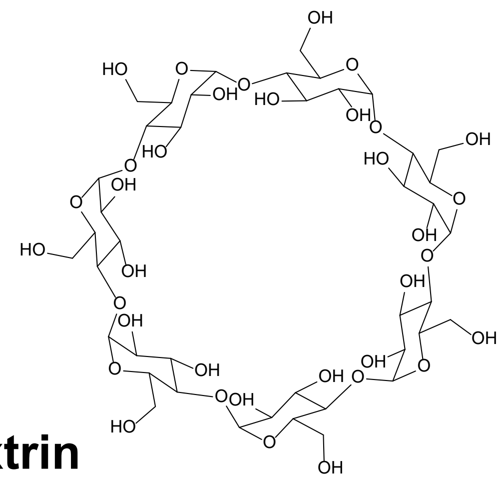
Hodul, J. N.; et al. *ACS Appl. Nano Mater.* **2020**, *3*, 10389 – 10398.

Changing the Chemistry Allows for Formaldehyde Detection

Polymer Composites Critical to Sensing Formaldehyde Gas

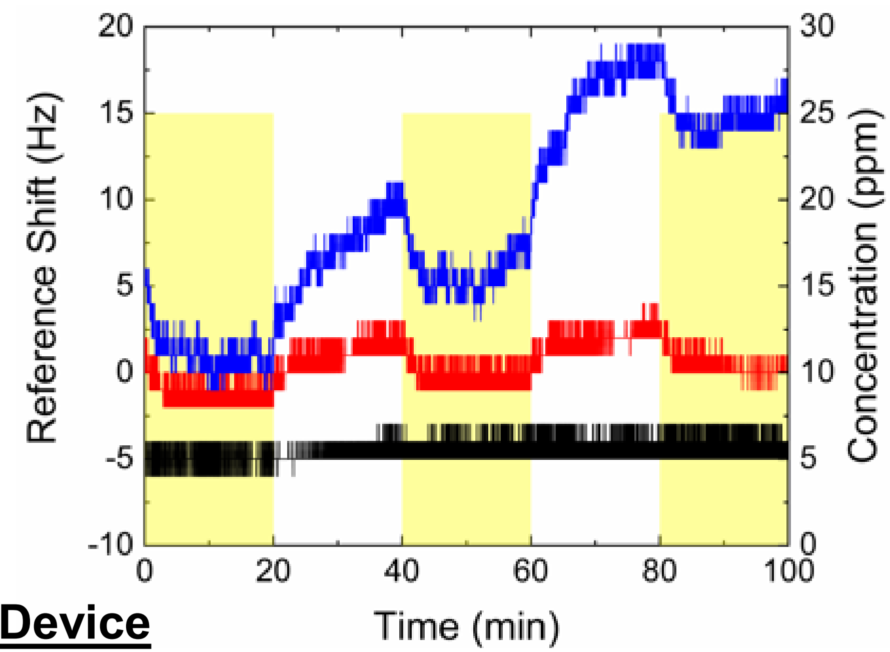
P5C





B-Cyclodextrin

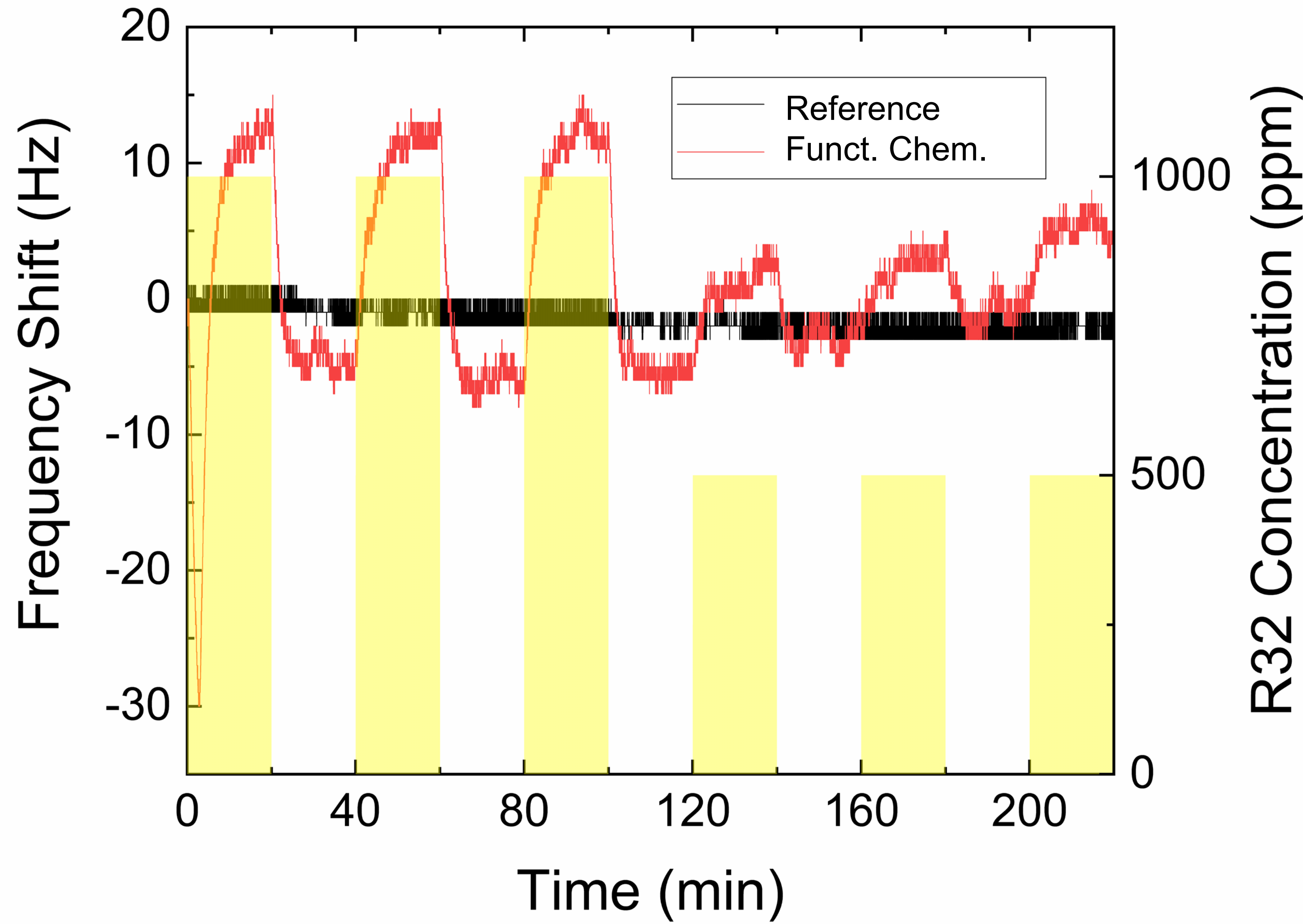
Sensing as Low as 25 ppm



Distractant Gases Due Not Interfere with Device

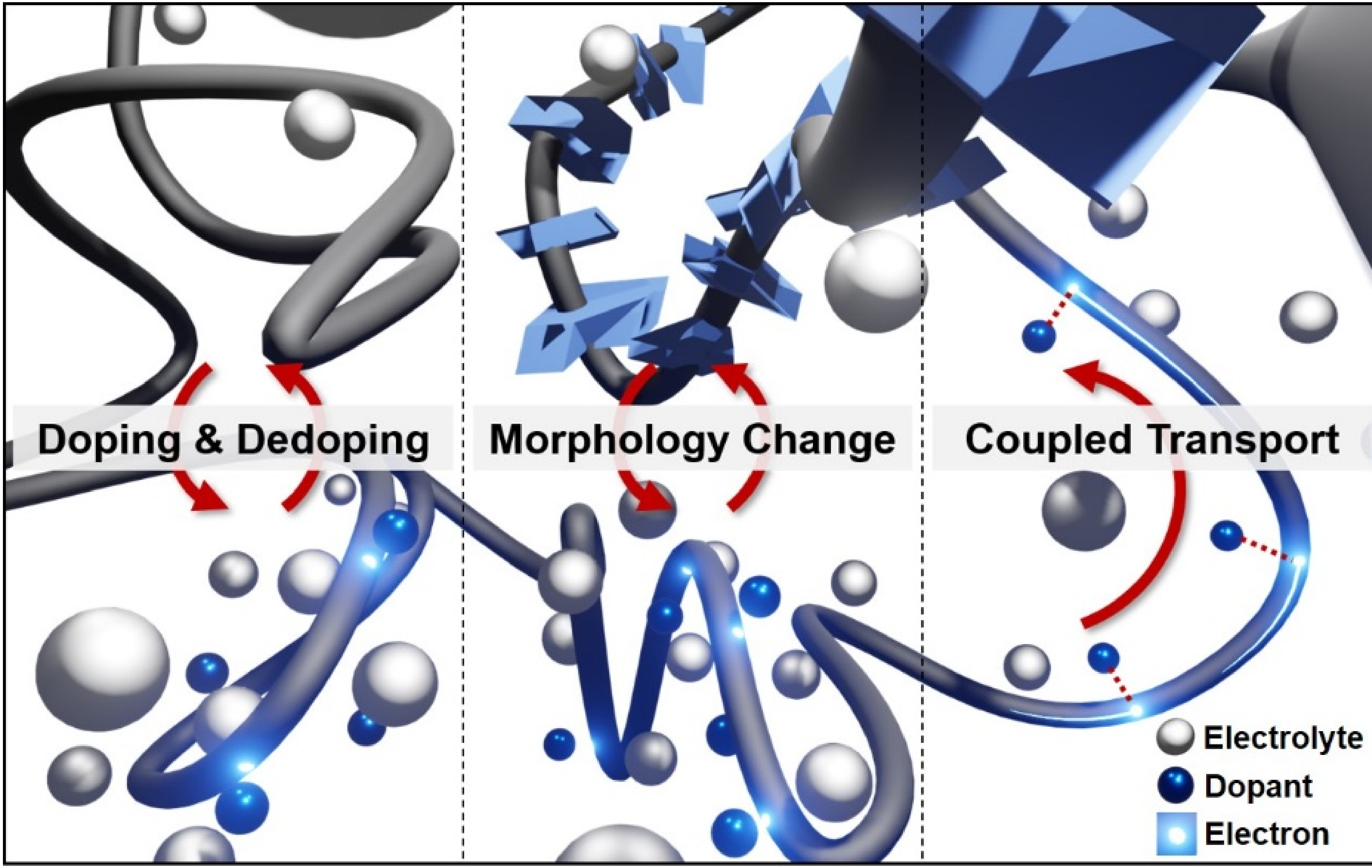
Analyte Concentration	Functionalization Chemistry without Exposure to Formaldehyde			Functionalization Chemistry with Exposure to Formaldehyde at 1,000 ppm		
	Reference	P5C	P5C-BCD	Reference	P5C	P5C-BCD
Acetone 500 ppm	0.9 Hz	1.4 Hz	1.1 Hz	1.8 Hz	6.6 Hz	11.3 Hz
Acetone 1,000 ppm	0.7 Hz	3.9 Hz	1.2 Hz	1.0 Hz	7.8 Hz	11.3 Hz
Methanol 500 ppm	0.6 Hz	0.8 Hz	0.2 Hz	0.9 Hz	5.6 Hz	8.5 Hz
Methanol 1,000 ppm	0.7 Hz	1.1 Hz	0.2 Hz	1.1 Hz	5.9 Hz	9.5 Hz

Detection of Flammable Refrigerants Occurs with Ease



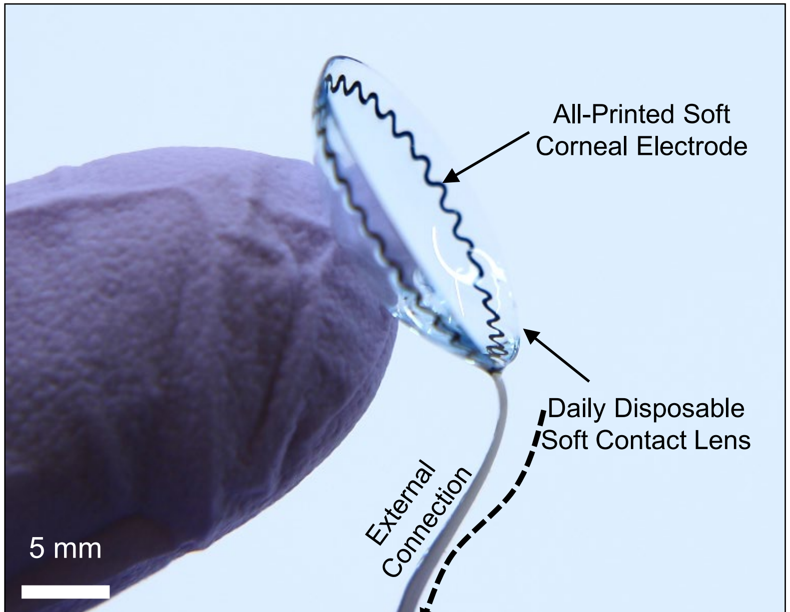
Have also demonstrated detection of isobutane with this chemistry as well.

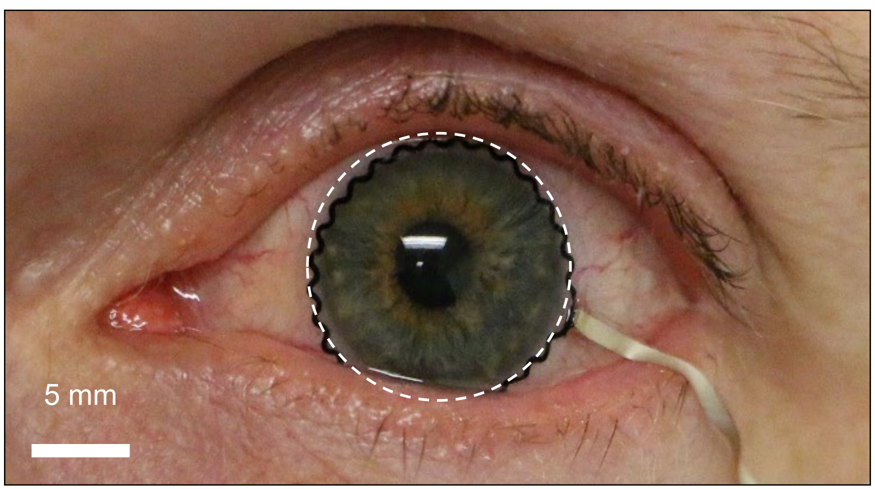
Functional Polymers Are Useful in Mixed Conduction Arenas

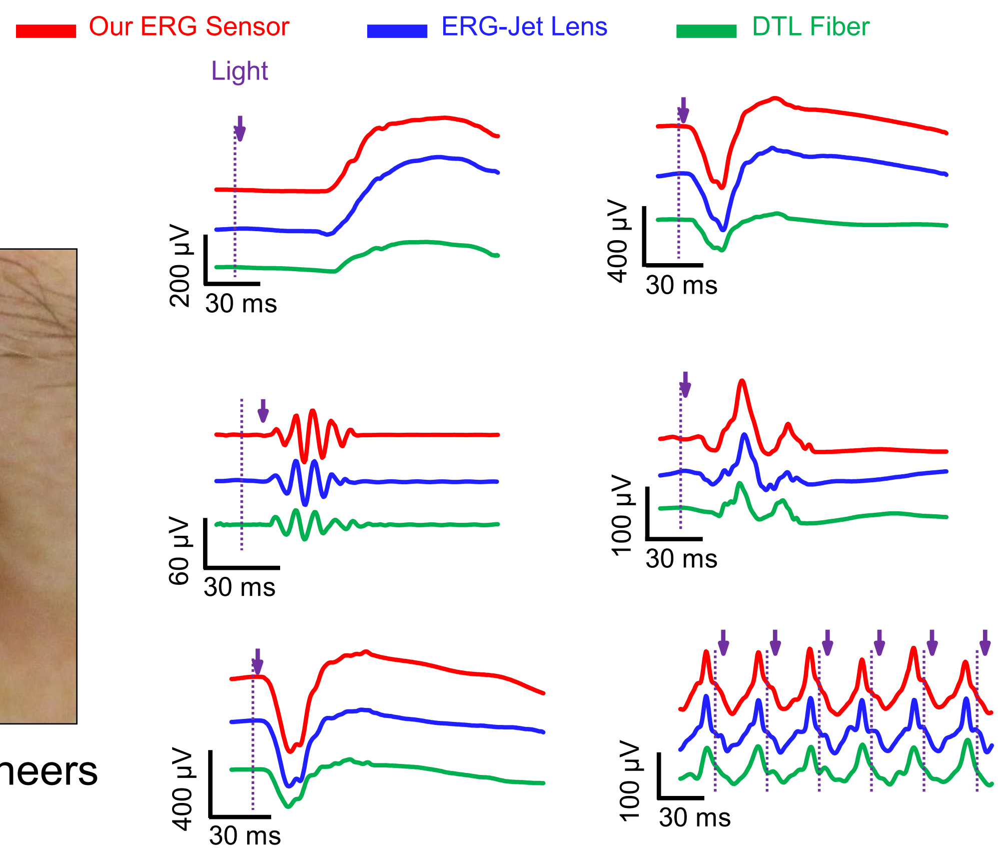


Chung, J.; Khot, A.; Savoie, B. M.; Boudouris, B. W. *ACS Macro Lett.* **2020**, *9*, 646-655.

Low-Cost Sensors for Human Health as Well

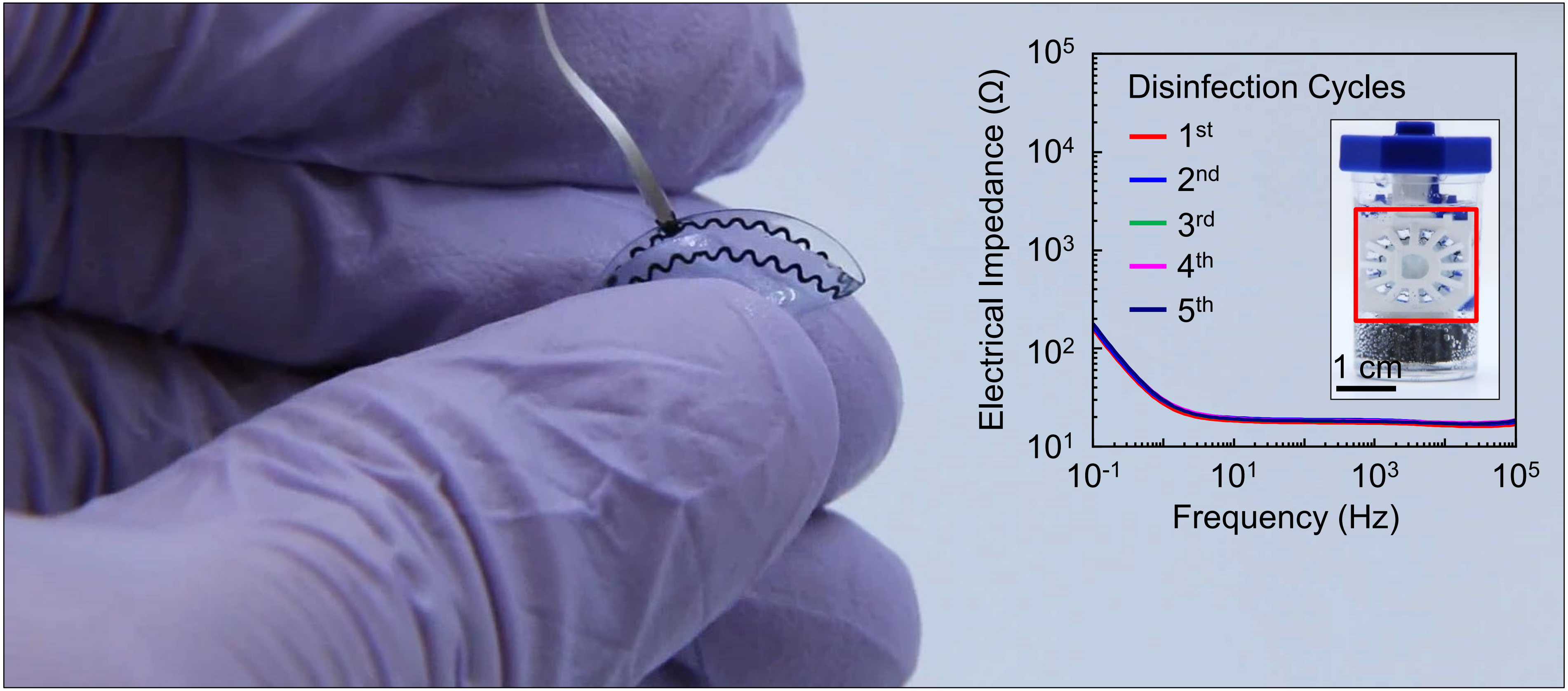






Collaborative work between Purdue Engineers and Dr. Pete Kollbaum (IU Optometry)

Stretchable and Flexible Sensors Built on A Commercial Lens



- ✓ **Mechanical Robustness** against lens handling, fitting, and cleaning.
- ✓ **Chemical Stability** for long-term storage in lens cleaning solutions and multiple disinfection cycles with formulated H_2O_2 solutions.

Nature Communications, In Press

Acknowledgements

Boudouris Research Group

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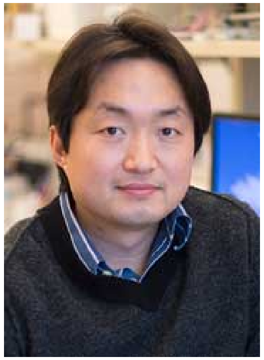
- Ryan Mulvenna (Dow); Darby Hoss (Intel); Jennifer Laster (Intel); Teng Chi (University of Notre Dame); Xikang Zhao (Chinese National Petroleum Corporation); Teng Chi (University of Notre Dame)

Collaborators

- Jeff Rhoads (ME Purdue)
- Chi Hwan Lee (ME Purdue)



- Jim Braun
- George Chiu
- David Corti
- Letian Dou
- Chris Evans
- Julia Kalow
- Jianguo Mei
- Brett Savoie

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