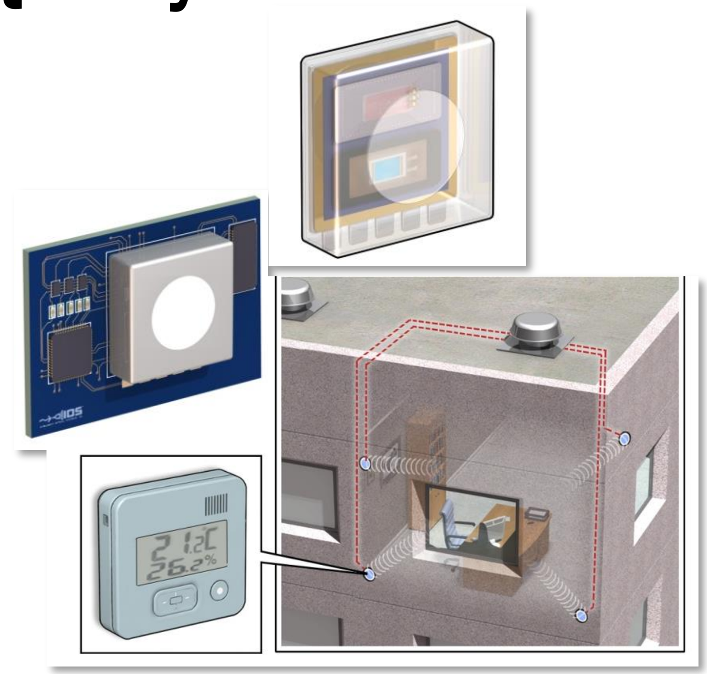
Optical Humidity Sensors for Building Energy Performance and Air Quality Control



Intelligent Optical Systems, Inc.
Jesús Delgado Alonso, Senior Scientist
jdelgado@intopsys.com

Project Summary

Timeline:

Start date: June 13, 2016

Planned end date: July 30, 2019

Key Milestones

- Novel sensor materials demonstrated. (July 2018)
- Sensor signal processing module developed. (December 2018)
- Electronic device fabricated and validated. (February 2018)
- System validation in the field conducted. (June 2019)

Budget:

Total Project $ to Date:

- DOE: $716,662 Phase I and Phase II Year 1
- Cost Share: $0

Total Project $:

- DOE: $1,149,963
- Cost Share: $0

Key Partners:

Circuit Seed – Electronics development
Sensata – Sensor and control industry leader / commercialization partner
Symmetry Advisors – Business development
Optech – IP protection and business development

Project Outcome:

Develop a cost-effective humidity sensor for closed loop air quality control with performance superior to that of current state-of-the-art that is compatible with open source platforms for control applications.

Team – Direct Project Work

Intelligent Optical Systems, Inc. (IOS) – over 15 years of experience in chemical sensor development

Over the past seven years, IOS has developed advanced humidity sensors for a number of aerospace and defense applications.

Dr. Jesús Delgado Alonso
Senior Scientist – sensor system

Dr. Paul DiCarmine
Scientist – sensitive polymeric materials

Circuit Seed, LLC – revolutionary electronic technology for sensor systems integrated in a chip

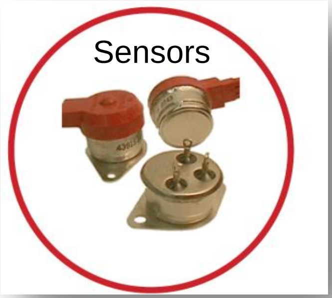
Mr. Robert Schober
Chief Technology Officer – electronics

Circuit Seed™

Team – Collaborations

Sensata – in-depth knowledge of the competition and market, and an established market presence; will participate in field validation

Mr. Karl Abrahamson
Sr. Director, Office of the CTO



Symmetry Advisors – over 20 years of experience in deal origination, deal-making, and high technology and life science commercialization

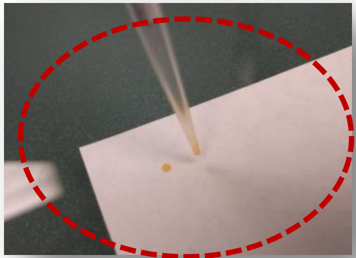
Mr. Riccardo Cannaviello – President

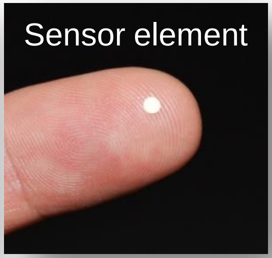
Challenge

- Advanced management of air humidity, a component of occupant comfort, is essential to meeting the BTO goals for occupant-centric sensors and controls and achieving 40% HVAC-based energy savings by 2030.
- Sensing air humidity is essential for assessing air quality and collecting key information for control systems. Humidity sensing must be part of any advanced indoor air quality system.
- ***Existing humidity sensors do not maintain accuracy over extended periods of time, limiting their use for IAQ.***
- Most if not all existing humidity sensors exhibit: hysteresis after being exposed to elevated humidity; poor accuracy near saturation; and drift over time due to the absorption of water by the hydrophilic sensor material.
- Humidity sensing technologies with long-term stability at costs competitive with those of current sensor products are needed. Devices capable of monitoring multiple air quality parameters – RH, T, CO, CO_2 – at low cost are preferred.

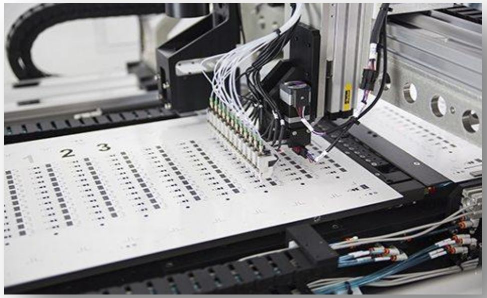
Approach

- **Sensor Element:** The use of a passive material doped with a luminescent dye for enhanced stability - **we use hydrophobic materials, which do not retain water, doped with humidity-sensitive indicator dyes.**

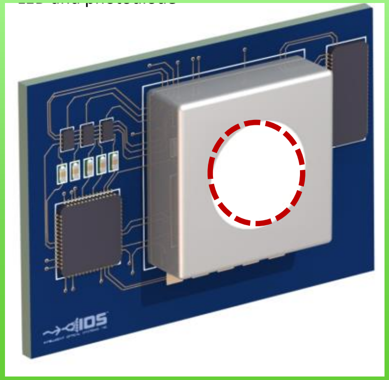




- The manufacturing process takes advantage of established biosensor fabrication systems to produce low cost sensors.



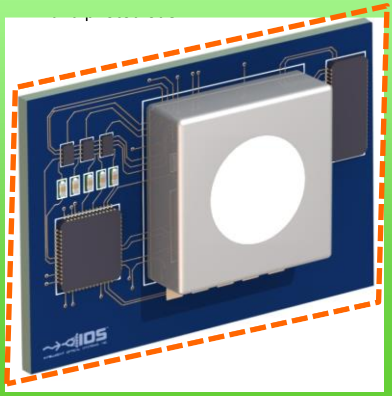
Luminescent Sensor =
Sensor Element +
Electronic Device

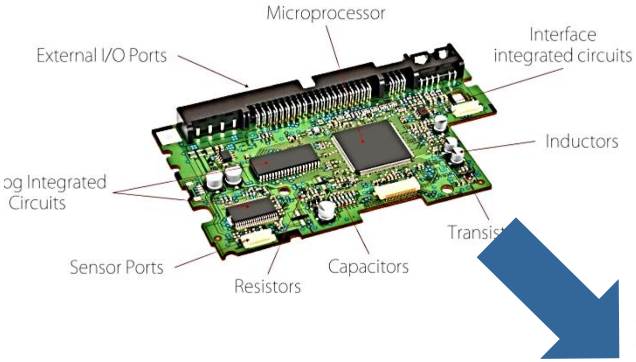


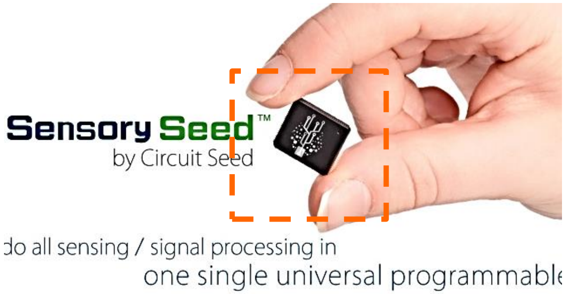
Approach

- **Electronic Device**: The implementation of Circuit Seed, a family of circuits that process analog signals on 100% digital components, enables low cost production:
  - High performance luminescence detectors have been developed but are not competitive in size, power, and cost – **we will develop low-cost, low-power, miniature luminescence detectors.**

Luminescent Sensor =
Sensor Element +
Electronic Device







- Electronic device compatible with additional air quality fluorescent sensors (CO, CO_2,) with marginal cost increase, producing multiparameter devices at low cost.

Approach

Sensor Element

Task 1. Generate a System Requirements Document
Task 2. Develop advanced RH sensors
Task 3. Evaluate potential long-term stability, and compare with that of COTS sensors – life studies and accelerated degradation studies (ADT) under stress conditions

Electronic Device

Task 4. Develop sensor signal processing module on a CMOS chip
Task 5. Develop electronic unit

Integration and Validation – Field Demonstration

Task 6. Analytically characterize first series of demonstrators
Task 7. Perform system validation in the field – select at least two applications representative of markets of interest to BTO and Sensata – include humidity monitors from the Sensata portfolio of products – operation for three months + stress conditions + operation for one month
Task 8. Design review – identify areas of improvement to implement in second generation

Beyond Relative Humidity Monitoring

Task 9. Demonstrate compatibility of electronic unit with other gas sensors

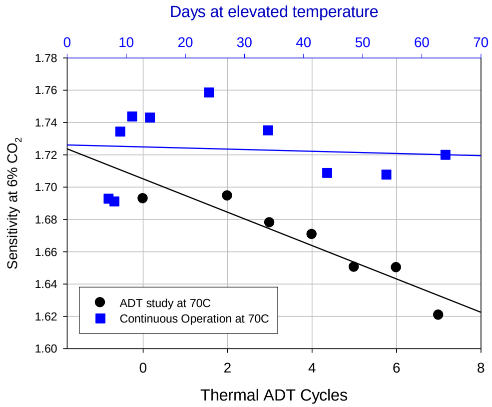
Towards Commercialization

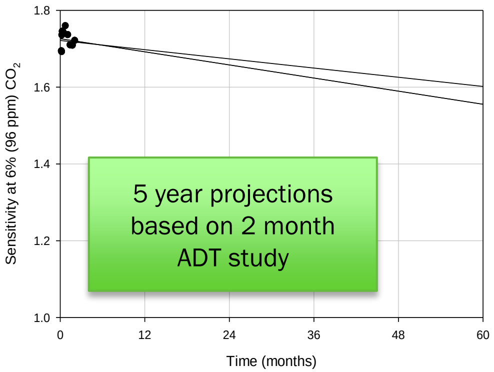
Task 10. Explore commercialization relationships for Phase II and beyond.

Impact of IOS sensor and Phase II SBIR Project

The main advantages of IOS's technology towards the BTO goals are

- **Superior stability and tolerance to stress** (±1% deviation for a period of 10 years) *will be demonstrated by conducting life studies and accelerated degradation tests (ADT)*





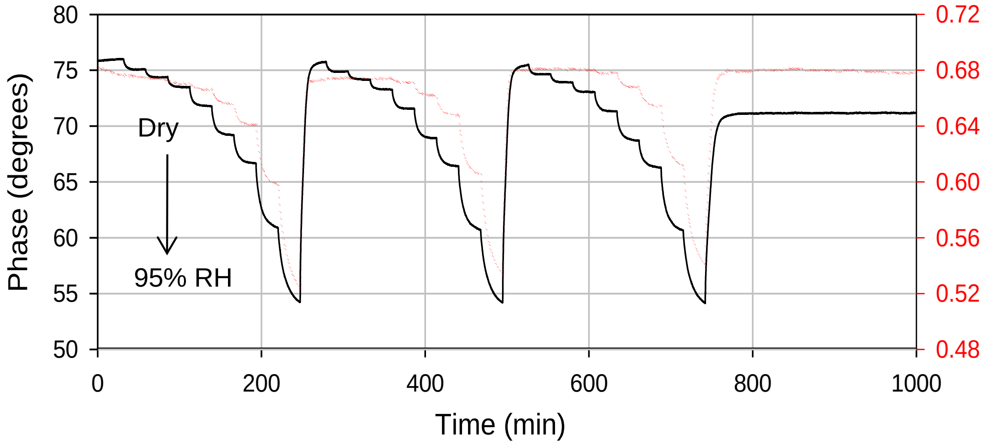
- **Multi-paramenter sensing** in a single sensor platform (humidity, temperature, carbon dioxide, and oxygen) *will be demonstrated by integrating sensor elements developed for space applications.*
- **Low cost** sensor element *will be demonstrated by generating protocols compatible with high output, well-established, sensor fabrication machinery and protocols for biosensor fabrication* – sensor element target cost $10.
- **Minimal power requirement.** Analog components integrated in a single CMOS chip, enabling mass production and **minimal power requirements** *will be demonstrated by developing and characterizing a sensor processing signal module in a CMOS chip.*

Progress – 8/24 months

- **TASK 1. Generate a System Requirements Document - completed**
- **TASK 2. Develop Advanced RH Sensors - completed**
  - Commercial membranes and custom polymers exhibited the best results in initial screening. Custom polymers offer numerous opportunities for optimization and improvement – we **reformulated sensors based on custom polymers,** and **developed novel composite sensor materials.**
  - Preliminary screening of new sensor formulations – sensitivity, reversibility, short-term stability – we selected best candidates from over 100 formulations already studied.

Film sensor element fabricated with custom polymers

Acrylate-base polymer **SN02 - Standard**	
Sensitivity	+
Reversibility	++
Short term stability	++
Response time	+



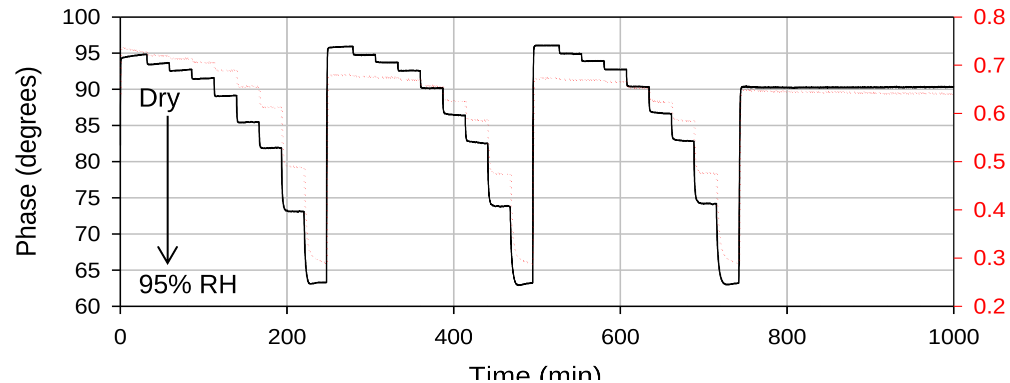
- **Phase II reformulated sensors based on custom polymers exhibit comparable reversibility, and improved stability and repeatability than those demonstrated in Phase I.**

Progress – 8/24 months

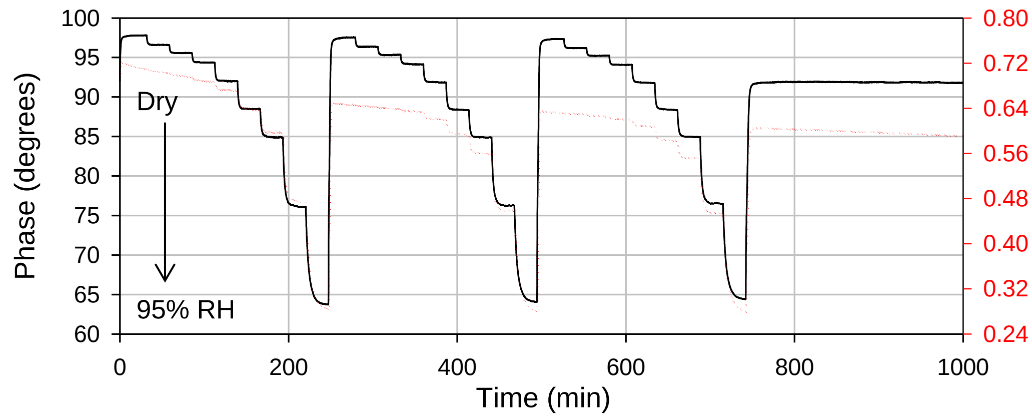
- **TASK 2. Develop Advanced RH Sensors - completed**

Composite sensor element

Acrylate-base polymer **SN03 - Composite**	
Sensitivity	++
Reversibility	++
Short term stability	++
Response time	++



Acrylate-base polymer **SN05 - Composite**	
Sensitivity	++
Reversibility	++
Short term stability	++
Response time	++



- Phase II novel composite sensors exhibit comparable reversibility, improved stability and repeatability, and faster response time than those demonstrated in Phase I.

Progress

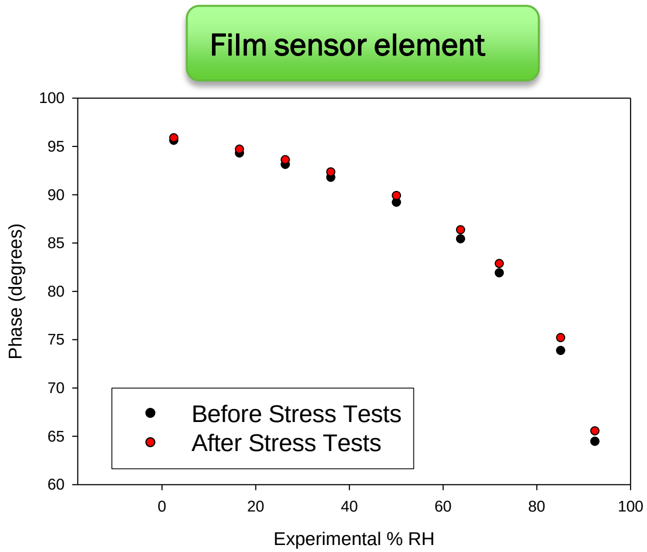
- **TASK 3. Evaluate Potential Long-term Stability - in progress**

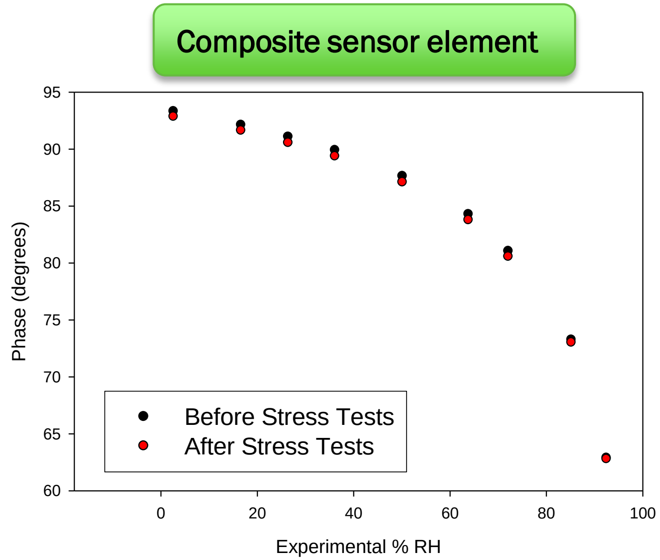
Stress Test 0: Sensor is stressed by cycling between conditions of dry (dry flow of synthetic air) and water condensation – completed

Stress Test 1: Sensor is stressed by exposure to aqueous salt solutions – in progress

Stress Test 2: Sensor is stressed by exposure to high concentrations of airborne contaminants – in progress

Stress Test 3: Sensor is stressed by quickly cycling between conditions of heat (100°C) and humidity (100% RH) and ambient conditions – in progress





- **Selected sensor formulations were not affected by condensation stress tests.**

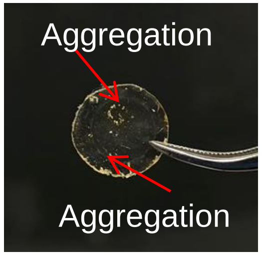
Progress

- **TASK 3. Evaluate Potential Long-term Stability - in progress**

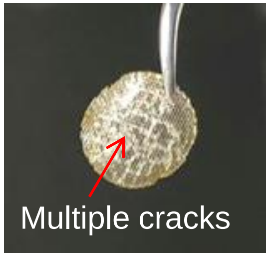
Stress Test 1: Sensor is stressed by exposure to aqueous salt solutions – in progress

After exposure to stress conditions

Film sensor

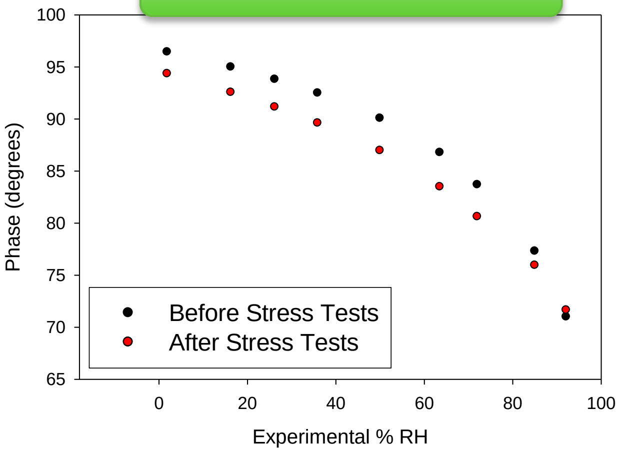


Initial composite

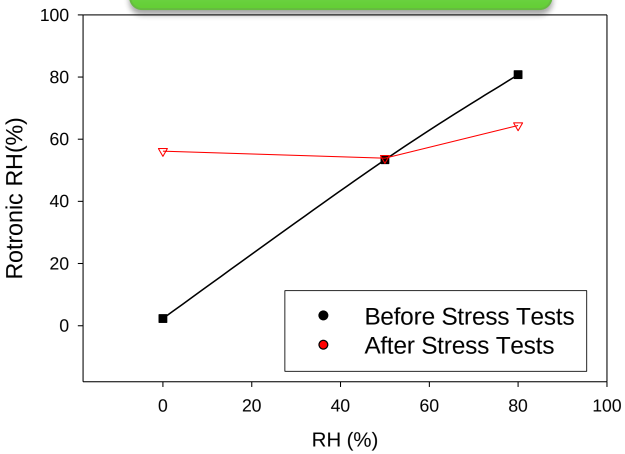


Optimized composite

Composite sensor element



Rotronic COTS sensor



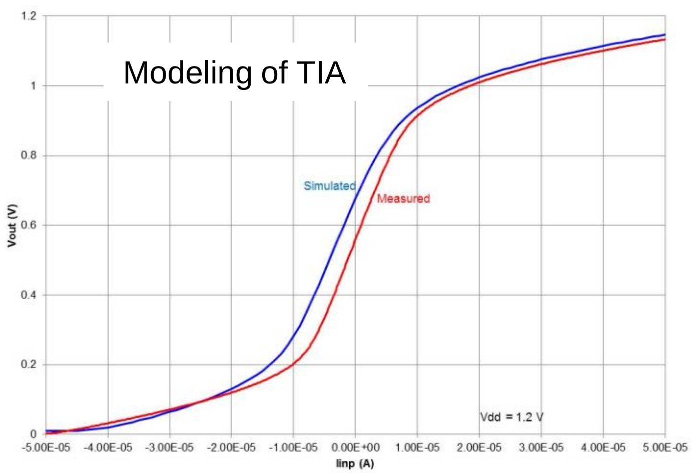
- **Selected sensor formulations exhibit significantly enhanced resistance to the corrosive environment (salt water) stress test, superior to that of the COTS sensor.**

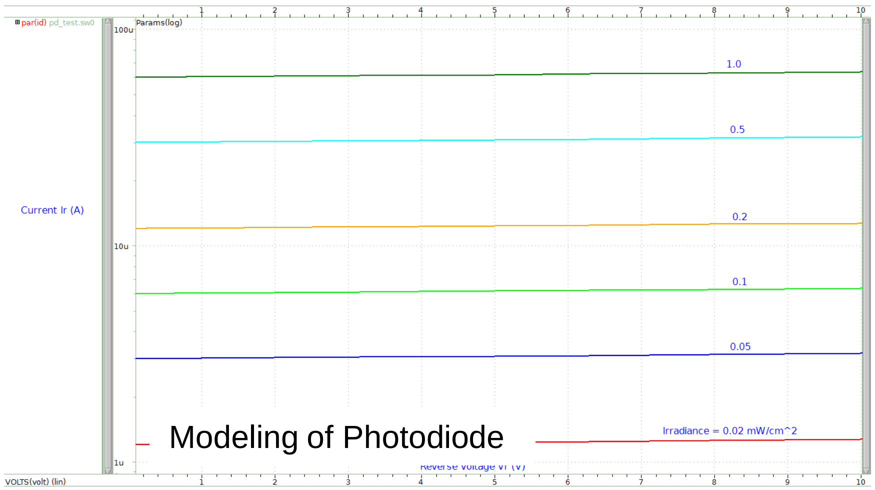
Progress

- **TASK 4. Develop Sensor Signal Processing Module on a CMOS Chip - in progress start 01/01/18 – end 09/30/18**

Subtask 4.1. Design Circuit and Perform Simulation of Sensor Signal Processing Module
4.1.1 Choice of technology and setup of design environment
4.1.2 Development of schematics
4.1.3 Simulation of chip operation

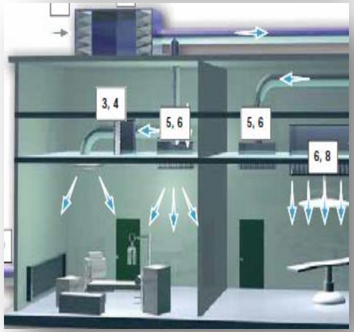
- Choice of technology: Global Foundries 130 nm (BiCMOS 8HP) – complete
- Set up design environment – complete
- Modeling of photodiode – complete
- Verification of TIA: simulation versus measurement – in progress
- Verification of TIA with photodiode – in progress





Stakeholder Engagement

- **Sensor market:** We have presented our technology, demonstrated sensor operation in our laboratories, and discussed a potential partnership for commercialization with Sensata, a global market share leader in the sensor and control industry.
- **Wireless communication & home automation:** We have presented the technology and discussed potential collaboration for commercialization with Melexis. Melexis is one of the five world leaders in automotive sensors and wireless communication, and is also active in smart appliances and home automation.
- **Indoor air solution:** We have initiated discussions with Camfil USA, Inc. The Camfil Group is a world leader in the development and production of clean air solutions.
- **DOE - Building Technologies Office:** We have maintained communication, presenting project plans, progress and discussed objectives and research approach.



We have reached an agreement with Symmetry Advisors to perform market analyses, digest market patterns and trends, conduct in-person outreach to stakeholders and industry leaders, and establish business relationships.

Remaining Project Work

Sensor Element

Complete

Task 1. Generate a System Requirements Document

Task 2. Develop advanced RH sensors

Active

***Task 3.** Evaluate potential long-term stability, and compare with that of COTS sensors*

Stress Test 1: Exposure to aqueous salt solutions

Stress Test 2: Exposure to high concentrations of airborne contaminants

Stress Test 3: Rapid cycling between conditions of heat (100°C) and humidity (100% RH), and ambient conditions

Tuning formulation if necessary

Electronic Device

***Task 4.** Develop sensor signal processing module on a CMOS chip*

- Circuit Design and Simulation
  Choice of technology and setup of design environment – develop schematics – simulate chip operation
- Design Review
  IC Layout – layout of chip using foundry design rules – Design Rules Check (DRC) – Layout vs. Schematic (LVS) – Design review – submission to foundry
- Foundry Shuttle Run
- Prototype Packaging

Future

***Task 5.** Develop electronic unit*

- PC board design and layout SC Phase Unit
- Interface Raspberry Pi – socket for Proto package – PCB fabrication & assembly – software development – detailed electrical evaluation – detailed functional evaluation.

Remaining Project Work

Future

Integration and Validation

Task 6. *Analytically characterize first series of demonstrators*

Two prototypes incorporating the advanced sensor materials developed in Tasks 2 and 3 will be assessed for precision, accuracy, measurement range, calibration function, and response time, under variable environmental conditions.

Field Demonstration

Task 7. *Perform system validation in the field*

Three months of operation in the field and data collection with two sensor systems. All instruments will then be subjected to stress conditions relevant to the selected application. Finally, the monitors will again be deployed in the field, and data will be recorded for at least one additional month. The performance of the demonstrators will be compared with that of the COTS devices.

Task 8. *Design review*

Identify areas of improvement to implement in second generation.

Beyond Relative Humidity Monitoring

Task 9a. *Demonstrate sensitive materials for moisture monitoring in the low ppm range*

Task 9b. *Demonstrate compatibility of electronic unit with other gas sensors*

Active

Towards Commercialization

Task 10. *Explore commercialization relationships for Phase II and beyond.*

Thank You

Intelligent Optical Systems, Inc.
Jesús Delgado Alonso, Senior Scientist
jdelgado@intopsys.com

REFERENCE SLIDES

Project Budget

Project Budget: Total contract amount $1,149,963. Current funded amount for Phase I and Year 1 of Phase II is $716,662
Variances: None
Cost to Date: $358,997
Additional Funding: $433,301 for Year 2

Budget History					
07/31/17 – FY 2017 (past)		FY 2018 (current)		FY 2019 – 07/30/19 (planned)	
DOE	Cost-share	DOE	Cost-share	DOE	Cost-share
$163,481	0.00	$626,122	0.00	$360,360	0.00

Project Plan and Schedule

- Start date was 07/31/2017 but Assistance Agreement with DOE was signed 09/26/2017
- Subcontract with Circuit Seed for Tasks 4 and 5 was signed 12/2017
  - Task 4 began in Month 6 – Task 5 began in Month 7

Tasks	Months After Project Initiation																							
	1	2	3	4	5	6	7	8		10	11	12	13	14	15	16	17	18	19	20	21	22	23	24
1	x	x	x																					
2	x	x	x	x	x	x	x	x	x	x	x	x												
3		x	x	x	x	x	x	x	x	x	x	x	x	x										
4			x	x	x	x	x	x	x	x	x	x	x	x	x	x								
5						x	x	x	x	x	x	x	x	x	x	x	x							
6																	x	x	x					
7																			x	x	x	x	x	
8																							x	x
9																		x	x	x	X	x	x	x
10	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
11	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x	x
Milestones				1								2			4			3	5	6			7	8/9

X= task schedule at the beginning of the project; blue shading=current schedule

Milestone 1. System Requirements Document generated - **Met**
Milestone 2. Novel sensor materials demonstrate stability superior to that of the sensors developed in Phase I
Milestone 3. Sensor signal processing module on a chip fabricated
Milestone 4. Electronic device detailed design generated
Milestone 5. Electronic device fabricated and validated according to system verification matrix
Milestone 6. Sensor life and calibration requirements projected based on data collected in life studies
Milestone 7. Analytical characteristics established
Milestone 8. System validation in the field conducted
Milestone 9. Sensor materials for moisture monitoring in the low ppm range demonstrated. Compatibility with CO_2 sensor materials demonstrated.