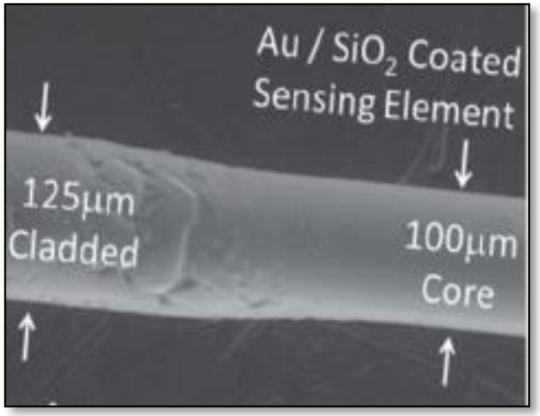
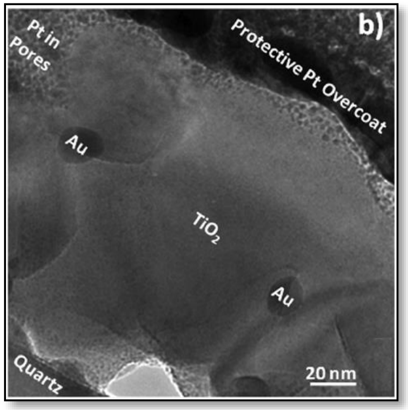
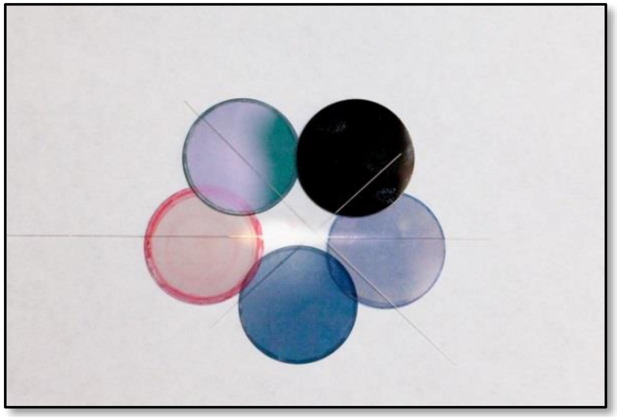
NATIONAL ENERGY TECHNOLOGY LABORATORY

Optical Material
Enabled Harsh Environment Sensors







Sensor Materials and Fiber Optic Sensors for Harsh Environment Sensing Applications at NETL

Dr. Paul Ohodnicki, Materials Scientist / Technical Portfolio Lead

Functional Materials Team

Materials Engineering & Manufacturing Directorate

NETL Research & Innovation Center

U.S. DEPARTMENT OF ENERGY

Locations of the National Energy Technology Laboratory

MISSION
Advancing energy options to fuel our economy, strengthen our security, and improve our environment

Oregon

Pennsylvania

West Virginia

Relevant Research Focus Areas in R&IC

- **Material and Device Research Focus Area**
  - Overview of Research Focus Area at NETL
  - Example of Cross-Disciplinary Integrated Research

- **NETL R&IC Sensor Material and Optical Fiber Sensor Program Overview**
  - Energy Related Harsh Environment Sensing Needs
  - Current Capabilities, Research Thrusts, and Partnerships

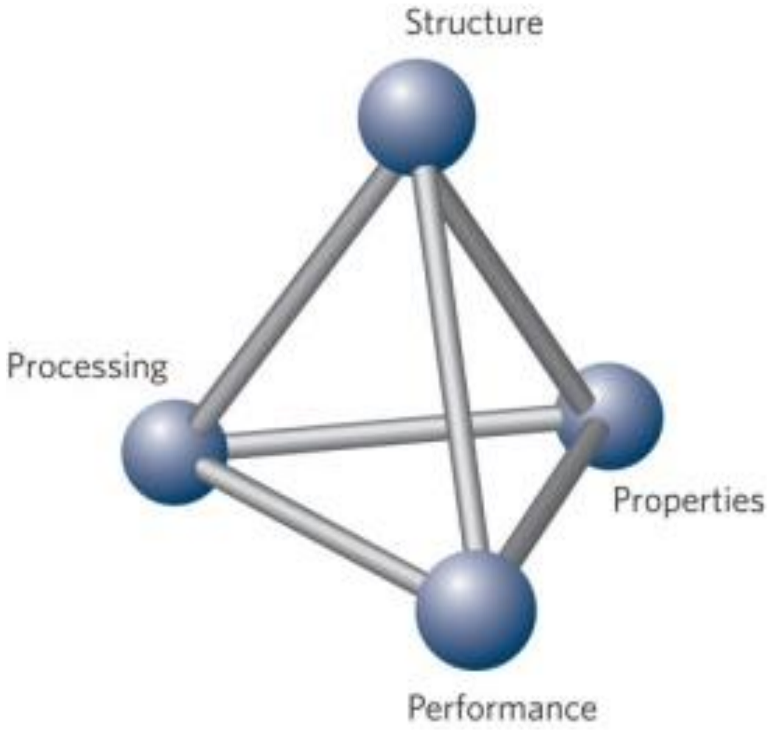
- **Highlights of Recent Successes and On-Going Activities**
  - H_2 Sensing Materials for SOFCs
  - Theoretical Investigations of High Temperature Oxide Sensor Materials
  - Thermal Emission Based High Temperature Sensing
  - Optical Fiber Materials Research and Development
  - Embedding of Sensors for High Temperature Applications
  - pH and CO_2 Sensing Materials for Subsurface Applications

- **Summary and Conclusions**

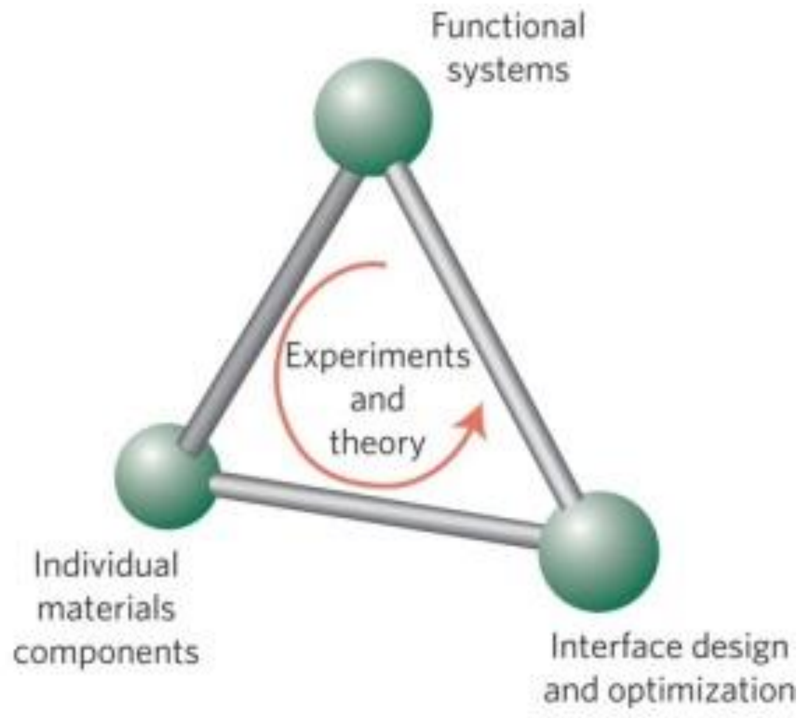
Materials and Device Research Focus Area

Functional Material Development for Devices and Systems

Classic Materials Science Paradigm



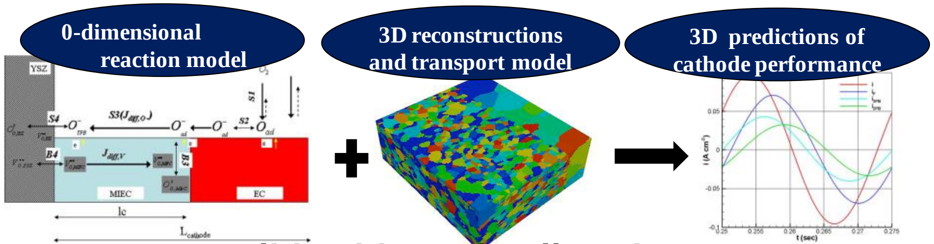
Emerging Paradigm
Materials Interface with Functional Systems and Devices



Materials Research Targeted at Device and System Level Benefits

Materials and Device Focus : Functional Material Team

Current Fiscal Year 2016

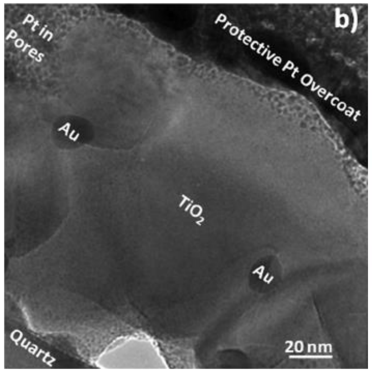


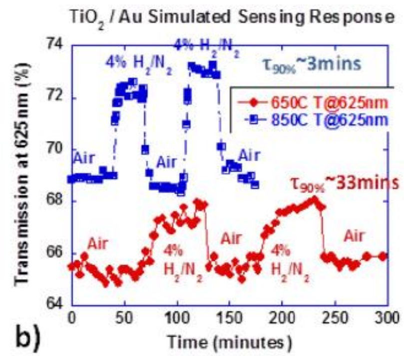
Solid Oxide Fuel Cell Devices

Modeling + Characterization → Optimal Device Performance

Solid Oxide Fuel Cell Materials / Devices
Function and Durability

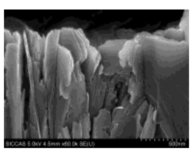
Current Fiscal Year 2016

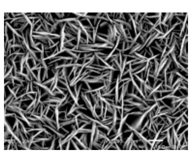


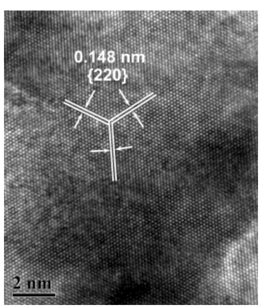


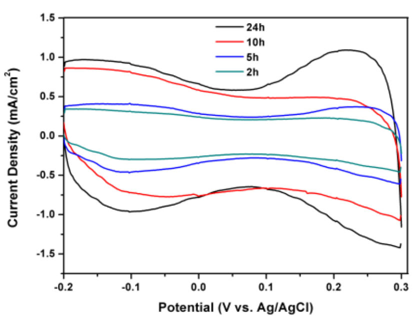
Sensor Materials / Devices
Chemical and Temperature Sensing

Ended Fiscal Year 2014



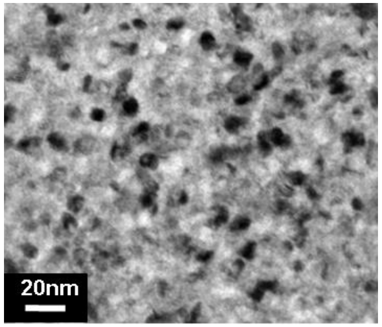


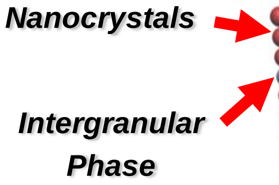


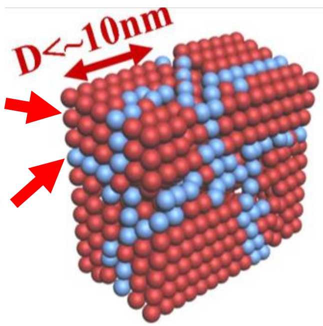


Energy Storage Materials / Devices
Enhanced Performance

Current Fiscal Year 2016



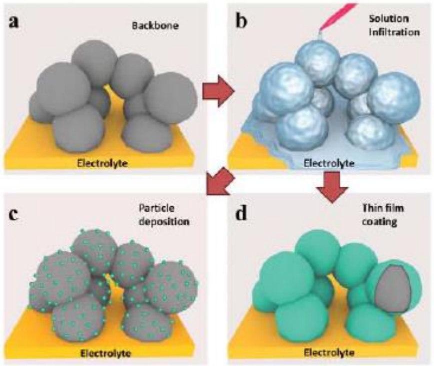




Soft Magnetic Materials / Devices
Inductors and Sensors

Solid Oxide Fuel Cell Material / Device Development

SOFC Materials Engineering for Improved Device Figure of Merits



Parameter	Base	Improved
SOFC Degradation (%/1000 hrs)	1.5	0.2
Cell Overpotential (mv)	140	70
Gasifier CH_4 (conventional)	5.9%	10.2%

Kristin Gerdes, "Advanced Coal Power Systems: Competing in Multiple Market Scenarios," 13th Annual SECA Workshop, July 24, 2012, Pittsburgh, PA

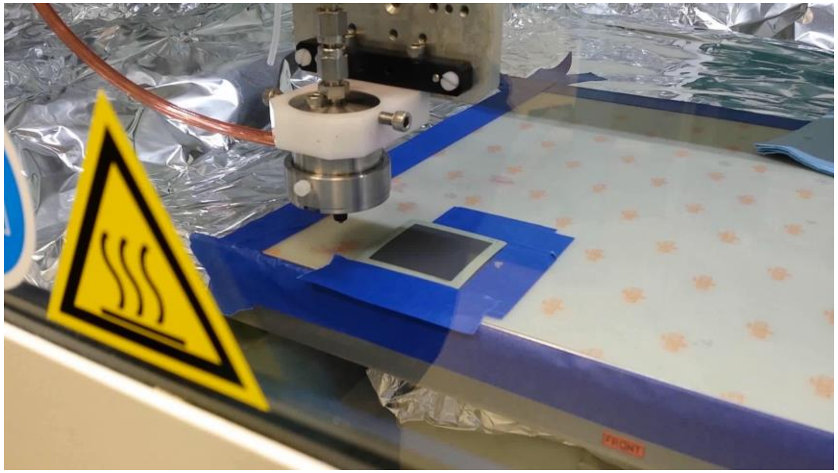
Supports DOE NETL SECA Program

- *Reduce cell production / operation costs*
- *Enhance cell activity / efficiency*
- *Improve cell lifetime (40+ khr)*

Key Success = Cathode Infiltration

Commercially scalable process developed at NETL :

10% ↑ in peak power, 33% ↓ in degradation, 200% ↑ in lifetime

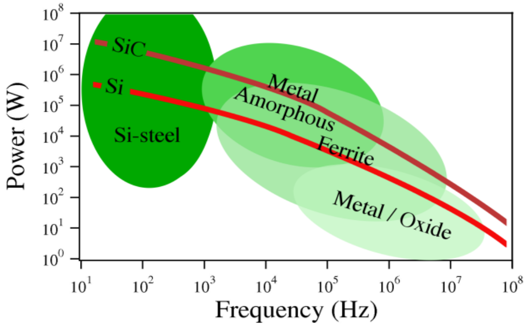


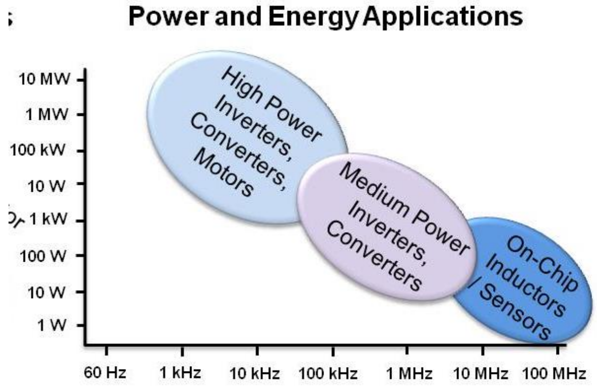
On-going Industrial Collaborations Demonstrating Performance Improvements on Commercial Cells

SOFCs Also Offer Many Advantages at Distributed Generation Scale

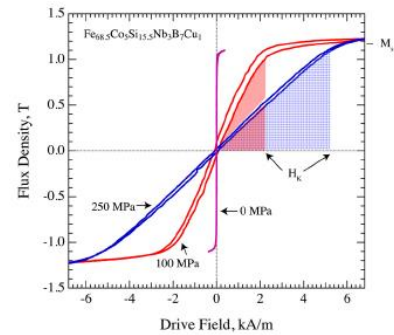
Soft Magnetic Material / Device Development

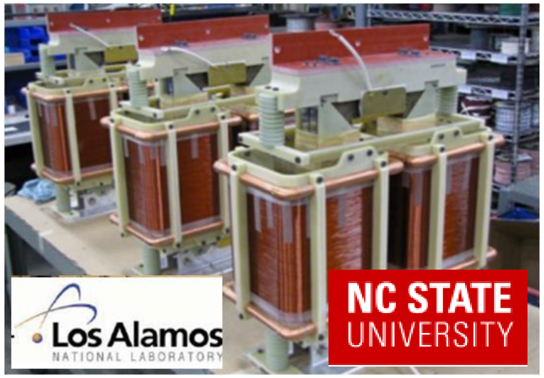
Carnegie Mellon University



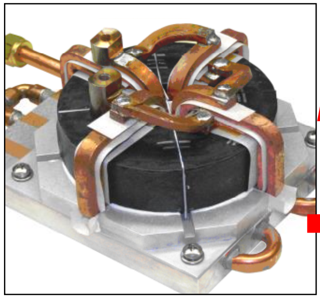


Key Success = Tunable Permeability Alloys





Tunable Permeability Enables New Device Innovations



e.g. Eliminate Gapping

Previously Supported by ARPA-E Solar ADEPT

Currently Supported by DOE EERE SETO

- *Manufacturing Research of alloys and magnetic cores*
- *Transformer / Converter functionality, cost, and efficiency*
- *Current / Field Sensor functionality, cost, and telemetry*

On-going Alloy and HF Transformer Development

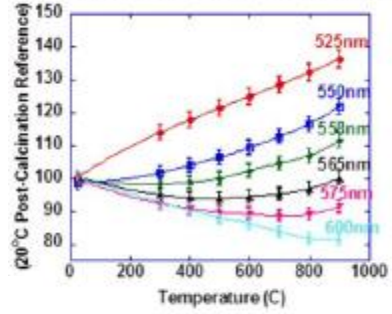
Overall Capabilities are Housed Across CMU, NETL, and NASA GRC

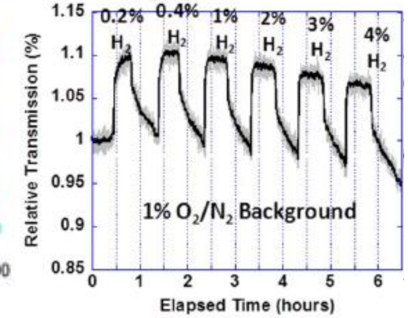
Harsh Environment Sensor Material / Device Development

Short Term Focus

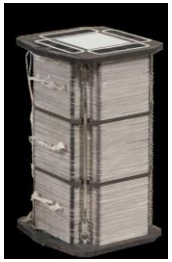
	Coal Gasifiers	Combustion Turbines	Solid Oxide Fuel Cells	Advanced Boiler Systems
Temperatures	Up to 1600°C	Up to 1300°C	Up to 900°C	Up to 1000°C
Pressures	Up to 1000psi	Pressure Ratios 30:1	Atmospheric	Atmospheric
Atmosphere(s)	Highly Reducing, Erosive, Corrosive	Oxidizing	Oxidizing and Reducing	Oxidizing
Examples of Important Gas Species	H_2, O_2, CO, CO_2, H_2O, H_2S, CH_4	O_2 Gaseous Fuels (Natural Gas to High Hydrogen), CO, CO_2, NO_x, SO_x	Hydrogen from Gaseous Fuels and Oxygen from Air	Steam, CO, CO_2, NO_x, SO_x

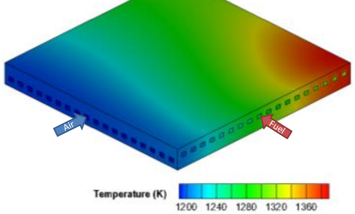
Key Success = In-Situ Anode Stream H_2 and Temp. Sensor





Example : Solid Oxide Fuel Cells Internal Gas and Temperature Distribution

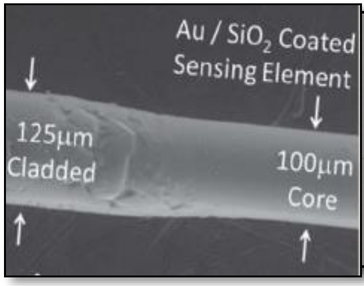


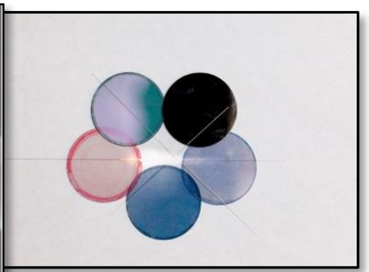


Incompatible with Traditional Sensing Technologies

1) Limits of High Temperature Electrical Insulation
2) Limited Access Space
3) Requires Multi-Point Sensing
4) Electrified Surfaces
5) Flammable Gas Atmospheres

Low-Cost, Multi-Parameter (H_2, T), Compatible with Distributed





Supports DOE NETL Crosscutting Program

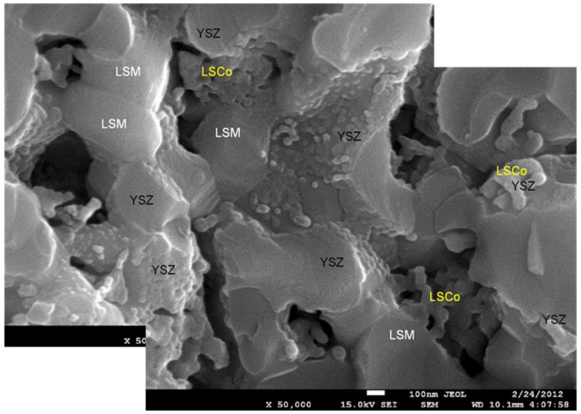
- *Enabling / demonstrating new embedded sensor technology*
- *Accessing high-value process information*

On-going Technology Development and Testing in Operational SOFCs

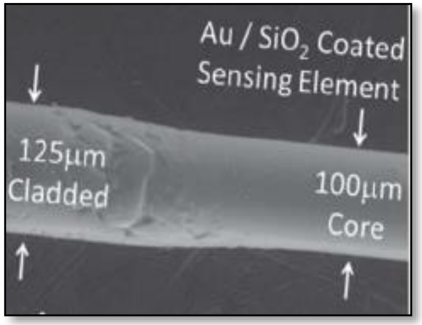
Sensor Development for Distributed, Multi-Parameter Monitoring

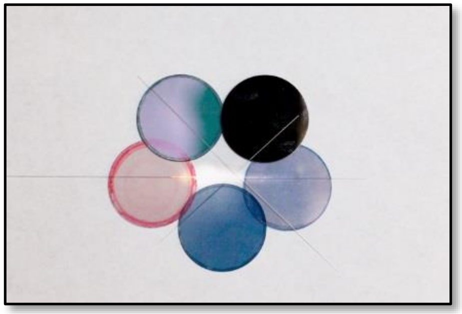
Example of Cross-Disciplinary Research

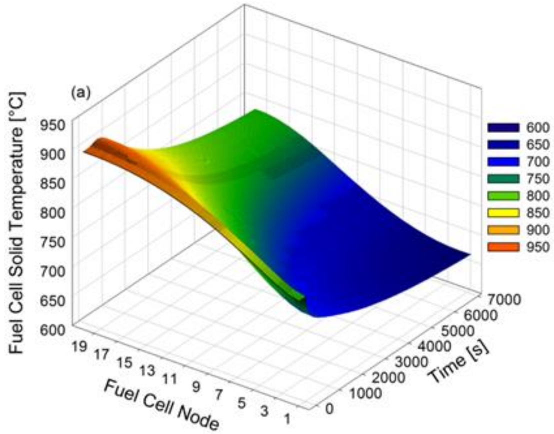
SOFC Materials Engineering for Improved Device Figure of Merits

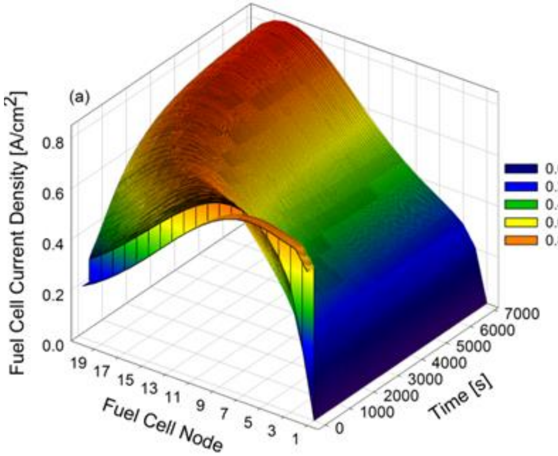


Sensor Materials Engineering to Enable Harsh Environment Sensors for Embedded SOFC Monitoring



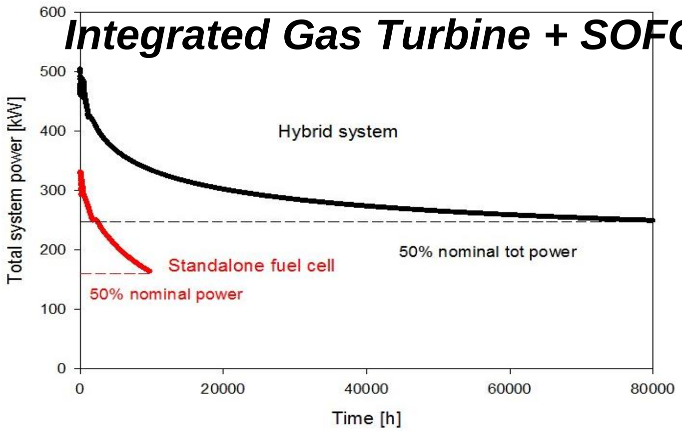






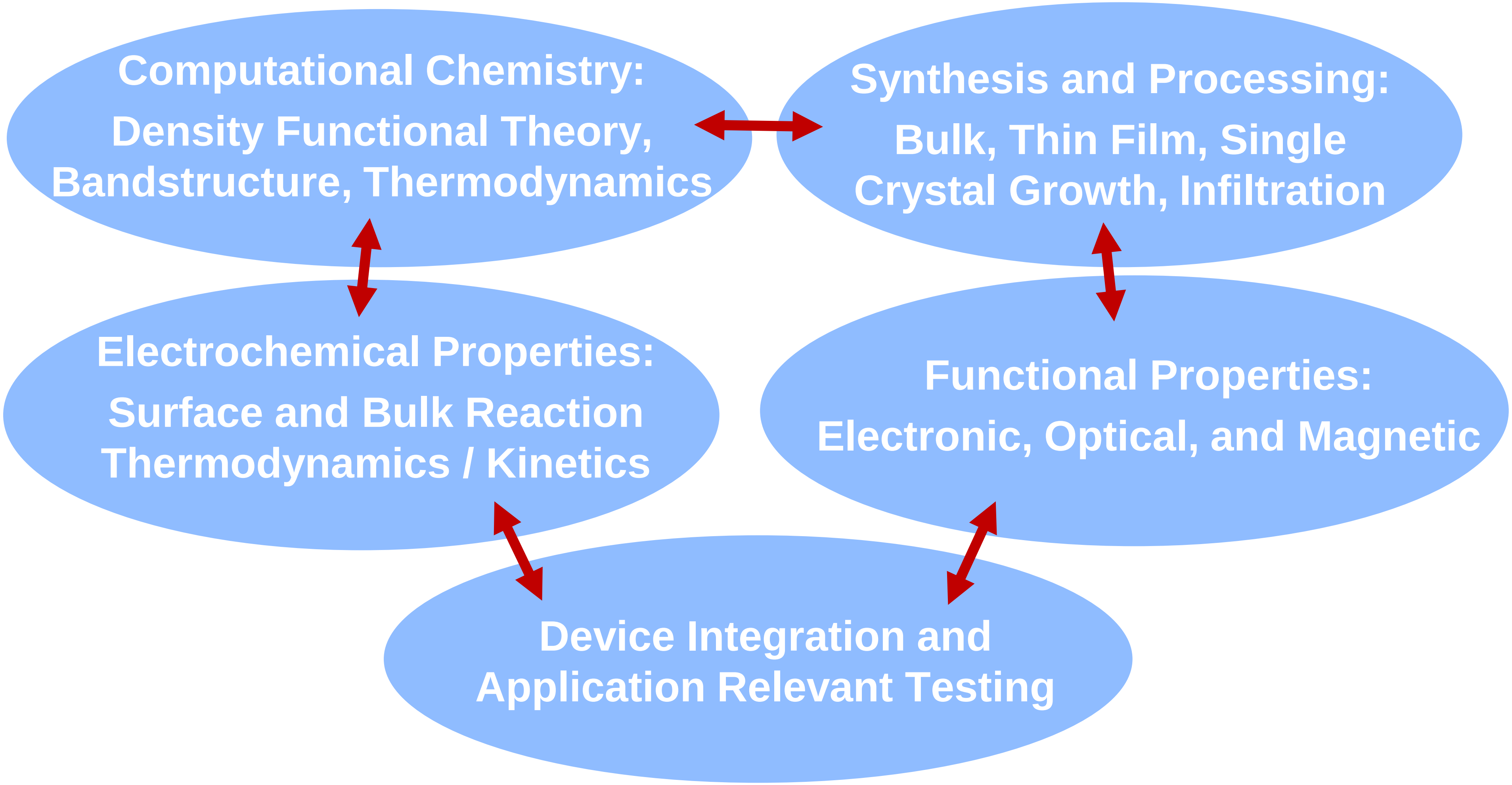
Hybrid Power Systems

Integrated Gas Turbine + SOFC



Combining Device Performance and Embedded Sensing Information with Advanced Controls in Hybrid Power Systems to Maximize Efficiency / Lifetime / Flexibility.

High Temperature Functional Electroceramic Oxides and Integration with Devices

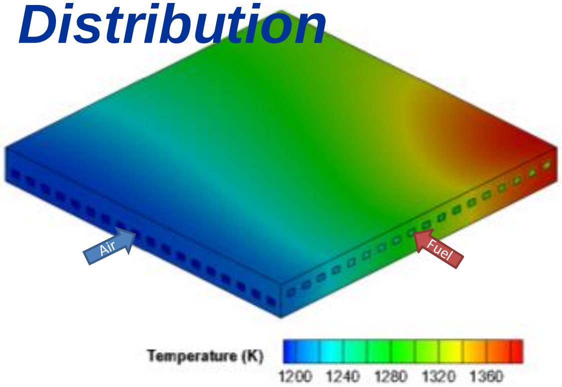


Research Efforts in Functional Oxide Material Research Spanning Use-Inspired Basic to Application Relevant Device Testing

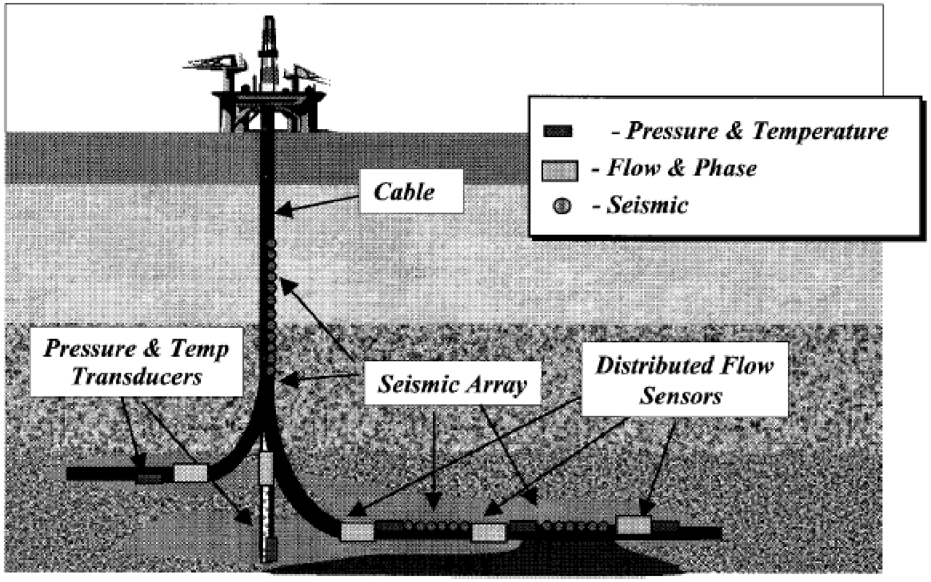
NETL Sensor Material and Optical Fiber Sensor Program Overview

NETL Needs / Capabilities in Harsh Environment Sensing

Example : Solid Oxide Fuel Cells Internal Gas and Temperature Distribution



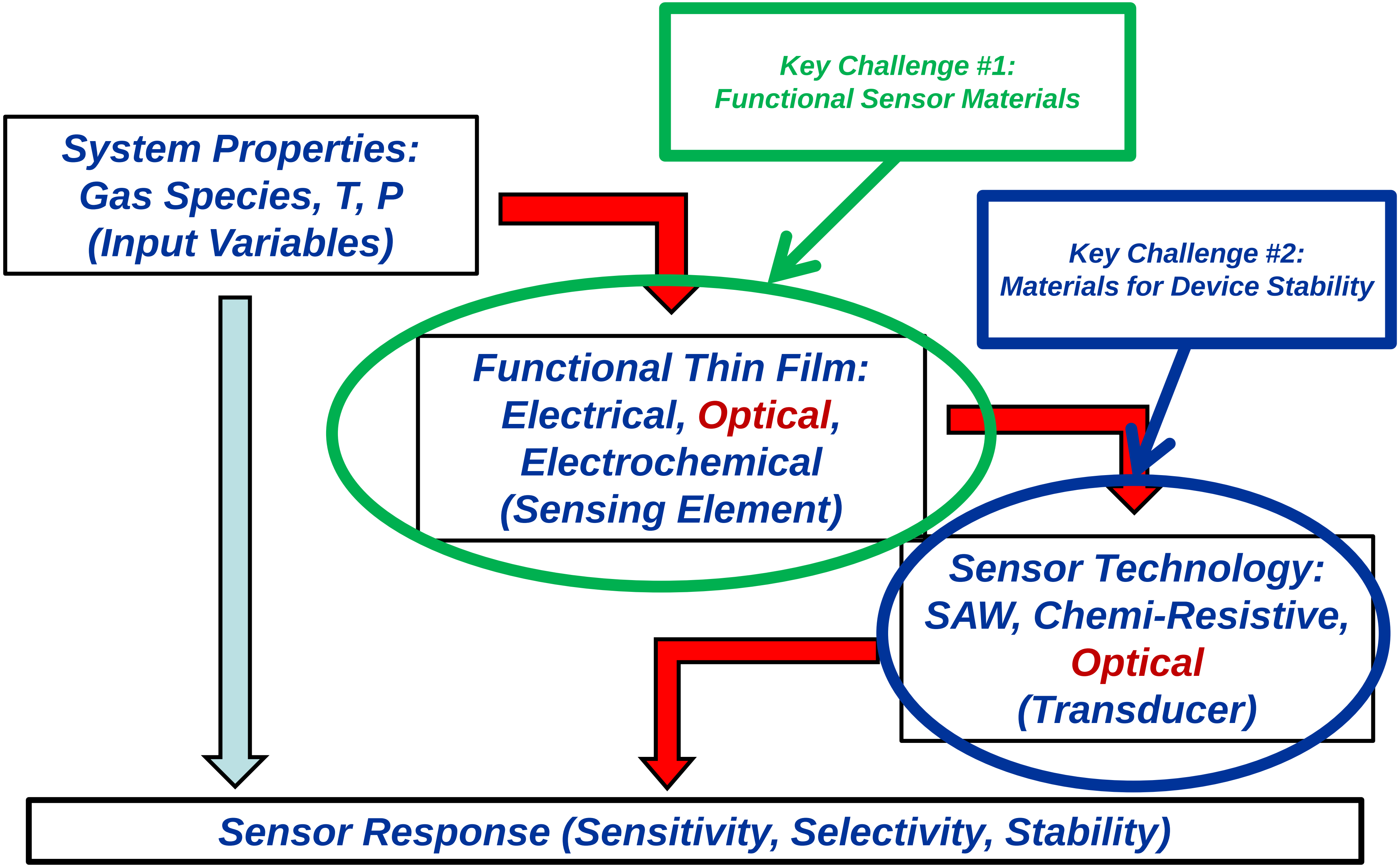
High Temperature Power Generation Systems



High Temperature, High Pressure Subsurface Wellbores and Geological Formations

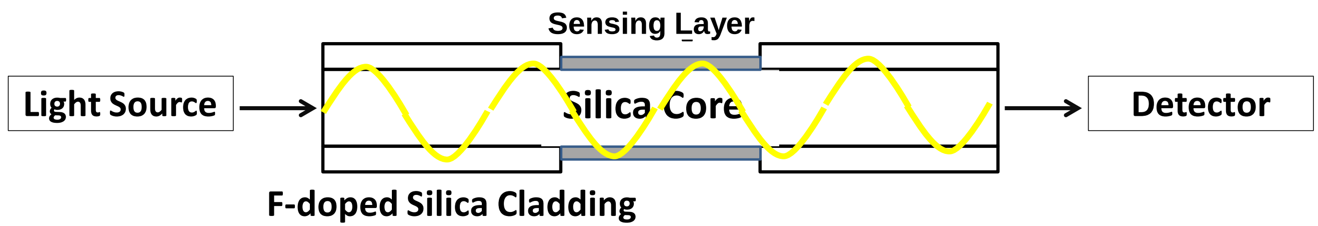
NETL Has Needs, On-going Funded Projects, and In-House Research Activity in Harsh Environment, Low Cost Sensing for a Broad Array of Applications

Sensor Materials in Harsh Environment Sensing Applications



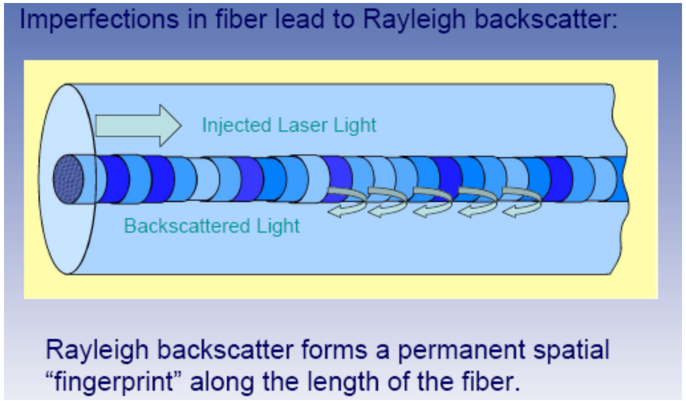
Emphasis on Optical Based Sensing Platforms / Materials

e.g. Evanescent Wave Sensors



Optical Backscattering Based Reflectometry

- → ***Elimination of Electrical Wiring and Contacts at the Sensing Location***
- → ***Can Be Tailored to Particular Parameters of Interest Through Integration with Functional Materials***
- → ***Eliminate EMI and Potential Interference with Electrical and Electrified Systems***
- → ***Compatibility with Broadband and Distributed Interrogation***

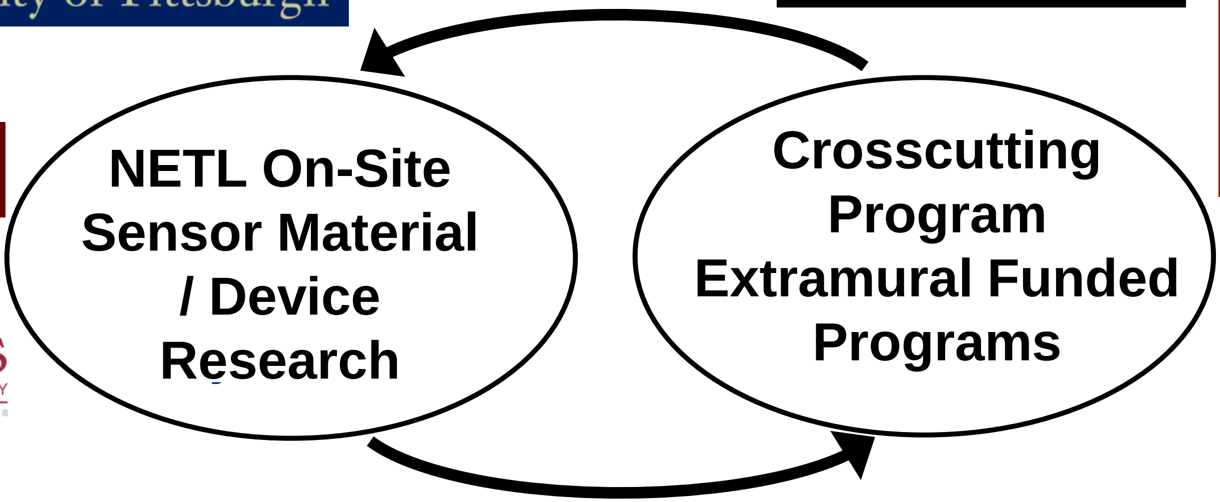


Optical Fiber Based Sensors are Particularly Well-Suited for Harsh Environment and Electrified System Applications.

Leveraging Partnerships with Extramural Funded Projects

10 – Joint Publications (U. Pitt, U. Albany, OSU, U. Conn. VA Tech)

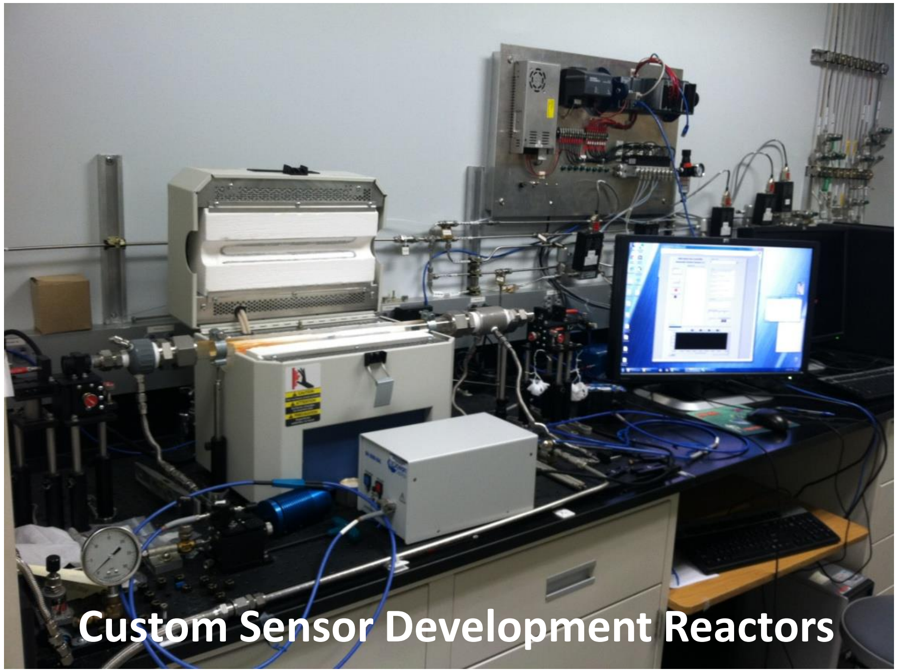
4 – Joint Patent Applications (U. Pitt., Stevens, OSU)

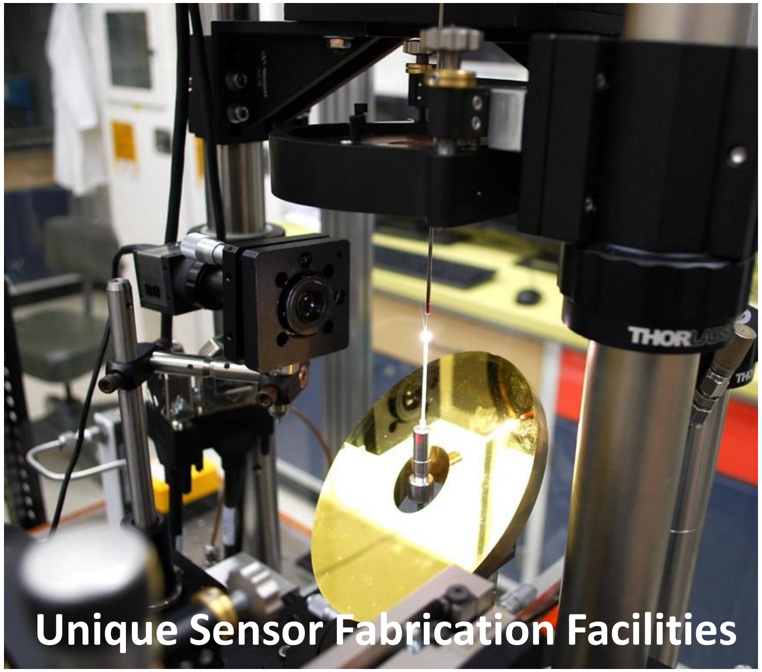


NETL On-Site Research Efforts Both Benefit From and Provide Additional Value to Extramural Solicited Programs in Related Areas.

NETL Manages Major Extramural Research Activity in Harsh Environment Sensing.

Unique Facilities of the On-Site Research Team





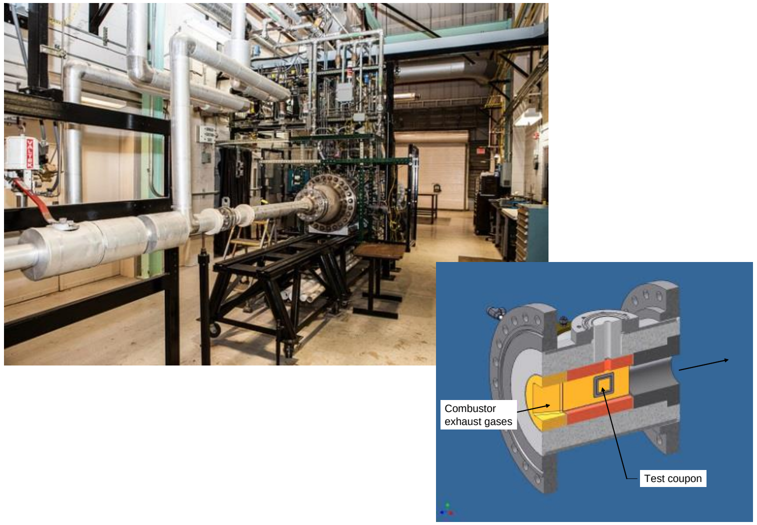
Custom Sensor Development Reactors Simulate:

→ **Power Generation and Combustion Systems**
→ **Subsurface / Geological Environments**
→ **Pressurized Gas and Oil-Based Systems**

NETL On-Site Research Has Developed Capabilities for Necessary for Sensor Material and Optical Fiber Sensor Device Development and Optimization for Harsh Environment Applications.

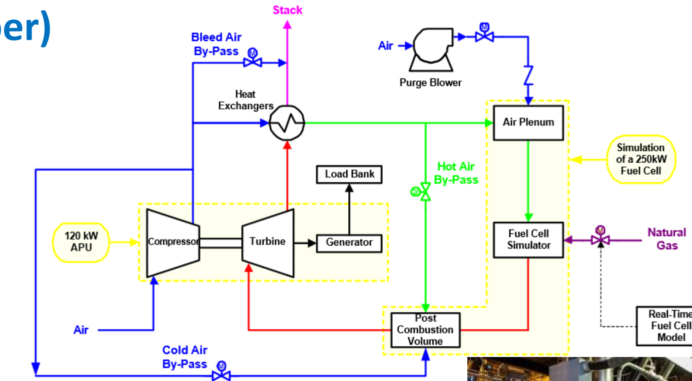
Pilot-Scale Combustion, Turbine, and SOFC Facilities at NETL

High-Pressure Combustion Facility (Aerothermal Rig)



- Simulates hot gas path of a turbine
- Natural gas or hydrogen fuel
- Capable of 2 lb/s air flow @ 10atm
- Temperature: up to 1300°C
- Optically-accessible combustor and test sections

Hybrid Performance Facility (Hyper)

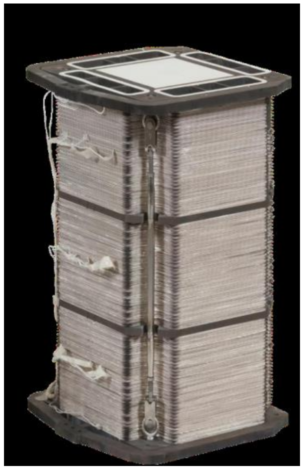


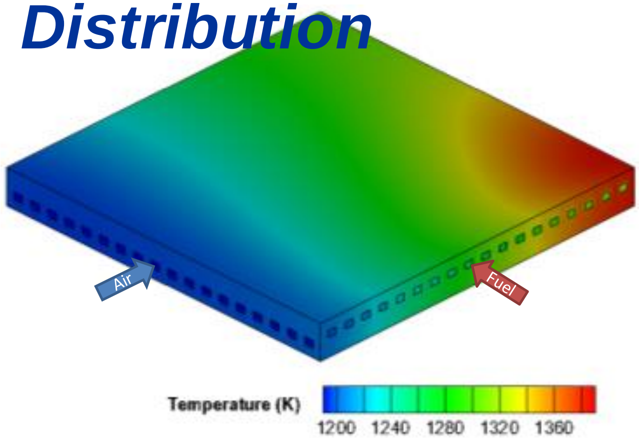
- A 300kW solid oxide fuel cell gas turbine (SOFC-GT) power plant simulator
- 120 kW Garrett Series 85 APU with single-shaft turbine, 2-stage radial compressor, and gear driven generator
- 100+ process variables measured including rotational speed (1,200Hz; 40,500 rpm), air/fuel flow, temperature (turbine: 637°C; SOFC: 1133°C), pressure (up to 260kPa), etc.

Sensor Development Efforts Benefit from Access to Pilot Scale Facilities for Demonstration of Prototype Sensor Devices in Near-Application Environments.

On-Site Research Targets Embedded Sensing

Internal Gas and Temperature Distribution





Temperature : 700-800ºC
Anode Stream : Fuel Gas (e.g. H_2-Containing)
Cathode Stream : Air or O_2

SOFCs:
Incompatible with Traditional Sensing Technologies

1) **Requires High Temperature Electrical Insulation**

2) **Limited Access Space**

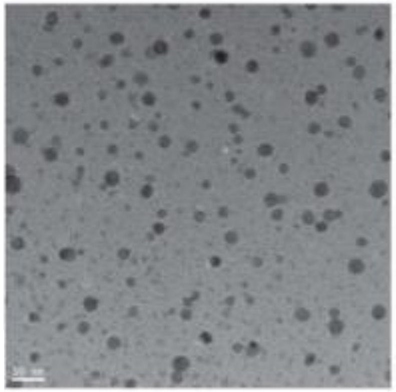
3) **Only Single-Point, Single-Parameter Sensing**

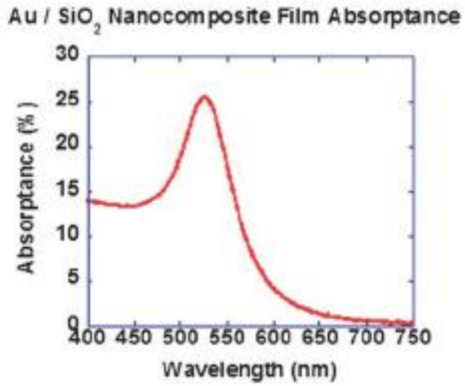
Gradients in Temperature and Composition of Gas Stream Internal to an SOFC are Critical Process Parameters for Maximized Efficiency / Lifetime.

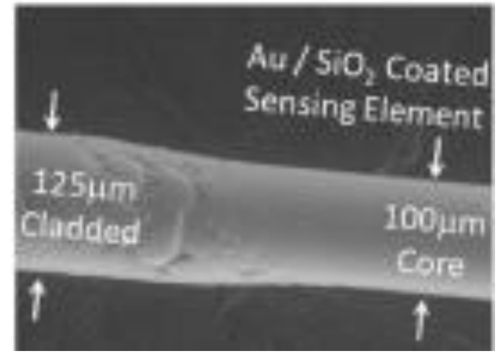
In-House Efforts Have Exploited the SOFC Technology as a Demonstration Platform for Harsh Environment Embedded Sensors in Electrified Components.

Highlights of Recent Successes and On-going Activities

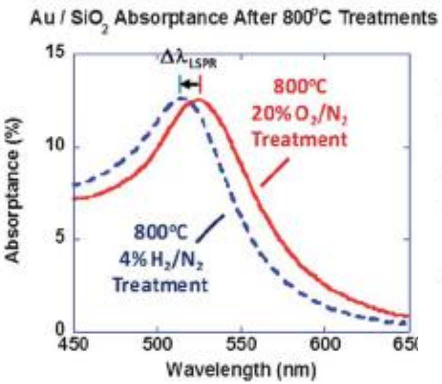
Plasmonic Nanocomposites for Optical Sensing



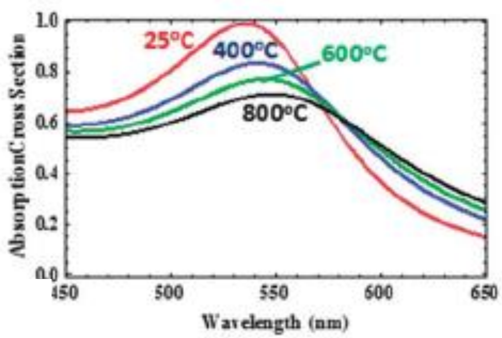




Gas Stream Response



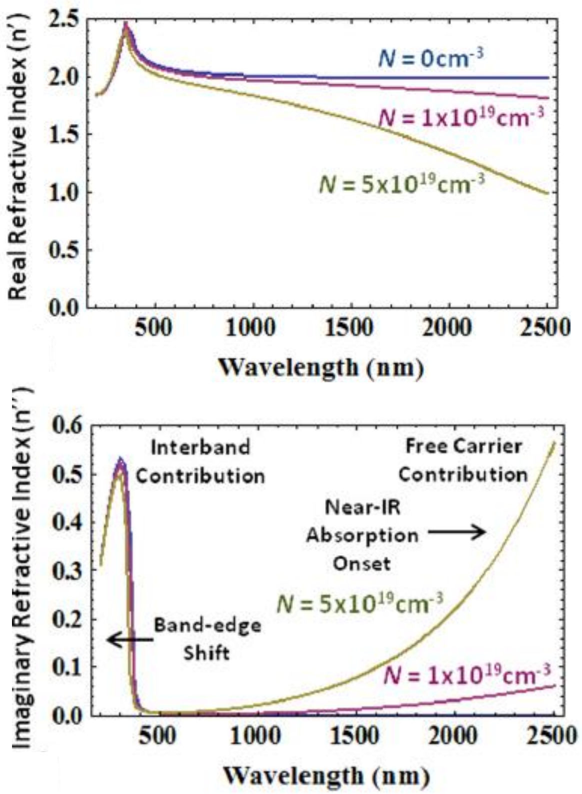
Temperature Response

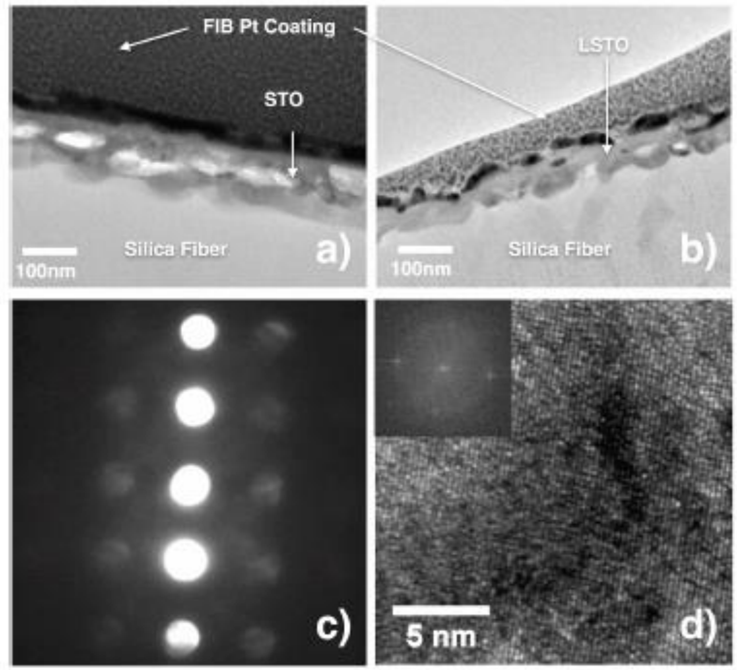


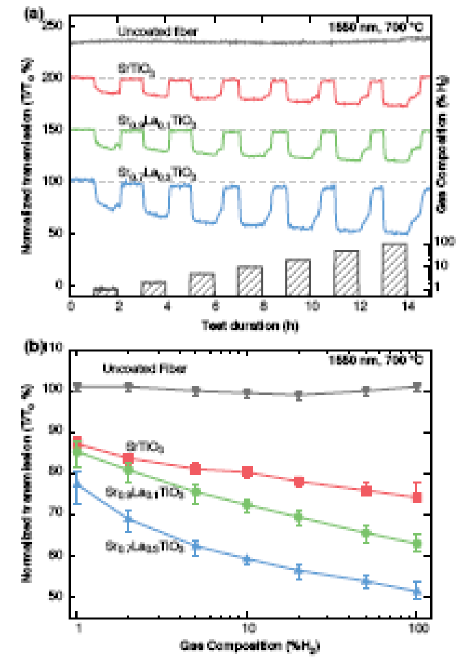
Au-Nanoparticle Incorporated Oxides Have Been Integrated with the Optical Fiber Sensing Platform to Functionalize for Temperature and Gas Stream Composition.

Broadband Wavelength Interrogation Allows for Multiparameter Monitoring Using a Single Sensor Element at Temperatures Relevant for Operational SOFCs (700-800ºC).

Plasmonic Oxides for Optical Sensing





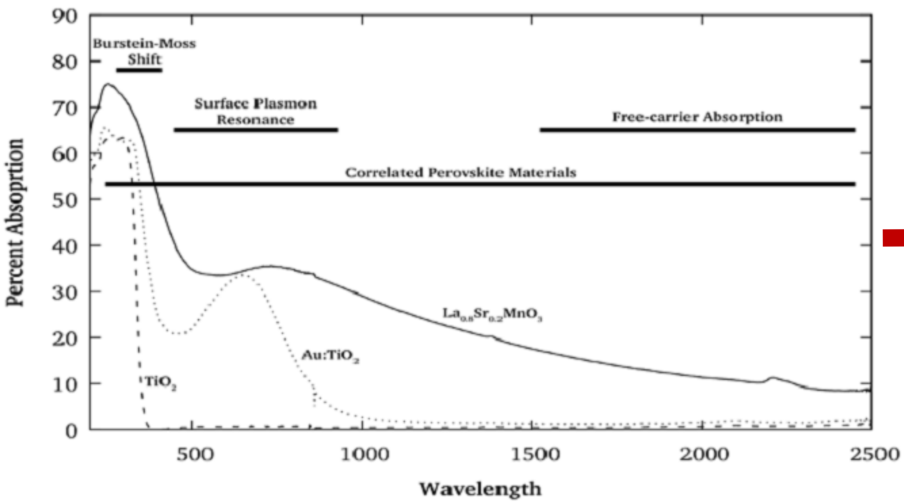


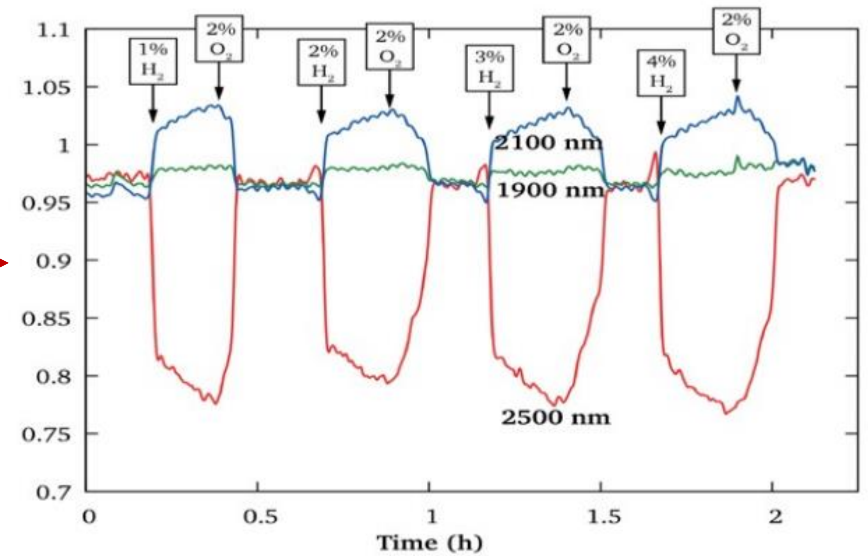
High Electronic Conductivity Oxides Have Been Demonstrated to Show Enhanced Sensing Responses as Compared to Traditional Sensing Oxides.

Perovskite Oxides Traditionally Used for SOFC Electrode Materials Have Been Leveraged as Sensing Materials in the Same Technology Platform.

Correlated Perovskite Oxides for Optical Sensing

$La_{1-x}Sr_xMnO_3$ and Related Perovskite Sensor Materials





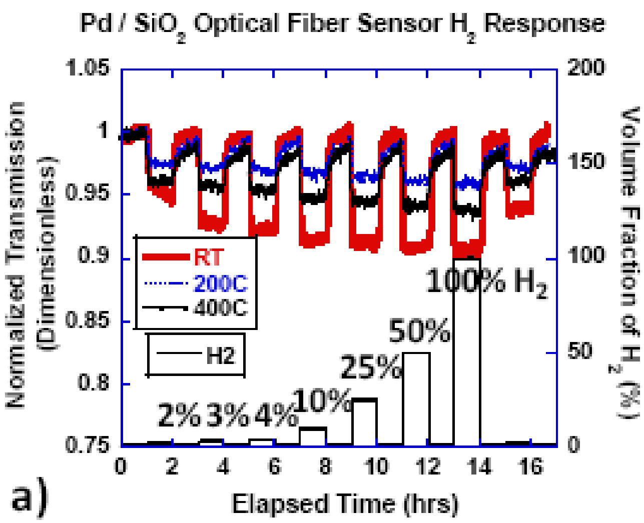
Nanophotonic Materials XII, edited by Stefano Cabrini, Gilles Lérondel, Adam M. Schwartzberg, Taleb Mokari,
Proc. of SPIE Vol. 9545, 95450I · © 2015 SPIE · CCC code: 0277-786X/15/$18 · doi: 10.1117/12.2188924

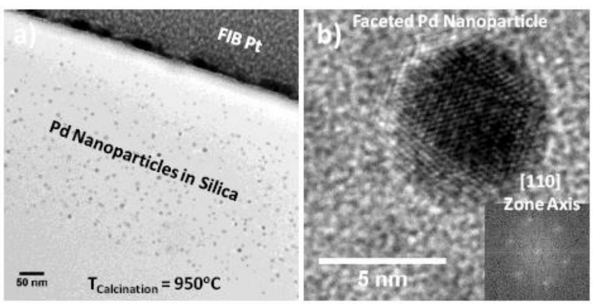
Correlated Perovskite Oxides are Currently Being Investigated in More Recent Efforts with Interesting Preliminary Results

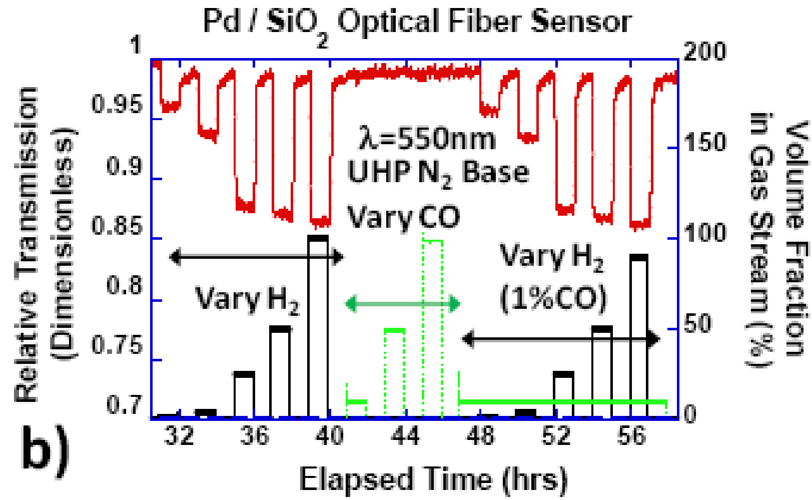
Basic Optical Properties in this Class of Oxides are Not Well Understood Due to Strong Electron – Electron Correlations

Pd-Nanoparticle Incorporated Oxides for Optical Sensing

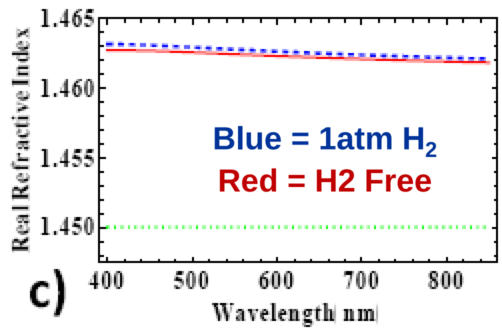
Monotonic and Selective H_2 Response from Ambient to Elevated Temperatures

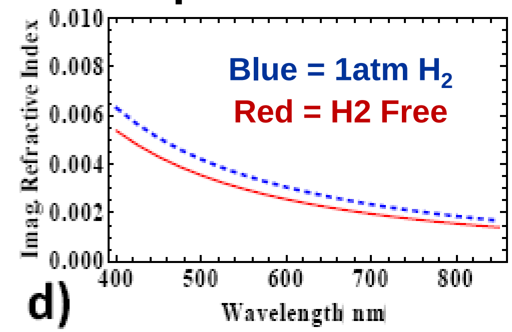






Pd-Index Mediated Responses



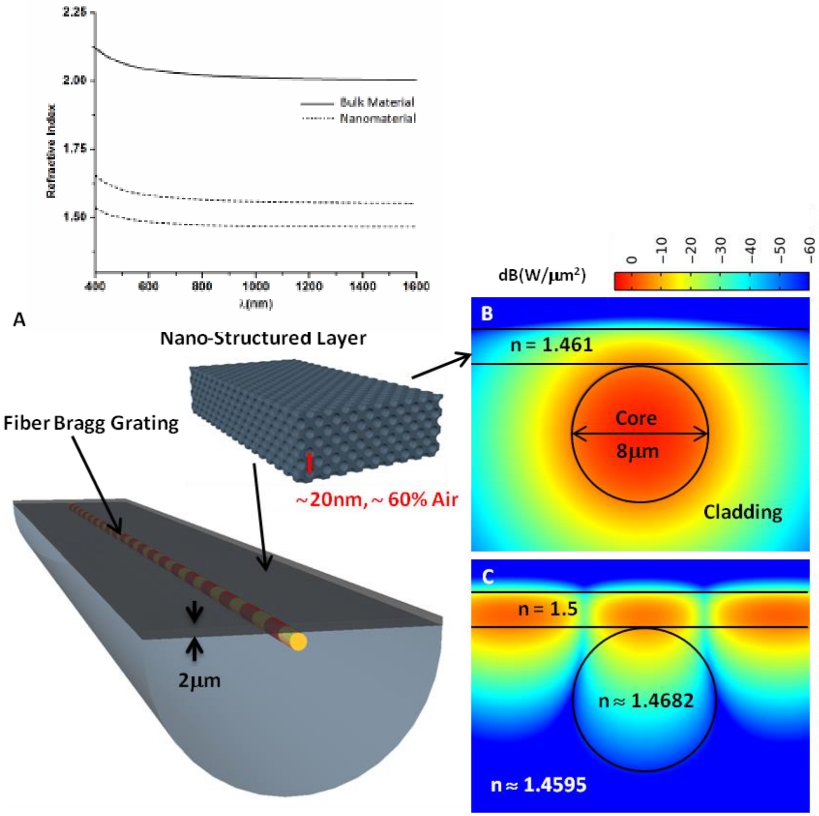


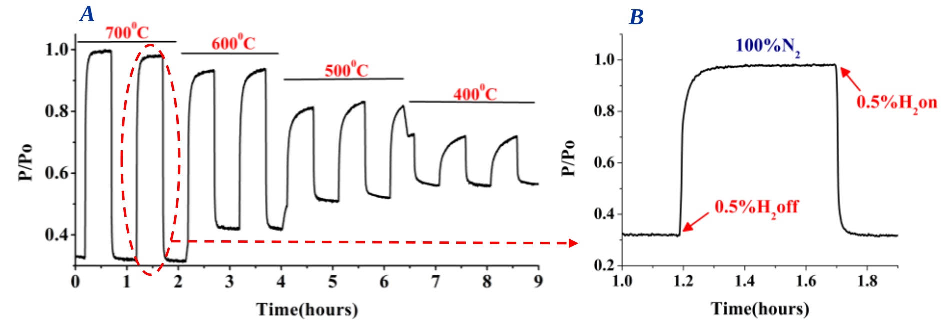
Optical Transmission Modifications for Pd-SiO2 and Related Systems are Associated with Changing Real and Imaginary Refractive Indices of Pd Nanoparticles Due to H2 Absorption in Bulk Lattice.

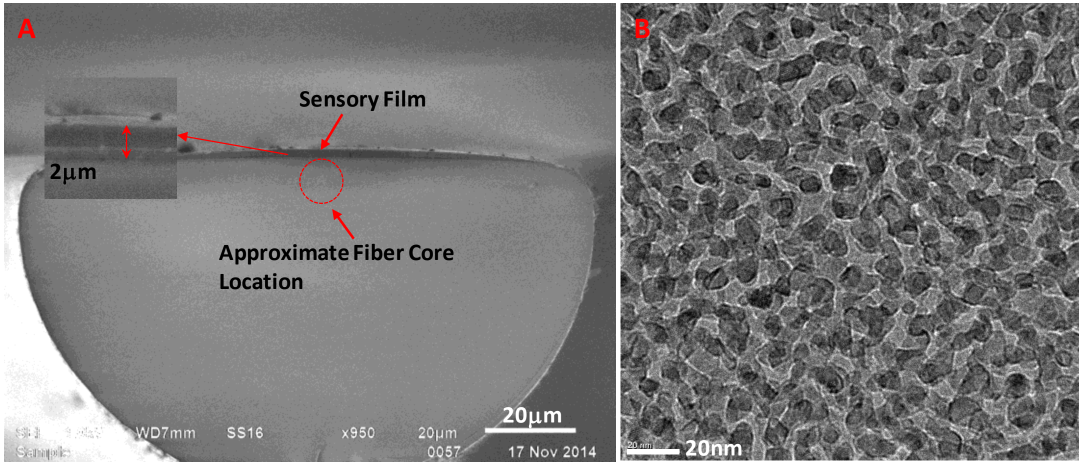
Nanostructuring of Functional Oxides for Optical Sensing

Nanostructuring to Tailor Refractive Index for Device Compatibility

University of Pittsburgh

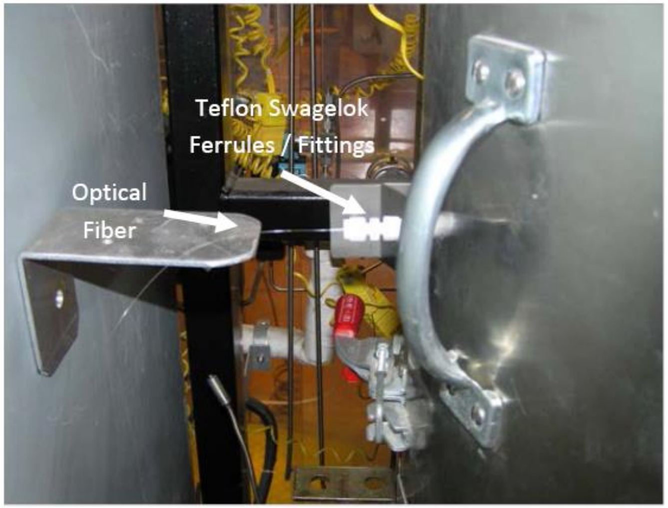


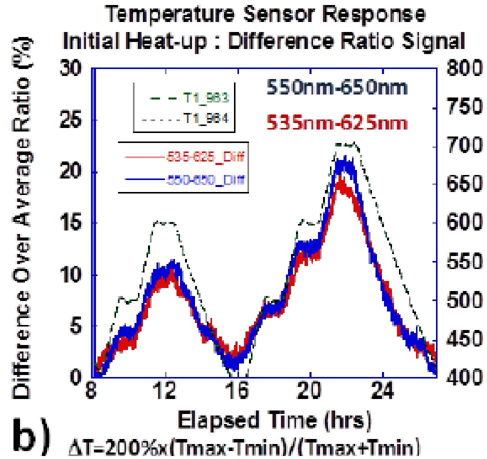


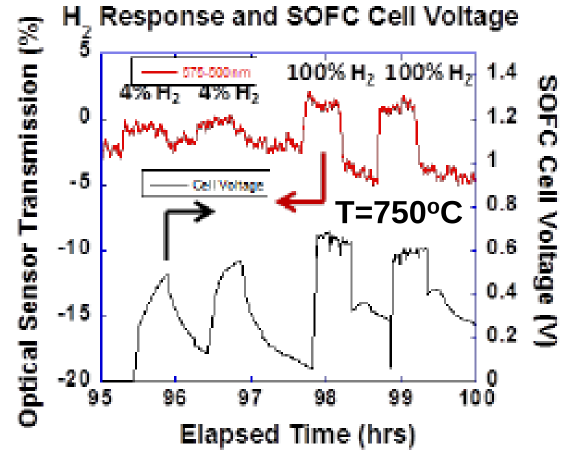


For Oxide-Based Functional Sensor Layers, Engineering of Sensing Layer Porosity can Enhance Responses for Thick Film Sensing Layers.

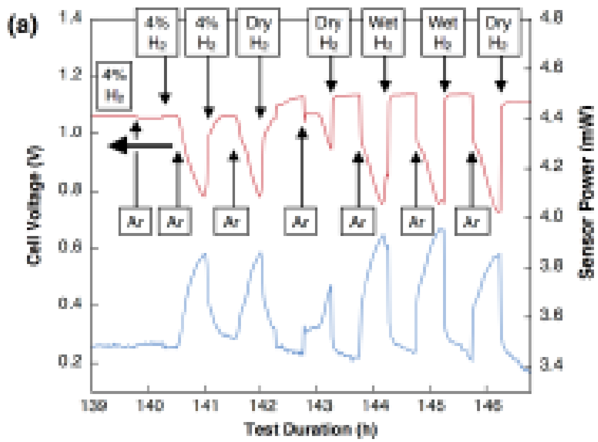
Demonstrations in Operational SOFC Systems



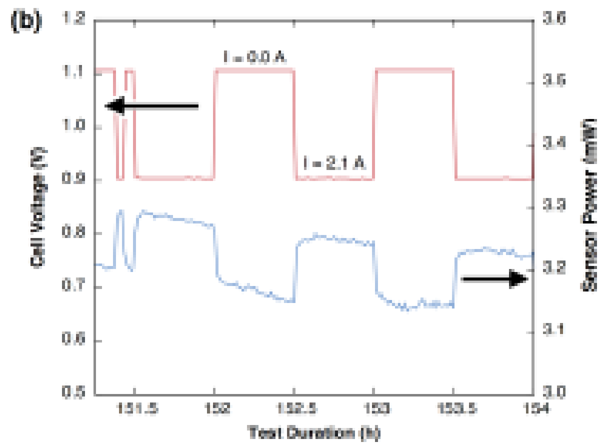




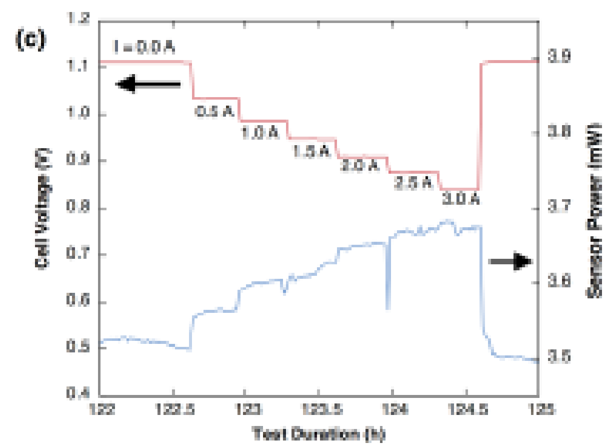
Fuel Gas Stream Variations



Fuel Utilization

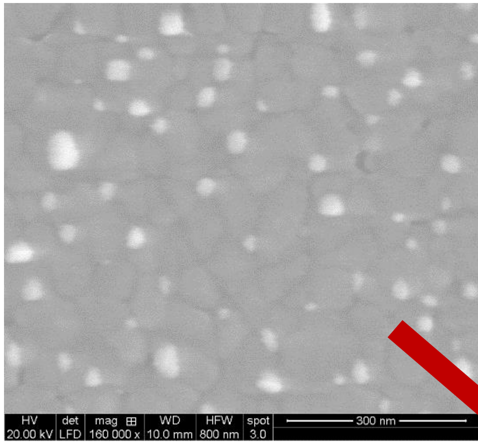


Fuel Utilization



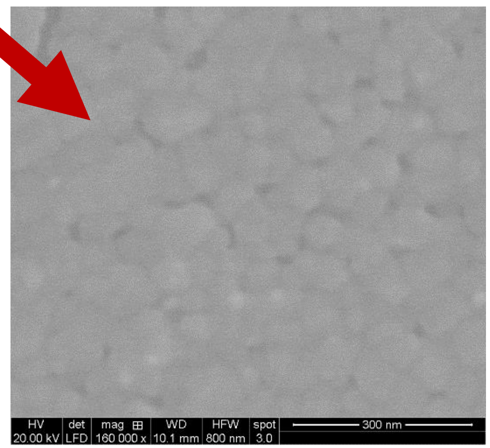
Optical Fiber Sensors Have Been Demonstrated for Temperature and H_2 Concentration in Operational SOFCs with Correlations to Electrochemical Potential and Fuel Utilization.

"Realistic" Exposure Testing of Sensor Materials

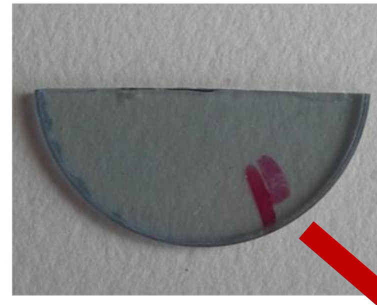


Au / TiO_2
Pre-Exposure

800^{o}C
29% H_2/N_2

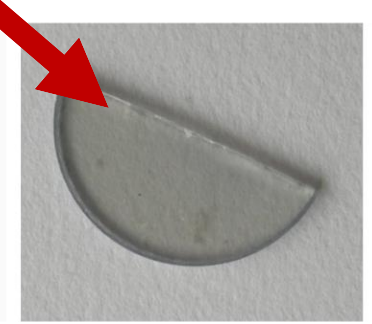


Au / TiO_2
Pre-Exposure



700^{o}C
29% H_2/N_2

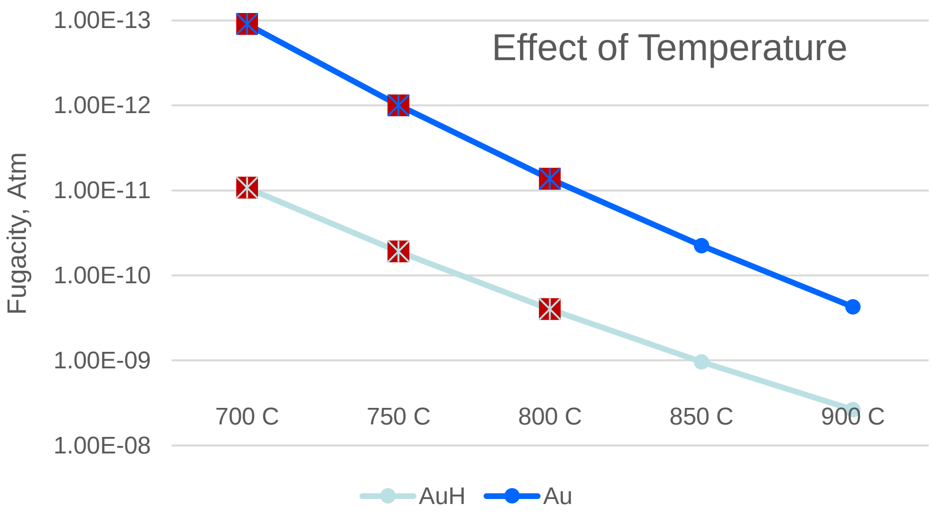
800^{o}C
1% H_2/N_2



800^{o}C
29% H_2/N_2

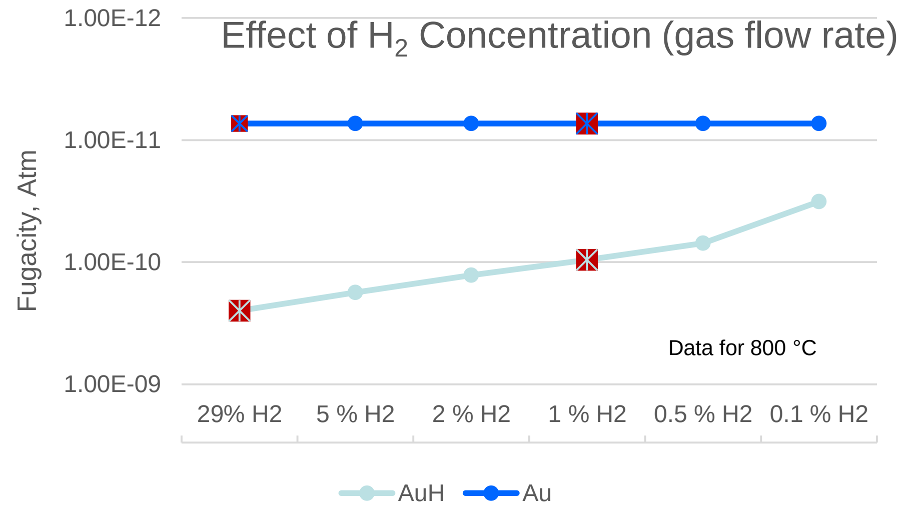
Application Relevant Exposures Illustrate Gas Composition Dependent Instabilities with Mass Loss of Au From the Substrate for Week-Long Exposures at ~800^{o}C.

“Realistic” Exposure Testing of Sensor Materials



Higher Thermodynamic Fugacity
= Higher Partial Vapor Pressure in Gas Phase

FactSage
Thermodynamic Calculations



The Mechanism Has Been Confirmed as Reactive Evaporation Based on Thermodynamic Calculations and Mitigation Strategies Are Being Developed.

Theoretical Modeling of High Temperature Oxides

DFT Based Modeling of Electronic Ground State

Dielectric Constants → **Optical Constants**

Lattice Phonon Dispersion → **Thermodynamic Properties**

Direct Summation Over Empty States

$$\varepsilon^{(2)}_{\alpha\beta}(\omega) = \frac{4\pi^2 e^2}{\Omega} \lim_{q\to 0} \frac{1}{q^2} \sum_{c,v,\mathbf{k}} 2w_{\mathbf{k}} \delta(\epsilon_{c\mathbf{k}} - \epsilon_{v\mathbf{k}} - \omega) \times \langle u_{c\mathbf{k}+\mathbf{e}_\alpha \mathbf{q}} | u_{v\mathbf{k}} \rangle \langle u_{c\mathbf{k}+\mathbf{e}_\beta \mathbf{q}} | u_{v\mathbf{k}} \rangle^*,$$

Kramers-Kronig Relationship

$$\varepsilon^{(1)}_{\alpha\beta}(\omega) = 1 + \frac{2}{\pi} P \int_0^\infty \frac{\varepsilon^{(2)}_{\alpha\beta}(\omega')\omega'}{\omega'^2 - \omega^2 + i\eta} d\omega',$$

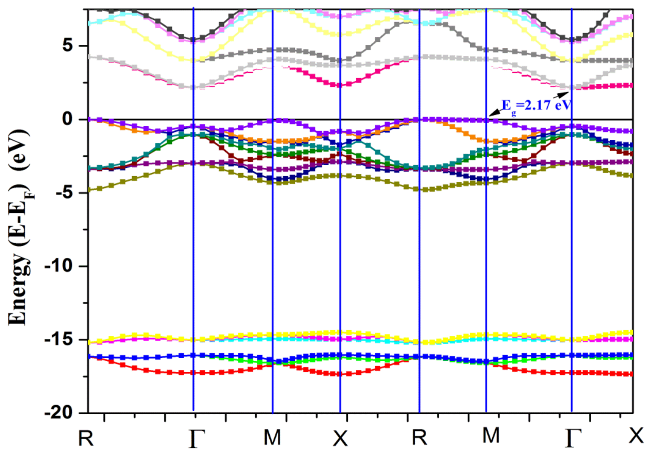
Supplement Ground State with Phonon Free Energy Contributions

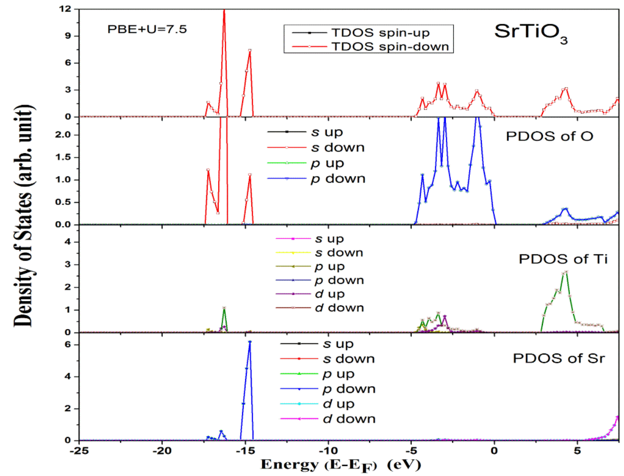
$$\Delta\mu^0(T) \approx \Delta E^{DFT} + E_{ZP} + F^{PH}(T)$$

$$F_{harm}(T) = rk_B T \int_0^\infty g(\omega) \ln[2\sinh(\frac{\hbar\omega}{2k_B T})] d\omega$$

First Principles Theoretical Modeling and Related Techniques are Difficult to Apply in the Area of High Temperature Operational Environments. This is Particularly True for Optical and Electronic Properties of Materials Which are Related to Bandstructure.

Theoretical Modeling of High Temperature Oxides





DFT+PBE+GGA+U

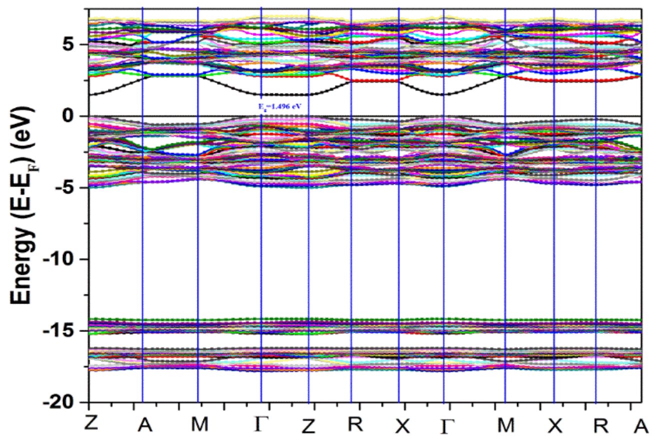
U(Ti(3d))=7.5

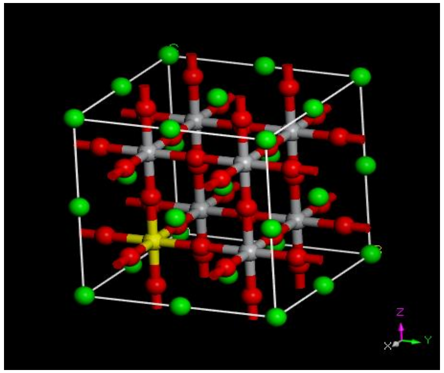
The calculated band-gap:

2.17 eV (indirect)

3.03 eV (direct)

Adjusted U-Parameter for Greatest Consistency with Experiment



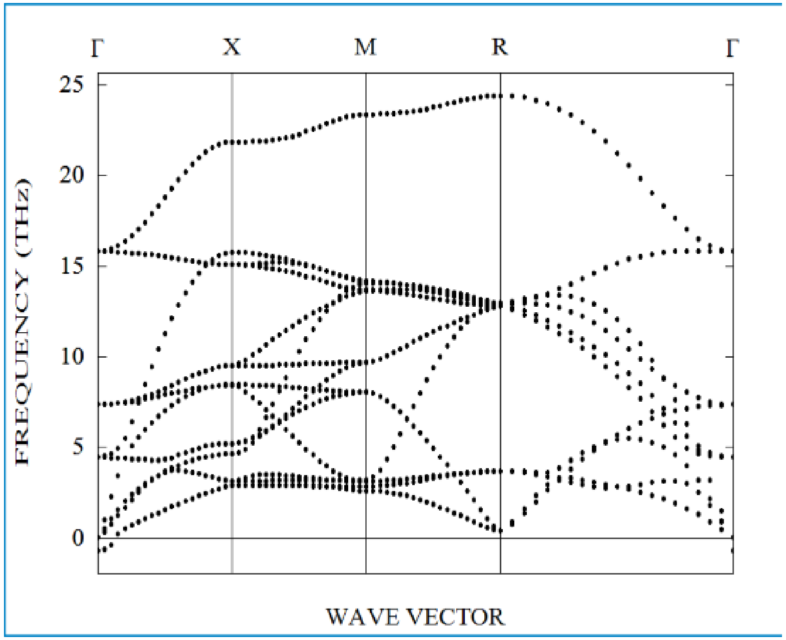


La – Doping Adds an Electron to the Conduction Band and is Predicted to Result in Spin Polarization

$SrTiO_3$ and Doped Variants are a Starting Point for the Calculations Due to Relative Simplicity and a Large Number of Previous Investigations.

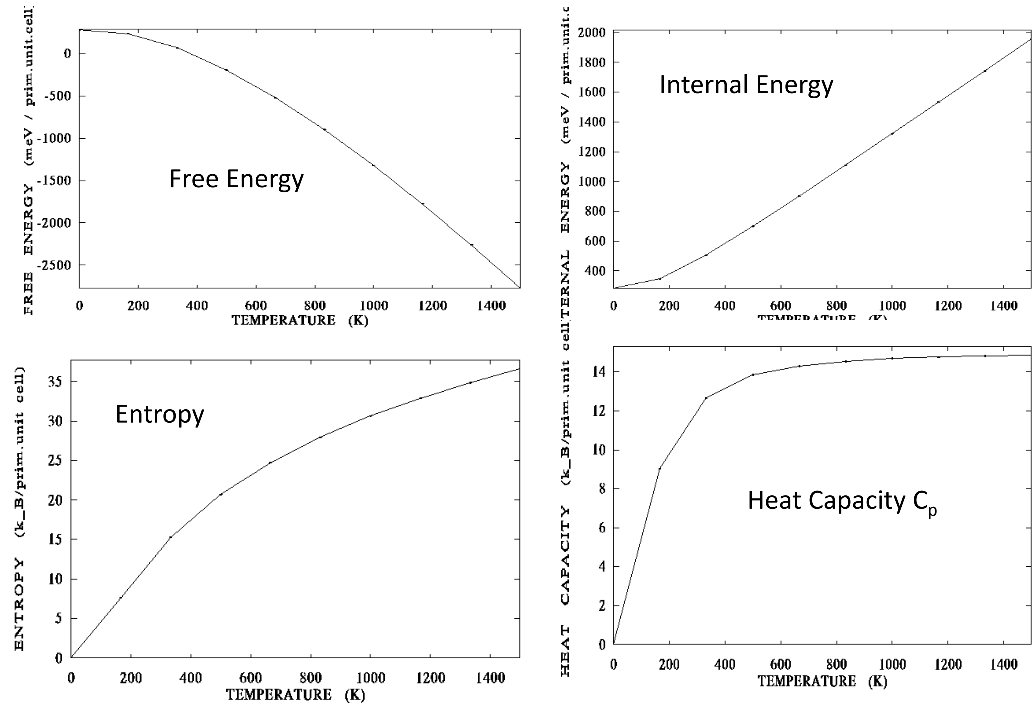
Theoretical Modeling of High Temperature Oxides

Phonon Dispersion



1 f.u. in primitive cell. N=5
3N vibrations with 15 branches

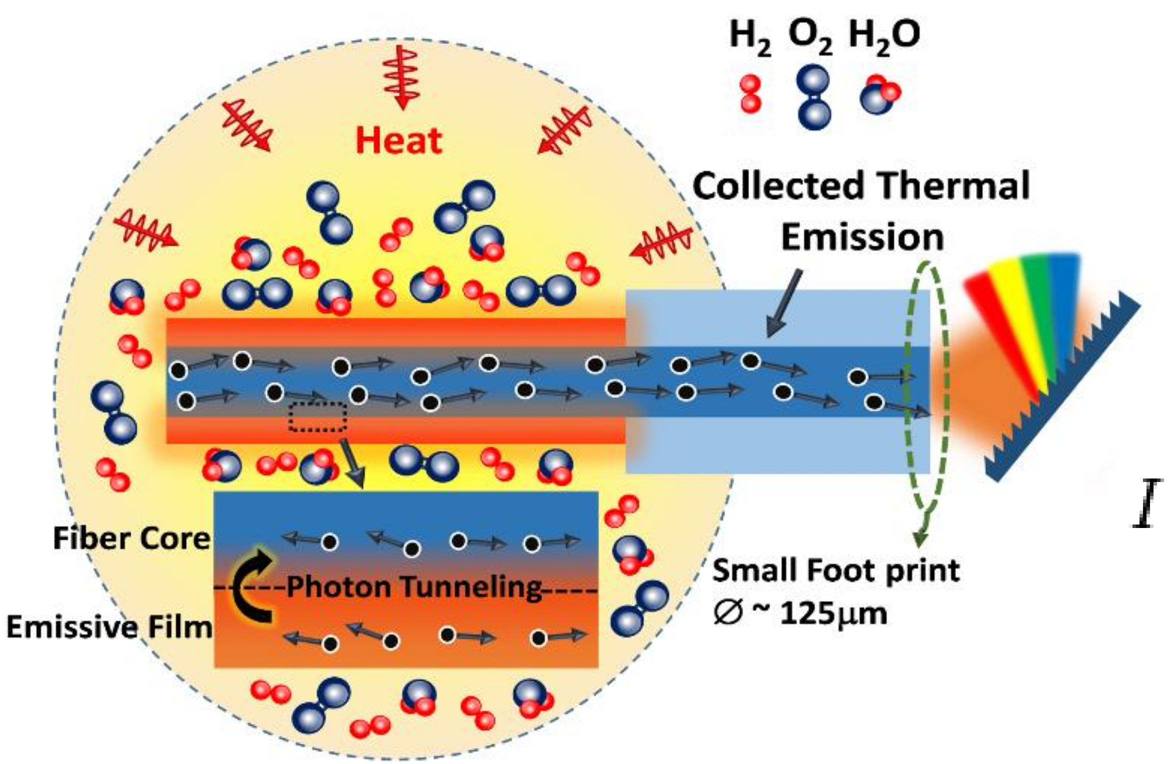
Calculated Thermodynamic Quantities



Derived from DFT Electronic Ground State

Phonon Dispersion for $SrTiO_3$ Has Been Calculated and is Being Used to Estimate Thermodynamic Parameters for Finite Temperature Simulations.

Thermal Emission Based Sensing



Exploiting Kirchoff's Law Between Absorptivity / Emissivity

Planck's Law of Blackbody Radiation

$$I(\nu, T) = \frac{2h\nu^3}{c^2} \frac{1}{e^{\frac{h\nu}{kT}} - 1}$$

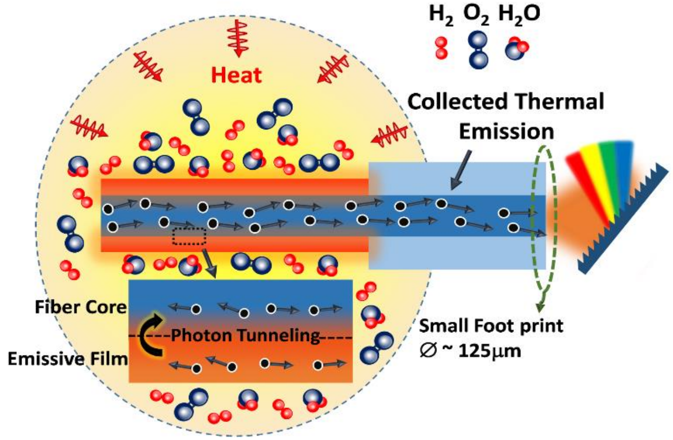
$$\alpha_\lambda = \epsilon_\lambda$$

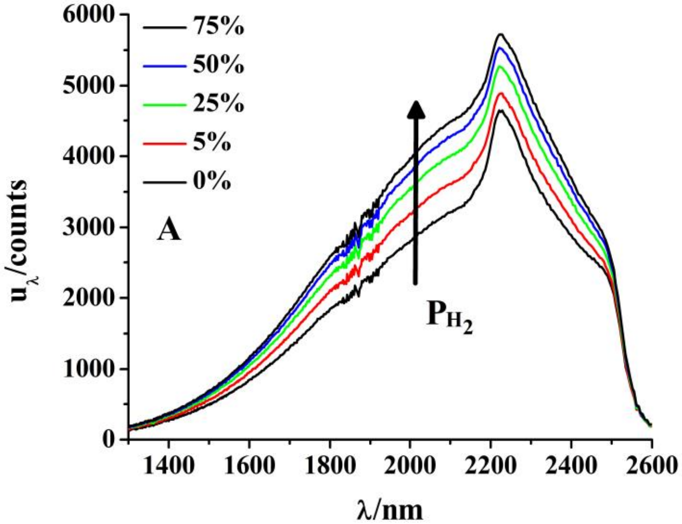
Absorptivity ***Emissivity***

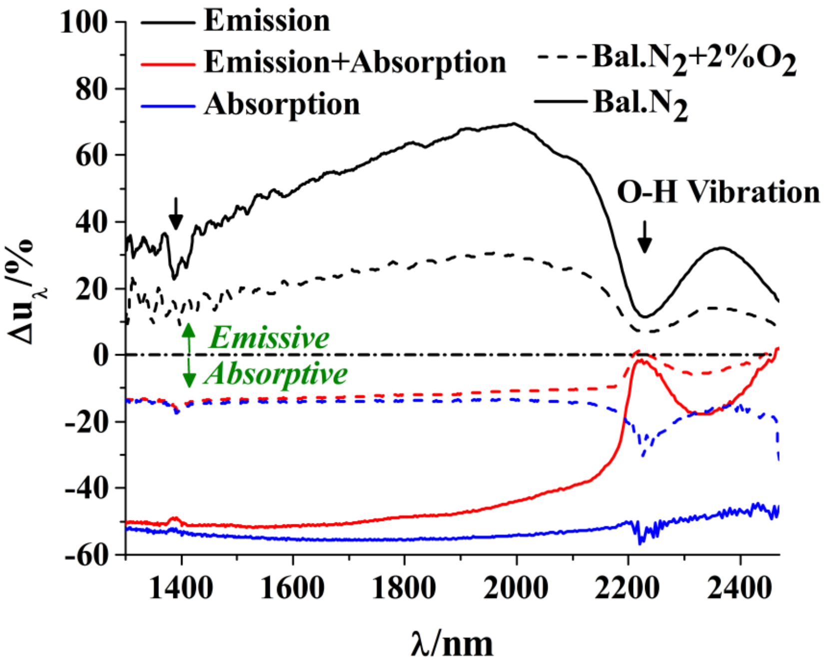
Thermal Energy Harvesting "Source-Free" Based Fiber Optic Chemical Sensors are Now Possible By Leveraging Thermal Emission Properties of Sensing Materials.

We are Working to Understand How This Discovery Can Be Fully Leveraged.

Thermal Emission Based Sensing





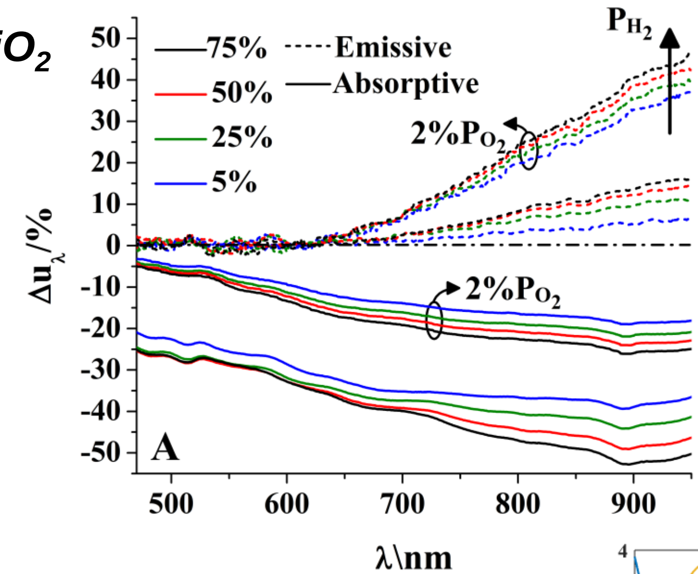


Thermal Energy Harvesting "Source-Free" Based Fiber Optic Chemical Sensors are Now Possible By Leveraging Thermal Emission Properties of Sensing Materials.

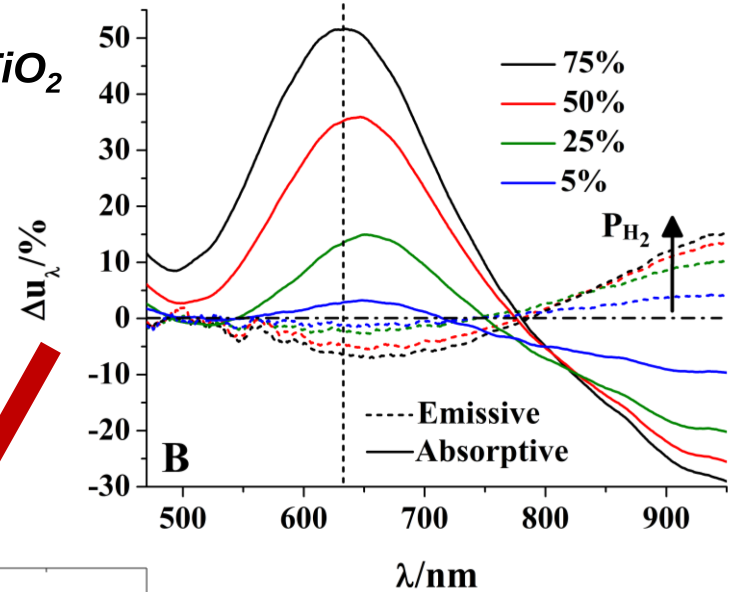
We are Working to Understand How This Discovery Can Be Fully Leveraged.

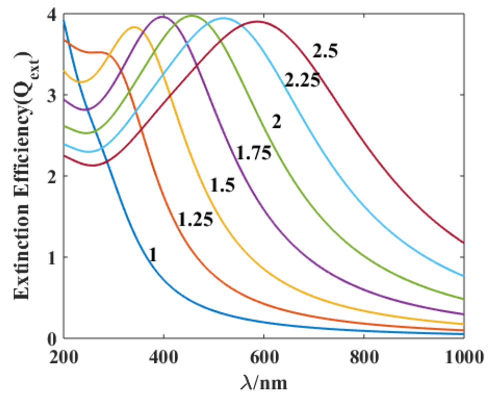
Thermal Emission Based Sensing

TiO_2



Pd / TiO_2





"Plasmonic" Response of Pd Incorporated Metal Oxide Films

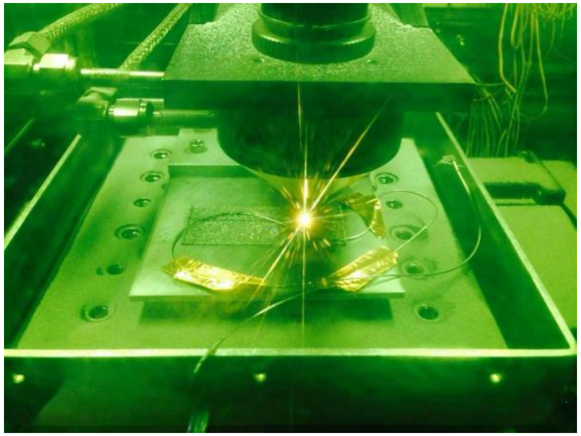
D_{Pd} > 50nm

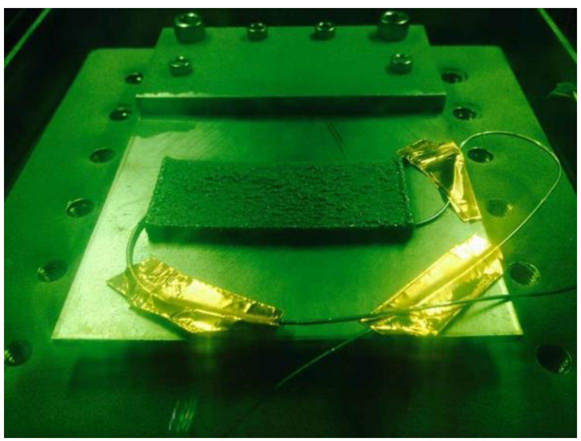
Thermal Emission Based Sensing Responses Can Be Observed in the Visible Range, Albeit Reduced in Magnitude Relative to Near-IR Emission Based Responses.

We Believe that Visible Range "Plasmonic" Sensing Activity was Observed for Pd / TiO2, and Are Working to Confirm with Films Deposited on Planar Substrates.

Additive Manufacturing Based Sensor Embedding

University of Pittsburgh





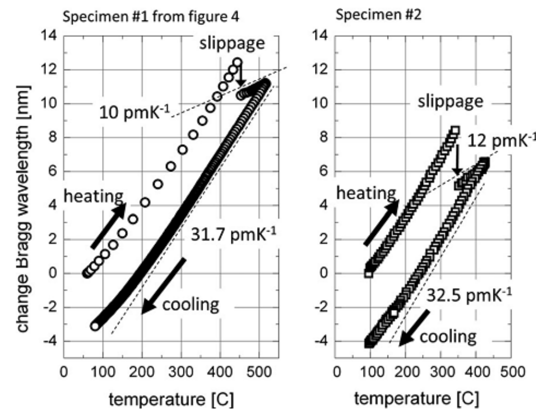


Fig. 5. Measured Bragg wavelength over temperature during temperature cycling for two samples where slippage occurred.

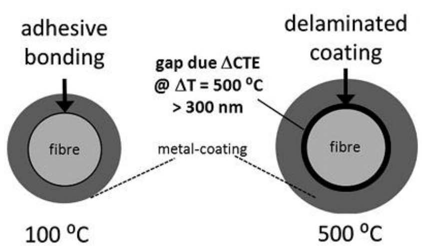


Fig. 6. Schematic visualisation of the delamination of the nickel coating from the silica fibre. Due to different CTE, estimates indicate gaps of more than 300 nm between fibre and metal coating.

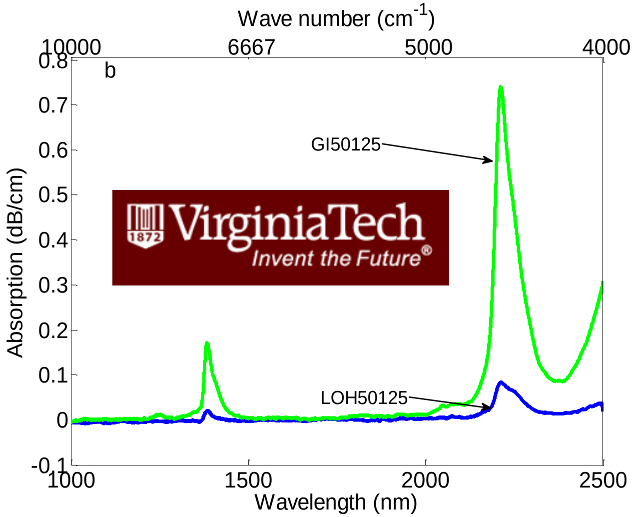
Temperature and Strain Measurements With Fiber Bragg Gratings Embedded in Stainless Steel 316

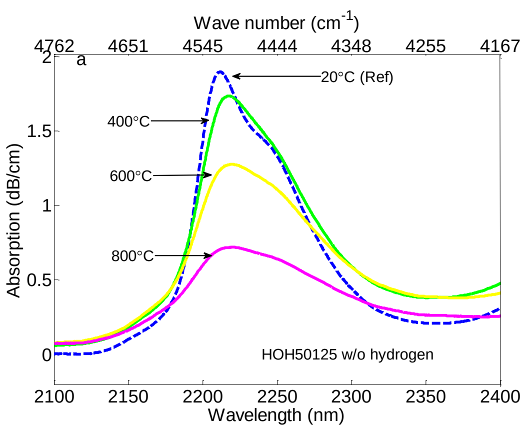
Dirk Havermann, Jinesh Mathew, William N. MacPherson, Robert R. J. Maier, and Duncan P. Hand

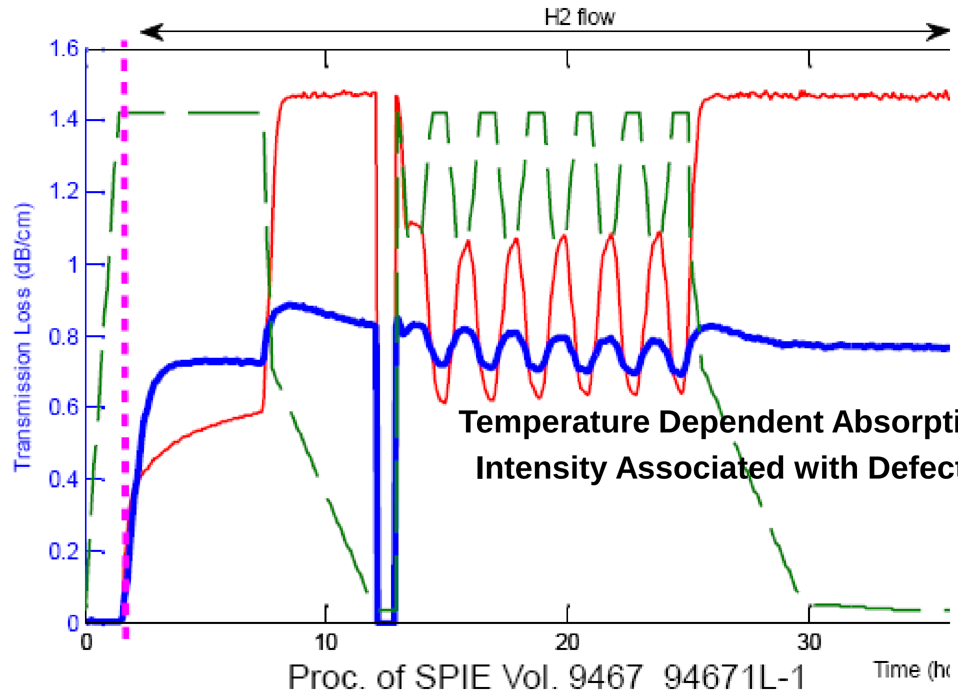
JOURNAL OF LIGHTWAVE TECHNOLOGY, VOL. 33, NO. 12, JUNE 15, 2015

Techniques for Embedding of Temperature and Strain Sensors Using Additive Manufacturing and Compatible with High Temperature Operational Environments are New Efforts for the Team Moving Forward.

High Temperature Stability of Silica Based Optical Fibers







Proc. of SPIE Vol. 9467 94671L-1

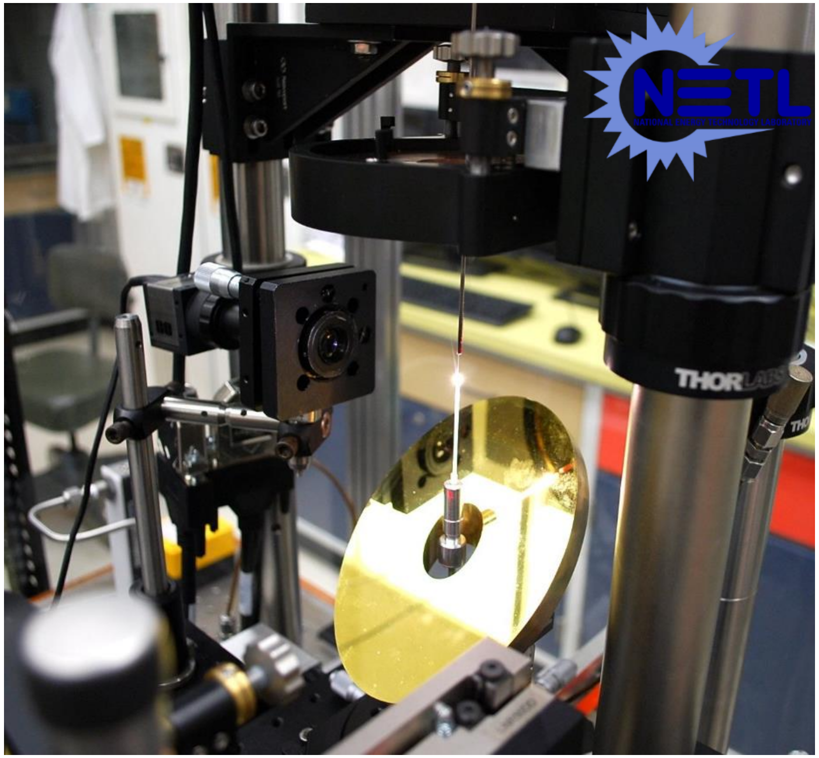
Temperature Dependent Behavior of Optical Loss from Hydrogen Species in Optical Fibers

Elizabeth Bonnell*[a], Li Yu[a], Dan Homa[a], Gary Pickrell[a], Anbo Wang[a]
[a]Virginia Tech, Center for Photonics Technology, Suite 303 Col. Sq. 460 Turner Street, Blacksburg, VA 24060

Understanding the Stability of Silica Based Optical Fiber Sensors Under High Temperature and Non-Ambient Conditions is an Area of Important Investigations.

OH- Defects Play an Important Role in the Near-Infrared Wavelength Range.

High Temperature Stable Alternative Fibers and Claddings



STEVENS INSTITUTE of TECHNOLOGY
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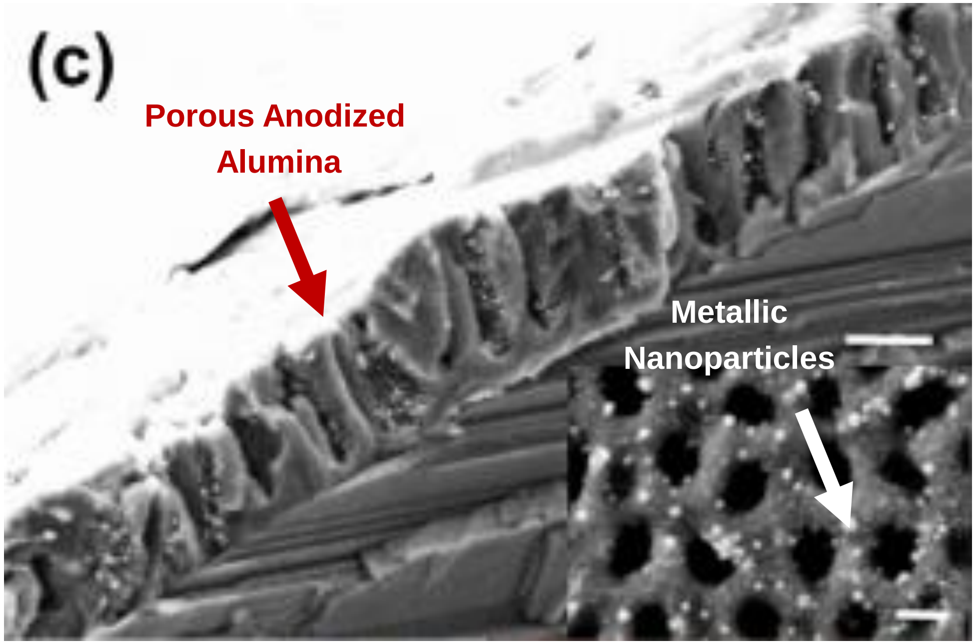
A scalable pathway to nanostructured sapphire optical fiber for evanescent-field sensing and beyond
Hui Chen, Fei Tian, Jiri Kanka, and Henry Du
Applied Physics Letters **106**, 111102 (2015); doi: 10.1063/1.4915325

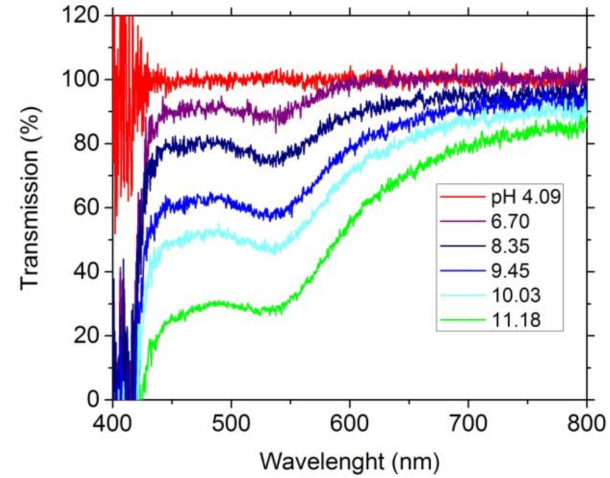


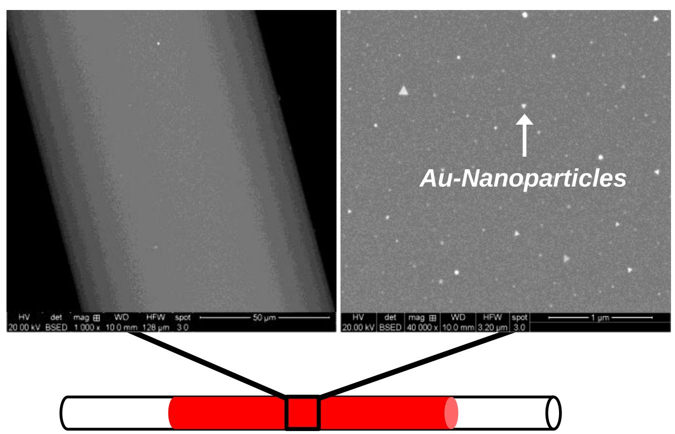
Investigation of New High Temperature Stable Optical Fiber Materials and Associated Claddings is an Area for Significant Future Research within the Group.

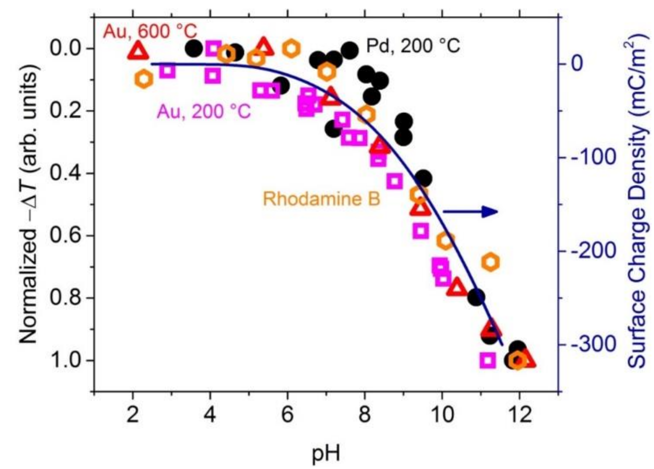
Current Collaborative Research is On-Going in the Area of Anodized Aluminum Oxide Based Claddings and Associated Functionalization.

Subsurface pH Sensing in Geological Formations

Sensing Material	Thermal Stability	Chemical Stability	pH Responsive Range	Reported Research
Dye	low (up to ~ 100 °C)	low – moderate	0 – 14	very well studied and have been investigated for down-hole sensing
pH responsive polymer	moderate (a few hundred °C possible)	moderate – high	2 – 13	some reports and not aware of down-hole sensing application
Au nanoparticles	high (up to 1000 °C)	high	2 – 12*	a few reports on using pH sensitive molecules/polymer to enable optical response from Au
Oxides	high (up to 1000 °C or more)	high	?	?





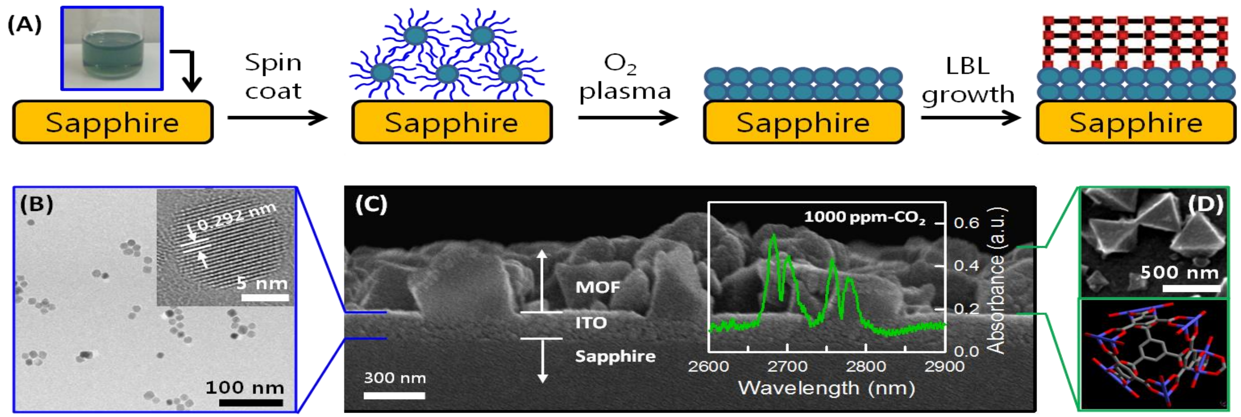


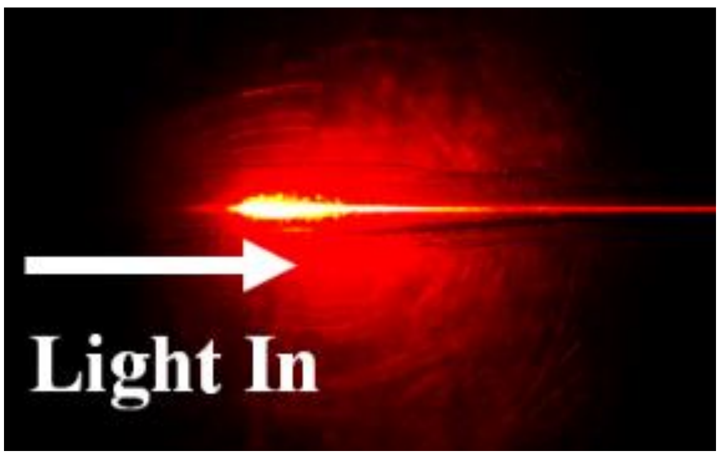
Optical Sensing Responses Associated with the Surface Charging Behavior of Metal Oxide Nanoparticles Has Been Demonstrated to Yield Reversible pH Sensing.

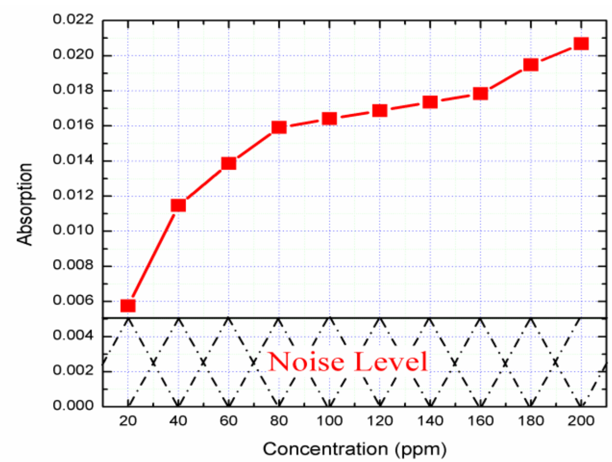
Experimental Work Combined with Optical Waveguide Modeling Suggests the Observations are Associated with Ionic Adsorption at Sensor Layer Surfaces.

Subsurface CO_2 Sensing in Geological Formations

Metal-organic framework (MOF) thin films







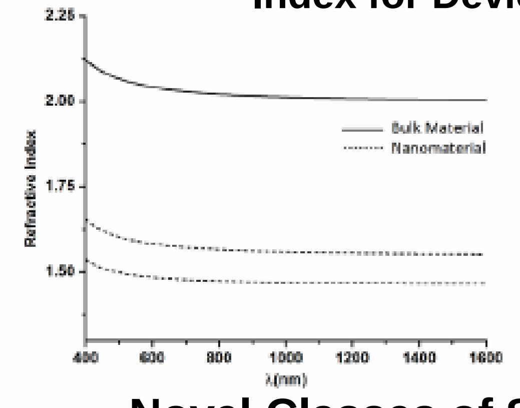
Metallorganic Framework Materials Have Been Pursued for Direct CO_2 Sensing Applications, and Combined with Plasmonic Nanoparticles in Some Cases.

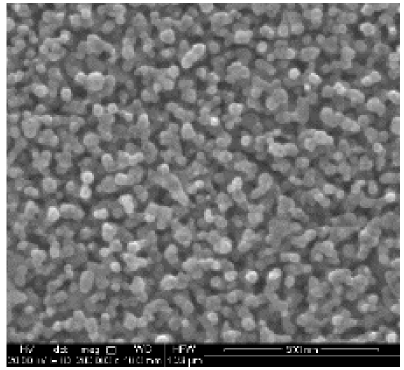
Investigations are Underway to Explore New Metallorganic Framework Materials and to Minimize Impacts of Water on CO_2 Sensing Responses.

Summary and Conclusions

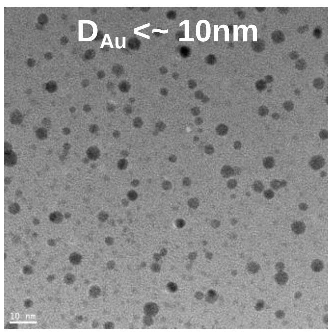
Collaboration and Licensing Opportunities

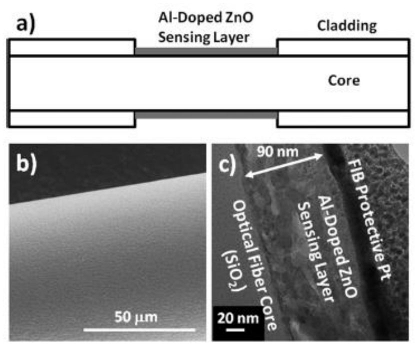
Nanostructuring to Tailor Refractive Index for Device Compatibility





Novel Classes of Sensing Materials





Sensor Material Approaches for Harsh Environment Sensing

University of Pittsburgh

OSU Oregon State University

NETL National Energy Technology Laboratory

Novel Sensor Applications in a Solid Oxide Fuel Cell Environment

A Significant Patent Portfolio Has Been Established and Collaboration / Licensing Opportunities Exist.

The Team is Always Interested in Engaging in Collaborative Relationships That Can Help us Move the Technology Forward and Into the Commercial Sector.

Summary and Conclusions

- **NETL Has a Well Established Focus Area in Materials and Devices Applied to a Range of Energy Related Problems**

- **NETL Has Excellent Capabilities for High Temperature and Harsh Environments Sensor Material and Device Development and Testing**

- **Functionalized Optical Fiber Sensors Show Great Promise for a Range of Energy Related Applications**

- **NETL Has Active In-House Research In a Broad Range of Areas**
  - **Power Generation**
  - **Subsurface CO_2 Storage / Oil & Gas**
  - **Natural Gas Pipelines**

- **We are Always Interested in Collaboration Opportunities as Well as Joint Technology Development and/or Licensing of Patented Concepts**