Smart Sensor Systems for Human Health and Environmental Applications

Gary W. Hunter, Ph.D.
Intelligent Systems Hardware Lead
Smart Sensing And Electronics Systems Branch
NASA Glenn Research Center
Cleveland, OH

OUTLINE

- INTRODUCTION
- DISTRIBUTED INTELLIGENCE
- SENSOR DIRECTIONS AND SMART SENSOR SYSTEMS
- SENSOR SYSTEM DEMONSTRATIONS AND APPLICATIONS
- NANOTECHNOLOGY
- SUMMARY AND CONCLUSION

Smart Sensing and Electronics Systems Branch (LCS)

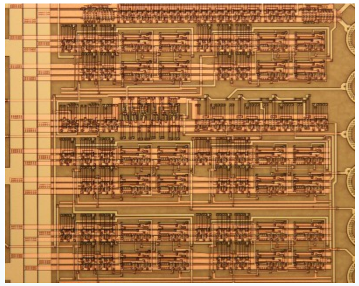
Description

Conducts research and development of **adaptable instrumentation to enable intelligent measurement systems** for ongoing and future aerospace propulsion and space exploration programs. Emphasis is on smart sensors and electronics systems for diagnostic engine health monitoring, controls, safety, security, surveillance, and biomedical applications**; often for high temperature/harsh environments**.

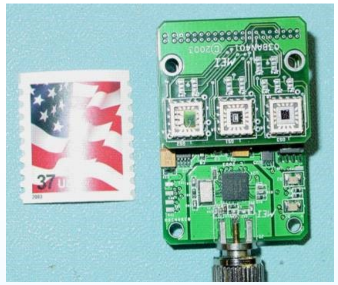
Microsystems Fabrication Facility

Facilities/Labs

- Microsystems Fabrication Facilities
  - Class 100 Clean Room
  - Class 1000 Clean Room
- Chemical vapor deposition laboratories
- Chemical sensor testing laboratories
- Harsh environment laboratories
  - Nanostructure fabrication and analysis
  - Sensor and electronic device test and evaluation



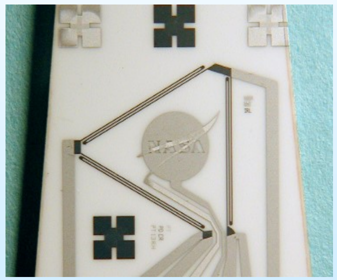
SiC Signal Processing



Chemical Sensors

Core Capabilities (technical areas)

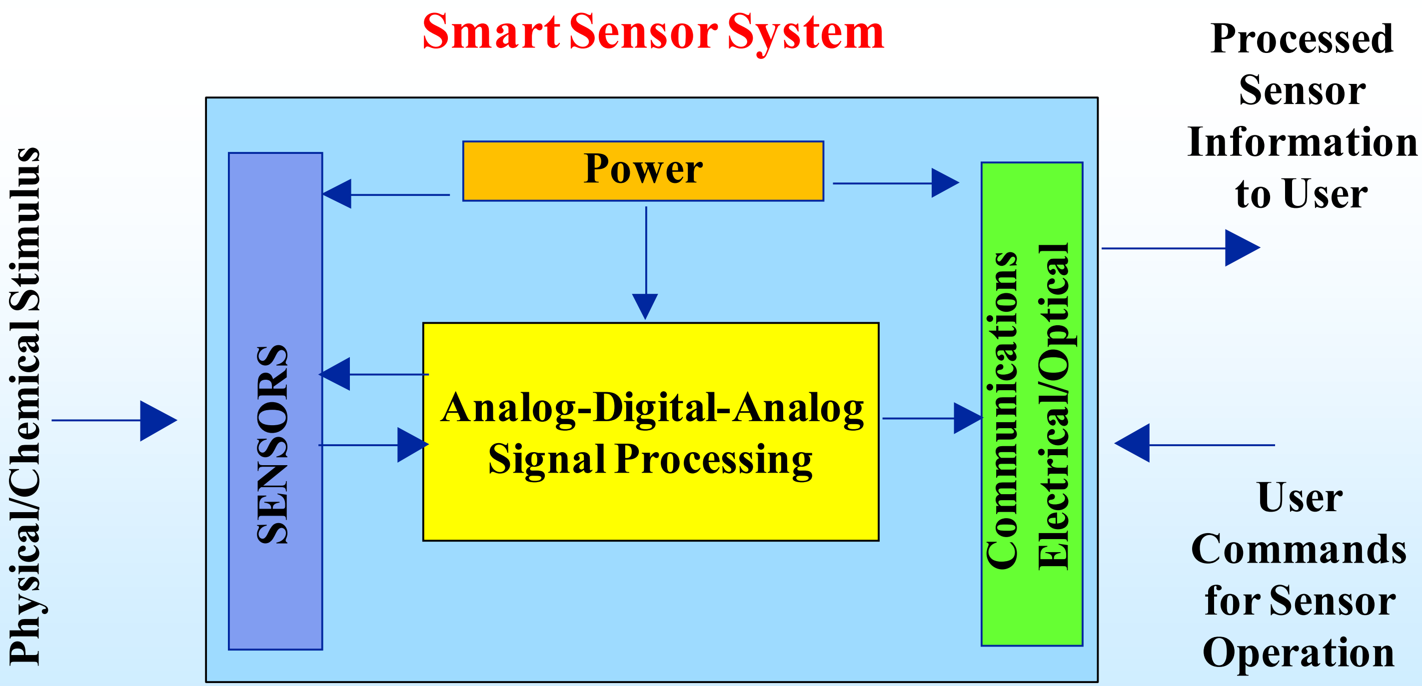
- Silicon Carbide (SiC) - based electronic devices
  - Sensors and electronics for high temp (600°C) use
  - Wireless sensor technologies, integrated circuits, and packaging
- Micro-Electro-Mechanical Systems (MEMS)
  - Pressure, acceleration, fuel actuation, and deep etching
- Chemical gas species sensors
  - Leak detection, emission, fire and environmental, and human health monitoring
- Microfabricated thin-film physical sensors
  - Temperature, strain, heat flux, flow, and radiation measurements
- Harsh environment nanotechnology
  - Nano-based processing using microfabrication techniques
  - Smart memory alloys and ultra low power devices



Thin Film Physical Sensors

SMART SENSOR SYSTEMS BASED ON MICROSYSTEMS TECHNOLOGY

- **A Range Of Sensor Systems Are Under Development Based On Microfabrication Techniques And Smart Sensor Technology**
- **Smart Sensor Systems Approach: Stand-alone, Complete Systems Including Sensors, Power, Communication, Signal Processing, And Actuation**
- **Microsystems Technology Moving Towards A Range Of Applications**
- **Enable System Level Intelligence By Driving Capabilities To The Local Level Using Distributed Smart Systems**



Smart Sensor Systems Approach

- Produce cutting edge sensor system technologies that provide critical information (data), thus, enabling vastly improved decision-making capability, whether it be regarding designs, operations, the environment, or hazards.
- In this modern era, making a measurement does not just involve a sensor element (like a thermocouple), but rather a whole sensor system that provides:
  - Multiparameter information needed to understand the problem
  - Local processing to optimize the quality and relevance of that information
  - Communication of that information in a manner that best fits the application
  - Tailoring of each integrated sensor system to meet the needs of the application.

In this Information Age, we suggest that small, smart sensor system technologies are an enabling first step in acquiring information (data) about a system and/or an environment, leading to cognition and decision-making capabilities.

This includes Aerospace Systems as well as Personal Health Care

MAKE AN INTELLIGENT SYSTEM FROM SMART COMPONENTS

POSSIBLE STEPS TO REACH INTELLIGENT SYSTEMS

- **"LICK AND STICK" TECHNOLOGY (EASE OF APPLICATION)**
  - Micro and nano fabrication to enable multipoint inclusion of sensors, actuators, electronics, and communication throughout the vehicle without significantly increasing size, weight, and power consumption. Multifunctional, adaptable technology included.
- **RELIABILITY:**
  - Users must be able to believe the data reported by these systems and have trust in the ability of the system to respond to changing situations, e.g., decreasing the number sensors should be viewed as decreasing the available information flow about a vehicle. Inclusion of intelligence more likely to occur if it can be trusted.
- **REDUNDANCY AND CROSS-CORRELATION:**
  - If the systems are easy to install, reliable, and do not increase weight/complexity, the application of a large number of them is not problematic allowing redundant systems, e.g., sensors, spread throughout the vehicle. These systems will give full-field coverage of the engine parameters but also allow cross-correlation between the systems to improve reliability of sensor data and the vehicle system information.
- **ORTHOGONALITY:**
  - Systems should each provide a different piece of information on the vehicle system. Thus, the mixture of different techniques to "see, feel, smell, hear" as well as move can combine to give complete information on the vehicle system as well as the capability to respond to the environment.

BASE PLATFORM SENSOR TECHNOLOGY

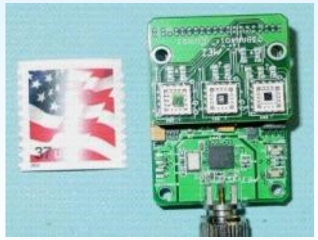
Integration of Micro Sensor Combinations into Small, Rugged Sensor Suites

Example Applications: AEROSPACE VEHICLE FIRE, FUEL LEAKS, EMISSIONS, ENVIRONMENTAL MONITORING, CREW HEALTH, SECURITY

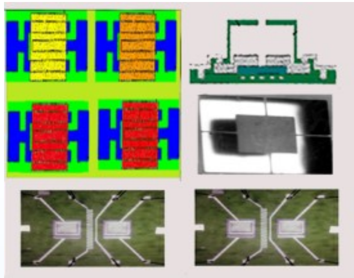
Multi Species Fire Sensors for Aircraft Cargo Bays and Space Applications

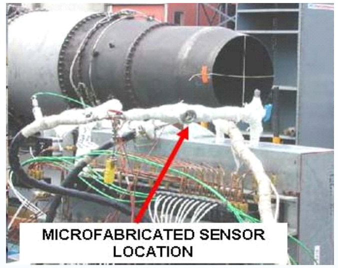
Environmental monitoring (ISS Whitesand Testing)

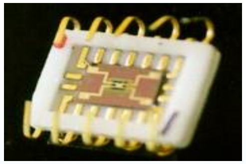
"Lick and Stick" Space Launch Vehicle Leak Sensors with Power and Telemetry



Aircraft Propulsion Exhaust High Temperature Electronic Nose

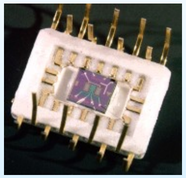




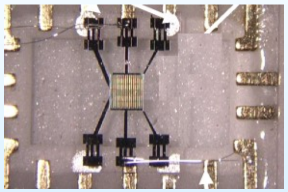


Oxygen Sensor

SiC Hydrocarbon Sensor



H2 Sensor

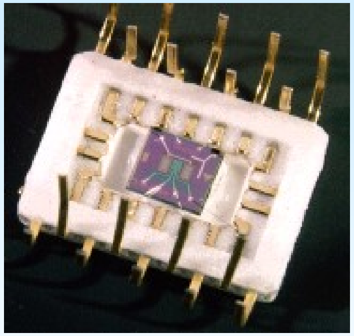


Nanocrystalline Tin Oxide NOx and CO Sensor

Breath Sensor System Including Mouthpiece, PDA Interface, And Mini Sampling Pump

Hydrazine EVA Sensors (ppb Level Detection)

HYDROGEN LEAK SENSOR TECHNOLOGY



- **STATUS: OPERATIONAL SYSTEM ON ISS WITH ASSOCIATED HARDWARE**
- **AVAILABLE FOR POSSIBLE CREW LAUNCH VEHICLE IMPLEMENTATION**

R&D 100 AWARD WINNER

NASA TURNING GOALS INTO REALITY SAFETY AWARD

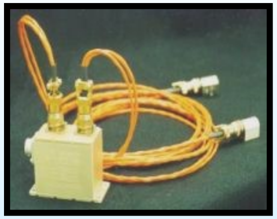
Shuttle

Aft Compartment Hydrogen Monitoring

X33

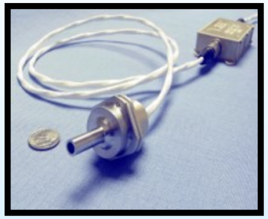
Hydrogen Safety Monitoring

X43



Hydrogen Safety Monitoring

Helios



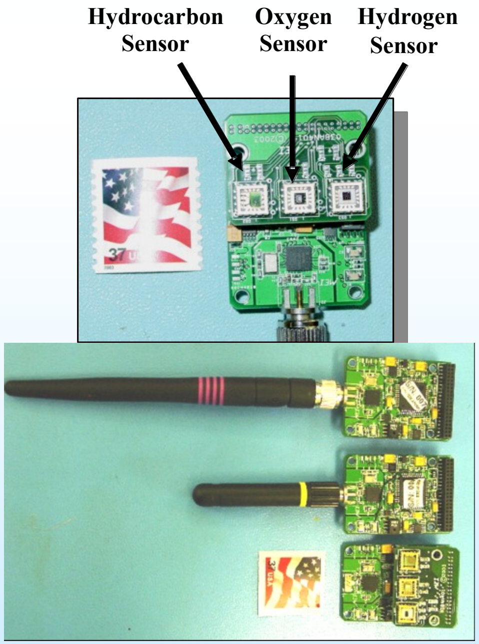
Fuel Cell Safety and Process Monitoring

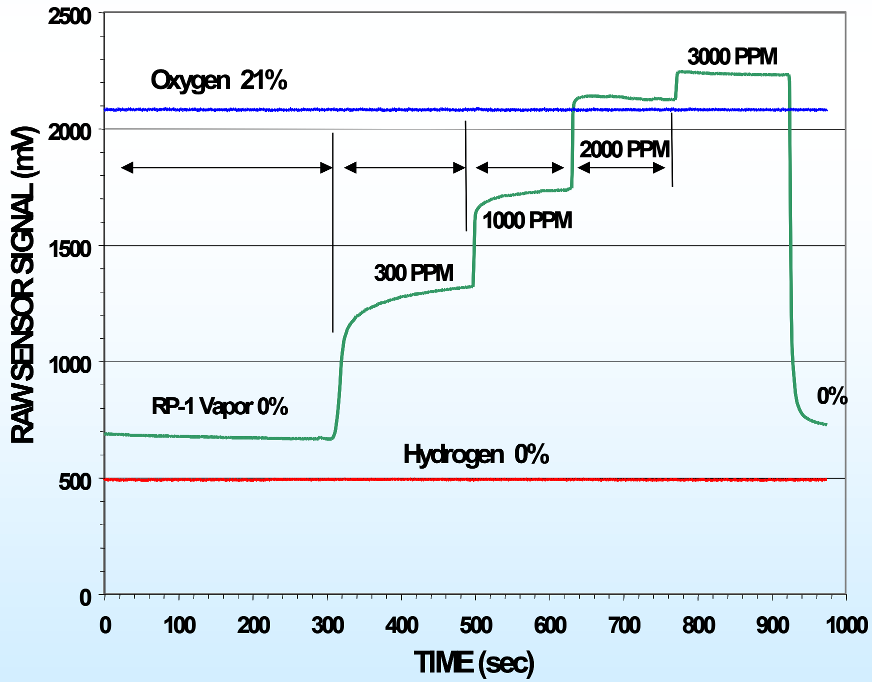
ISS

Life Support Process and Safety Monitoring

"LICK AND STICK" SENSOR SYSTEM AVAILABLE IN STANDARD SILICON TECHNOLOGY

- Sensors, Power, And Telemetry Self-contained In A System Near The Surface Area Of A Postage Stamp
- Microprocessor Included/Smart Sensor System
- Adaptable Core System Which Can Be Used In A Range Of Applications
- Built-in Self Check, Internal Data Tables
- Multiple Configurations Available

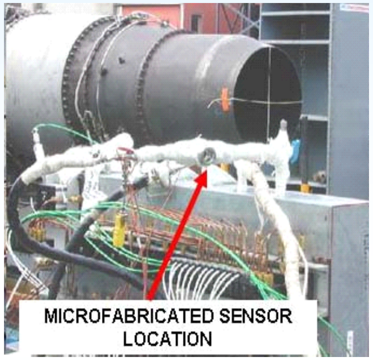




BASIC APPROACH: MEET THE NEEDS OF MULTIPLE APPLICATIONS BUILDING FROM A CORE SET OF SMART MICROSENSOR TECHNOLOGY

A WIDE RANGE OF SYSTEM DEMONSTRATIONS AND APPLICATIONS “LICK AND STICK” CORE HARDWARE

Jet Engines Emissions



Aircraft Fire Detection

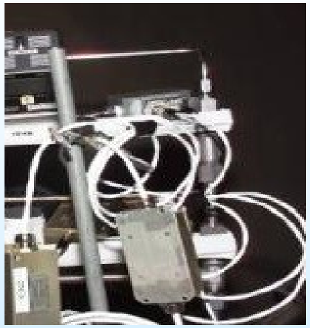
Breath Monitoring

NASA Helios Fuel Cells

International Space Station Safety System

Rocket Engine Teststands

Environmental Monitoring



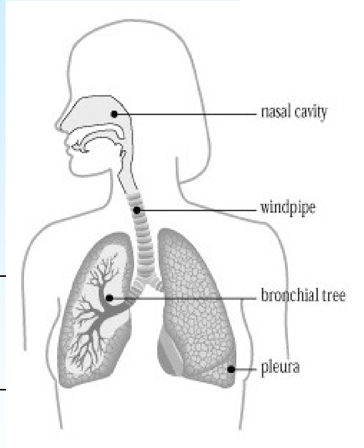
Cryogenic Fuel Line Monitoring

MicroSensor Arrays for Exercise and Health Monitoring

- **Use Array Of Sensors Of Very Different Types To Monitor Breath For Exercise And Health**
- **Cleveland Clinic Foundation Leader In Exercise/Breath Monitoring Research**
- **International Breath Analysis Summit**
- **CO2 And O2 Monitoring Expanded To Include Other Species As No And Co**
- **Multiple Gases Measured For Exercise Parameters But Also As Overall Health Indicators**
- **State Of Ohio Third Frontier Program: Produce Commercial Breath Monitoring Product**

The Ohio State University   Cleveland Clinic   Makel Engineering   CWRU

Biomarkers for the diagnosis of disease by breath test



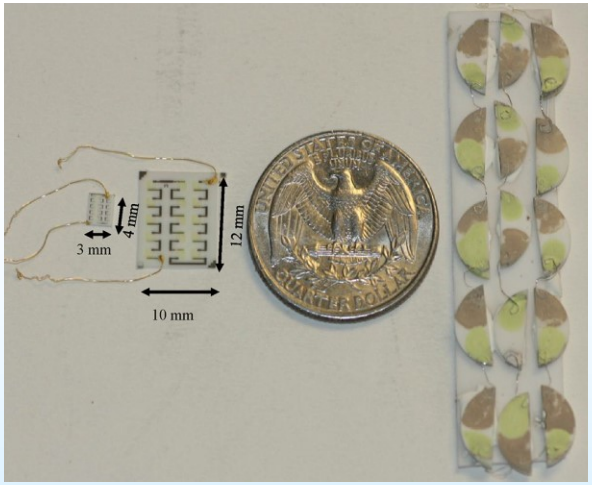
Disease	Compound as a disease marker	Analysis Instrument
Acute cardiac allograft rejection	Pentane	GC/FID
Myocardial infarction (MI)	Hydrocarbons	GC/FID
Asthma	Nitric Oxide	CL analyzer
COPD / ARDS	NO, CO	CL analyzer
Breast Cancer	Pentane	GC/FID
Diabetes	Acetone	GC/FID
Hemolysis	Carbon monoxide	EC CO analyzer GC/TCD
H. pylori infection	$^{13}CO_2$ or $^{14}CO_2$	Isotope Ratio MS Isotope Ratio IR
Alcoholic liver disease	Pentane	GC/FID
Liver cirrhosis	Dimethyl sulfide Volatile fatty acid	GC/FPD GC/FID
Weight Reduction	Acetone	GC/FID

Cleveland Clinic

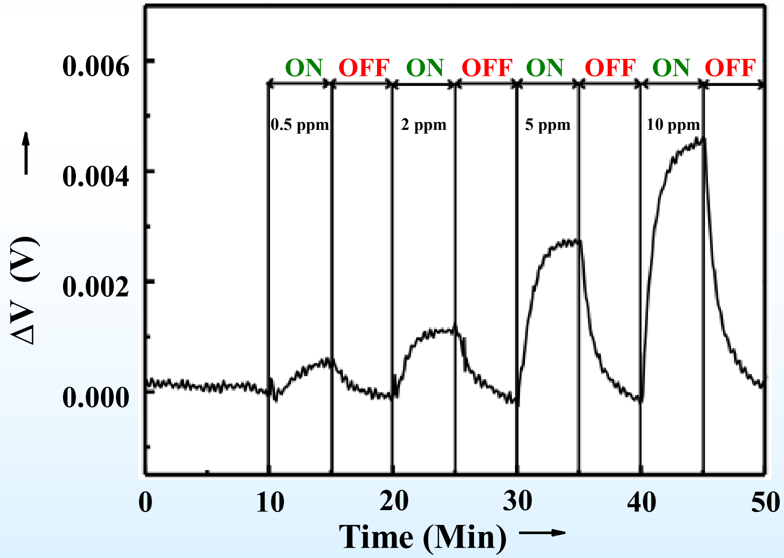
Exhaled NO analysis using electrochemical sensor

- Sensor Miniaturization Using Silicon Processing Techniques
- Electrochemical Cells In Series To Reach High Levels Of Sensitivity (500 PPB) With More Than An Order Of Magnitude Size Reduction
- Fundamental Understanding Of Sensing Mechanism Needed
- Integration into a system needed for evaluation/implementation

Sensors and Actuators B 204 (2014) 183–189



Miniaturization Activity: Hand fabricated sensor (baseline), shadow mask sensor, and photoresist processed sensor

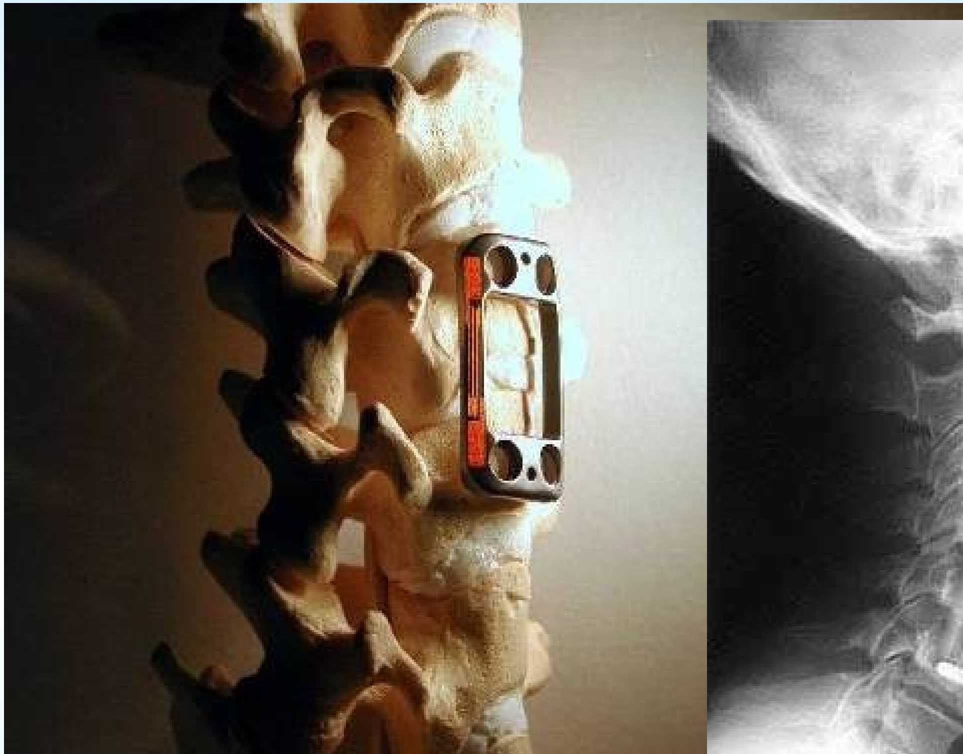


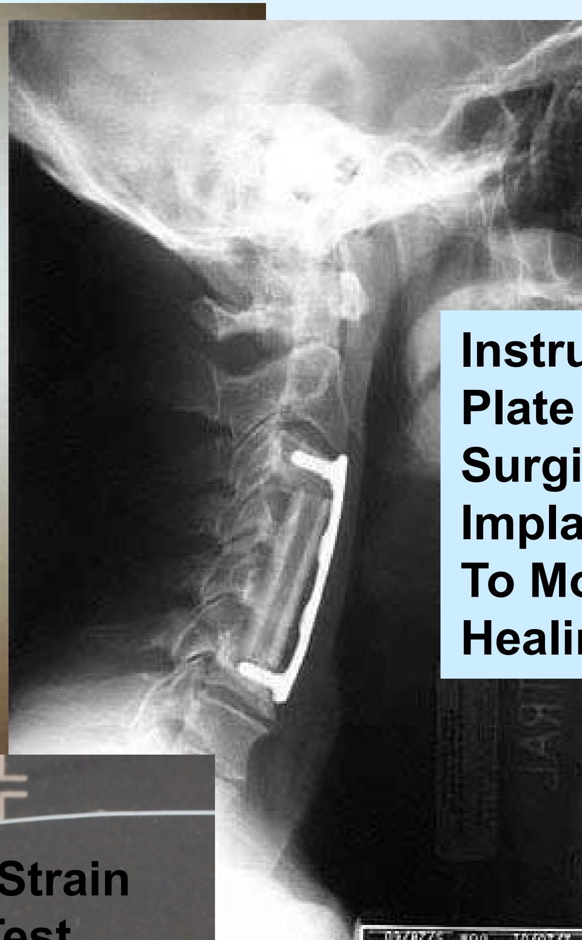
Sensor response of photoresist version sensor with 15 sensor arrays for 0.5–10 ppm in 20% O2 with 200 cm3/min total flow rate at 550◦C.

Cleveland Clinic
MAKEL ENGINEERING
CWRU
THE OHIO STATE UNIVERSITY

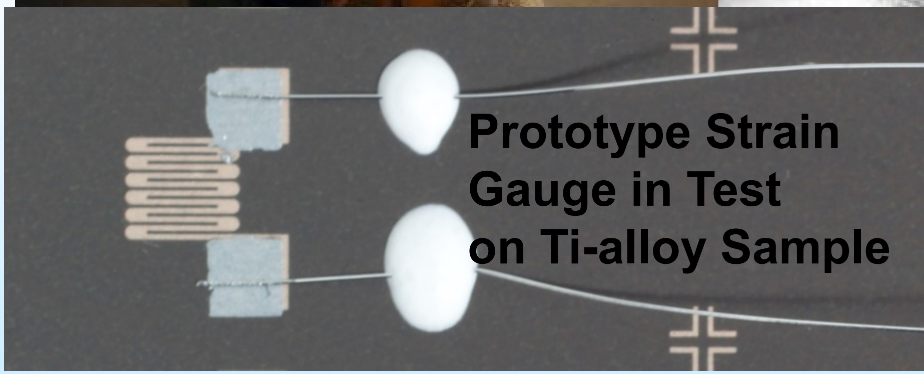
Cervical Plate Instrumentation Concept for Spinal Implants

Conceptual Strain Gauge Fabricated on a Ti-alloy Cervical Plate to Assist in Bone Fusion





Instrumented Plate Surgically Implanted To Monitor Healing



Prototype Strain Gauge in Test on Ti-alloy Sample

LERNER RESEARCH INSTITUTE
THE CLEVELAND CLINIC

Example Activity

Development of Real-Time Particulate and Toxic-Gas Sensors for Firefighter

Health and Safety

DHS/FEMA AFG FP&S R&D Project

EMW-2014-FP-00688

(Preliminary Study: EMW-2012-FP-01284)

Lead: Fumiaki Takahashi, Case Western Reserve University

NASA Glenn Research Center

Makel Engineering, Inc.

Objectives

- **Firefighter environmental sensors development**
  - Develop prototypes of a particulate and toxic-gas detection system to improve health and safety of **structure** and **wildland** firefighters
  - Newly develop **acrolein** and **formaldehyde** micro-fabricated sensors
  - Integrate new aldehyde sensors and existing NASA-developed particulate, CO, O_2, hydrocarbons sensors into a hand-held prototype capable to indicate/store real-time concentrations and trigger alarms when exceeding the exposure limits

Prototype Portable Unit as fabricated.

Final Report: https://engineering.case.edu/sites/default/files/Final%20report-Sensors-FY2014.pdf

Nanoplasmonic Sensor Development

New capabilities with plasmonics

- Independent/complementary sensing technique
- Real-time monitoring of biomarker binding kinetics
- Low-temperature operation
- Sensitive, label-free colorimetric readout

Multiple Nanoplasmonic Sensor Approaches in Development

- Metallic Photonic Crystal (MPC) sensor
- Plasmonic biosensing
- Tunable metal insulator metal (MIM)

Collaboration with Dartmouth College

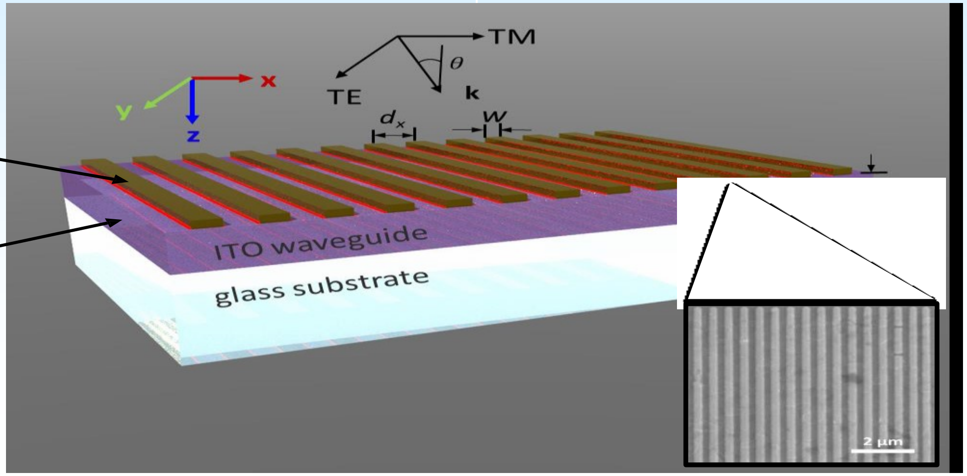
- T. Palinski/POC

Metallic Photonic Crystal (MPC) Sensor Development

TM-polarized light excites hybrid plasmonic-photonic resonance

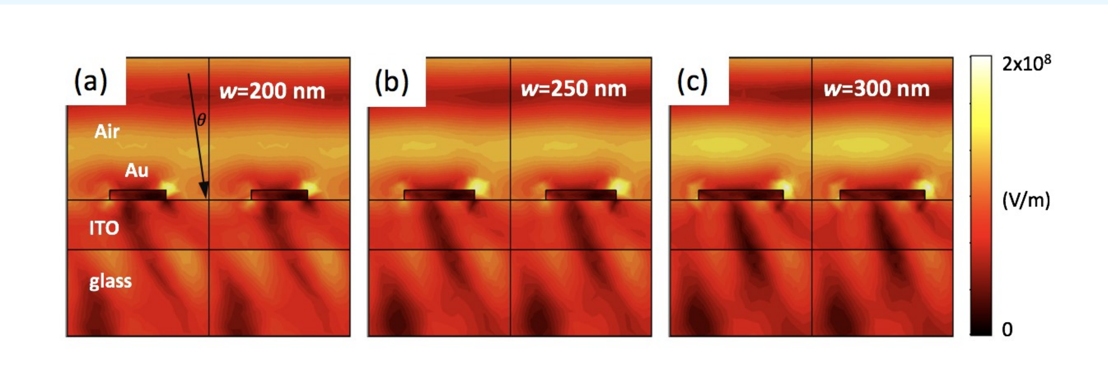
Plasmonic nanogratings

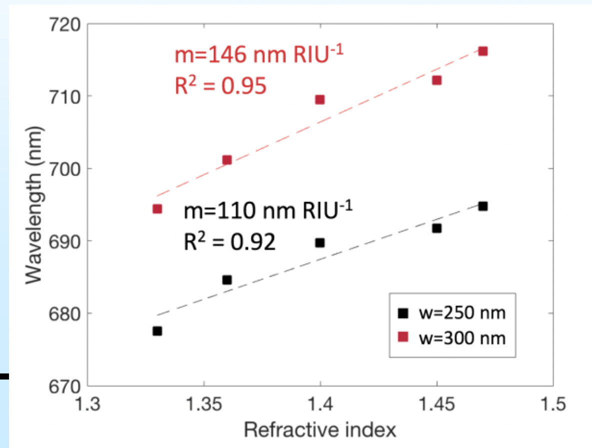
Photonic waveguide



Sensitivity optimization via tuning grating width

- Grating width affects coupling between plasmonic and photonic modes;
- Stronger coupling → higher field intensity, higher sensitivity

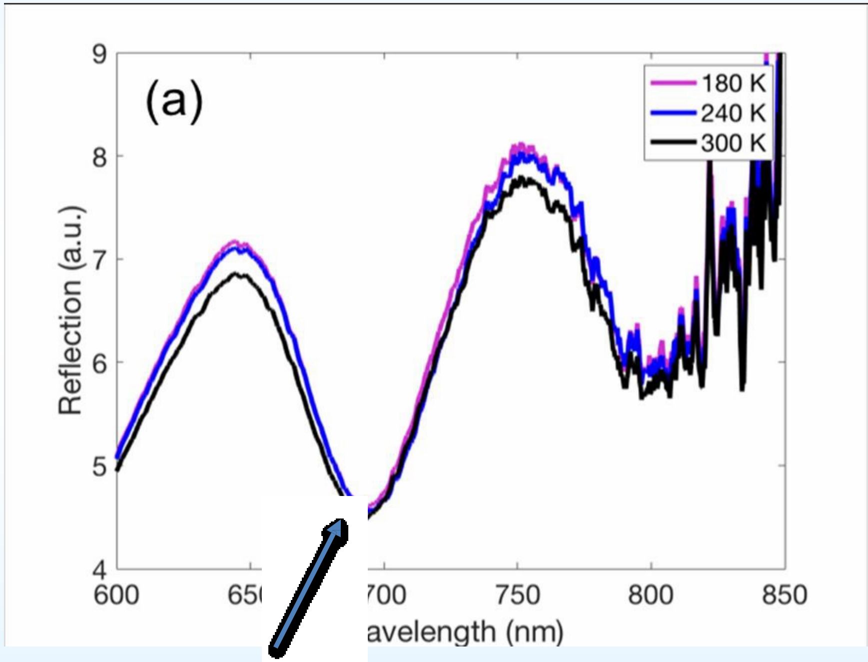




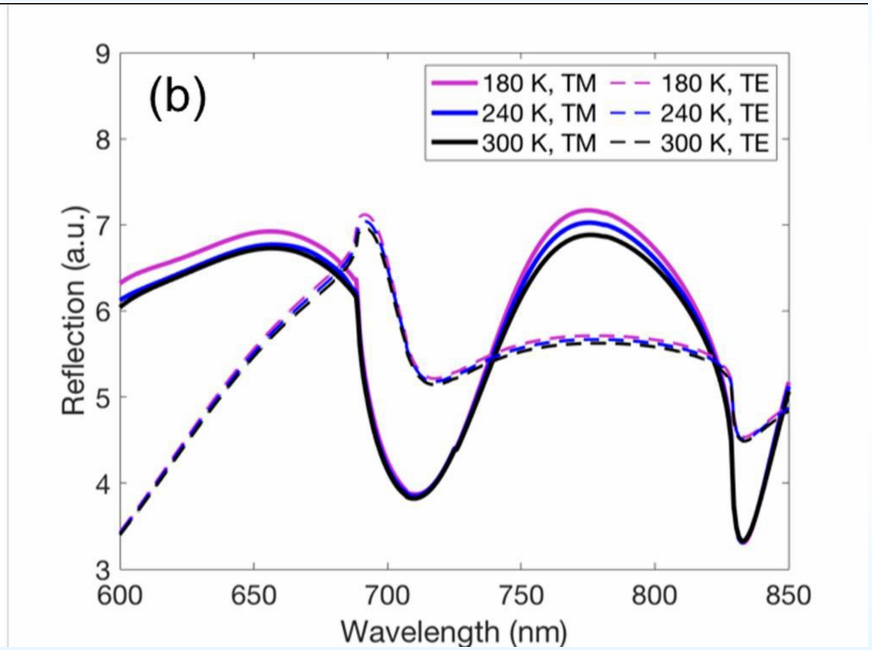
Metallic Photonic Crystal (MPC) Sensor Development

Low-temperature sensor characterization

Experiment



Simulation



Hybrid plasmonic-photonic modes offer good temp. stability & high refractive index sensitivity

Palinski *et al.*, *Opt. Express* 27, 11, 16344 (2019)

Plasmonic biosensing

Contents lists available at ScienceDirect

Biosensors and Bioelectronics

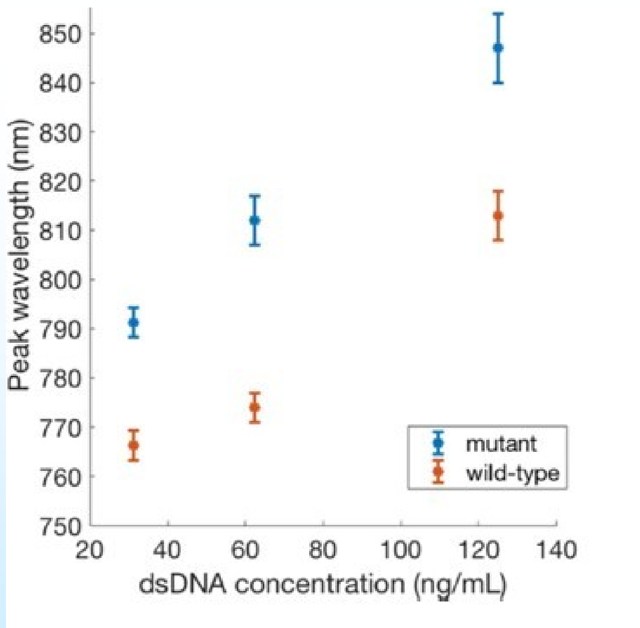
journal homepage: www.elsevier.com/locate/bios

(2019)

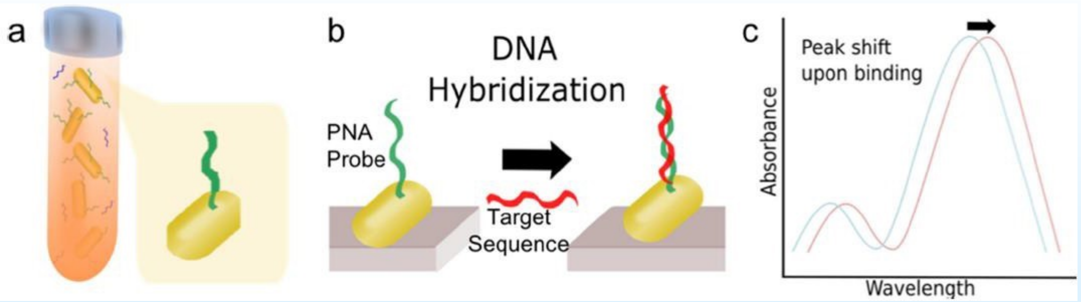
Design of peptide nucleic acid probes on plasmonic gold nanorods for detection of circulating tumor DNA point mutations

Amogha Tadimety[a], Yichen Zhang[a], Kasia M. Kready[a], Timothy J. Palinski[a], Gregory J. Tsongalis[b,c], John X.J. Zhang[a,c,*]

Discrimination between single DNA base pair mismatch

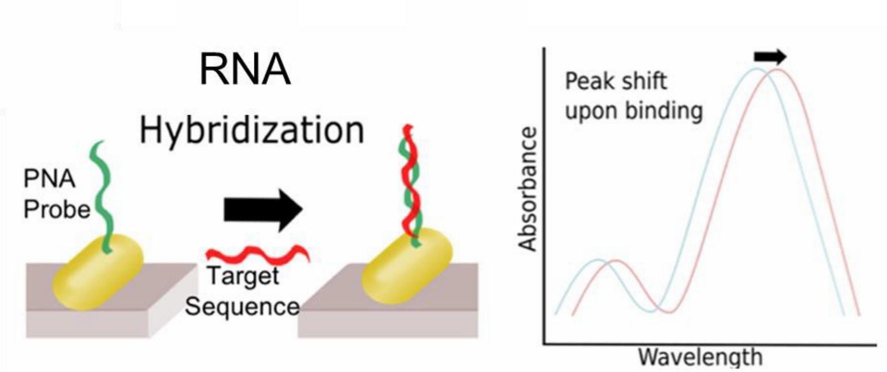


Biosensor workflow



Plasmonic biosensing

16s rRNA detection



- 16s rRNA subunit is highly conserved
- Commonly used to identify the presence of extremophile bacteria in a wide range of terrestrial environments[1]

[1]Boyd *et al., Env. Microbiol. Rep.,* 2, 5, 685-692 (2010)

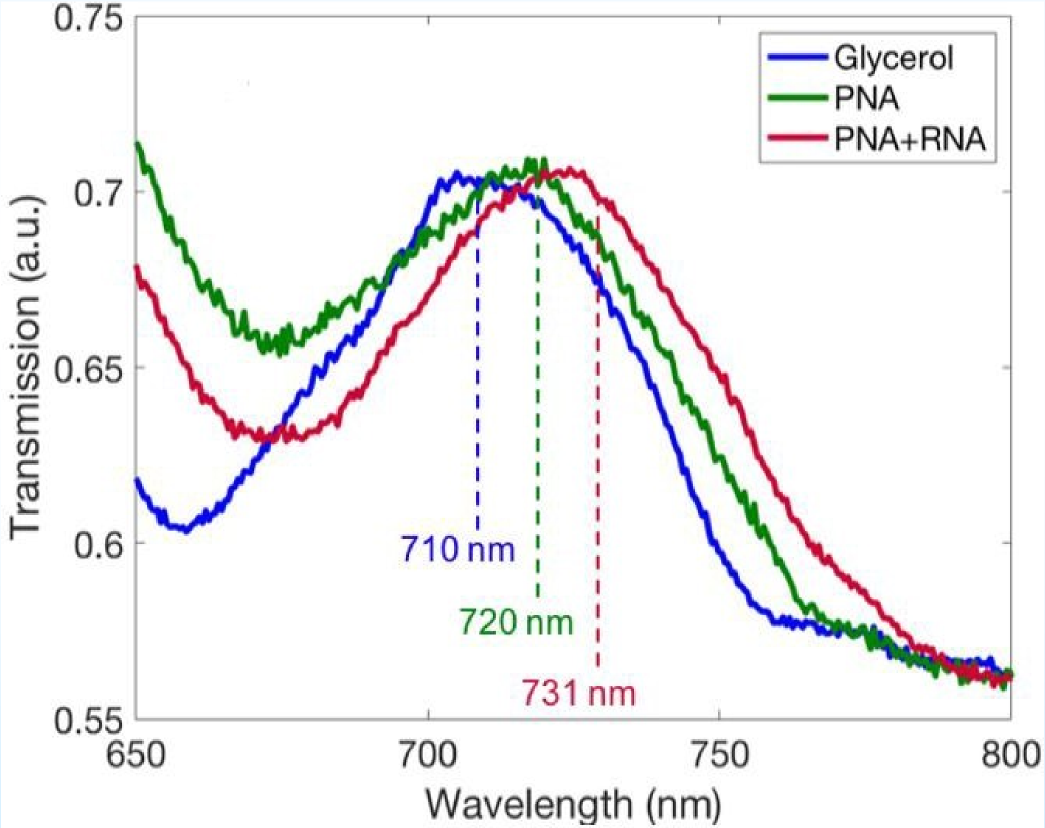
Survey of low-temp. solvents

Solvent	Freezing Point (C)	Reference
Ethylene Glycol	-12.9	(1) (Theodore T. Herskovits, 1962) (2) (Bonner & Klibanov, 2000)
Glycerol + Water	-38 (70% G + 30% H20)	(1) (Theodore T. Herskovits, 1962) (2) (Bonner & Klibanov, 2000)
Ethanol	-114.6	(1) (Theodore T. Herskovits, 1962) (2) (Bonner & Klibanov, 2000) (3) (T. T. Herskovits, Singer, & Geiduscheck, 1961)
Ethanol + Water	-119 (93%E + 7% W)	(1) (Theodore T. Herskovits, 1962)
Methanol	-97	(1) (Theodore T. Herskovits, 1962) (2) (Bonner & Klibanov, 2000) (3) (T. T. Herskovits et al., 1961)

From preliminary tests with gold nanorods, 70% glycerol is best path forward due to relatively low viscosity and gold nanostructure stability.

Plasmonic biosensing

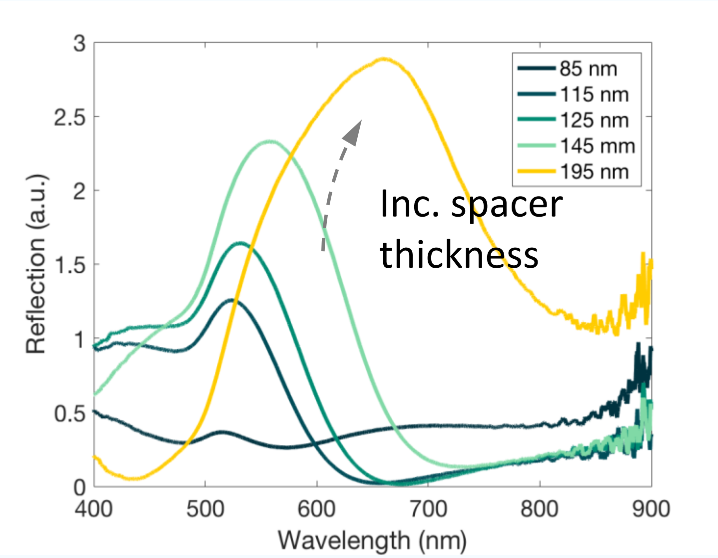
16s rRNA detection



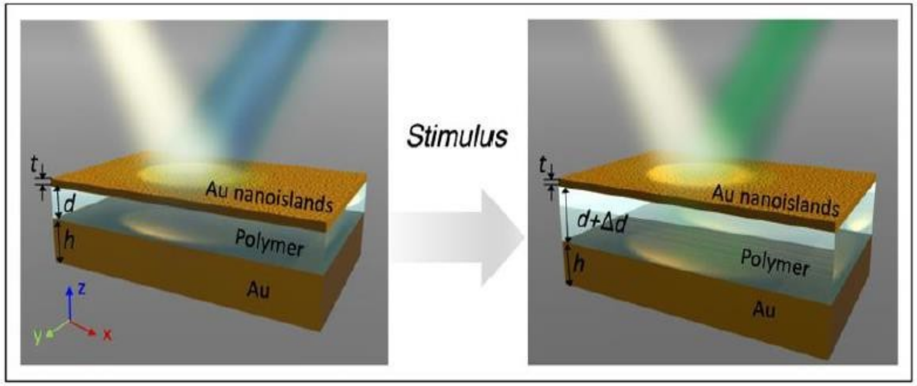
- Sequence-specific 16s rRNA detection in non-aqueous solvent (70% glycerol, 30% water) at room temp.
- Approx. 10 nm peak shift for 1.6 micromolar RNA
- Biosensing challenges at lower temps. (≤ -20 °C)… RNA denaturing?

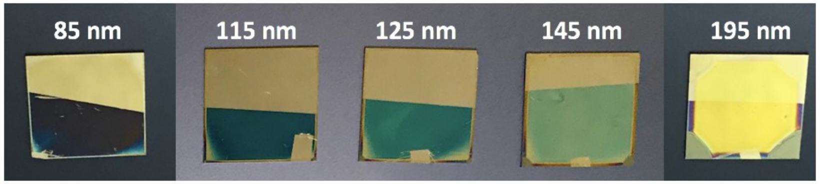
Tunable metal insulator metal (MIM) device

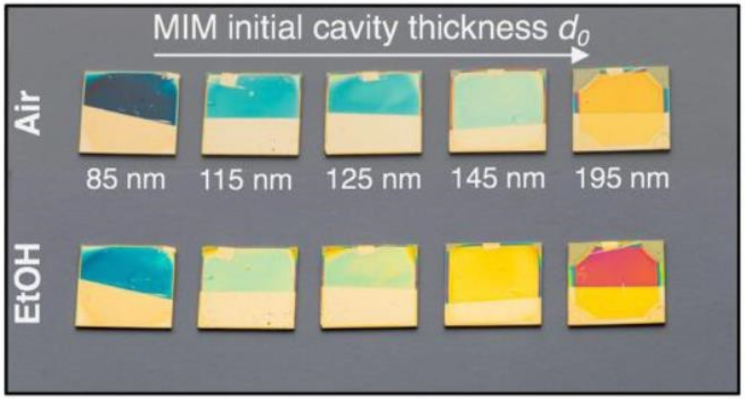
- Large-area fabrication
- Bright/naked-eye structural colors which are sensitive to device parameters
- Color tuning via active polymer spacer



Colorimetric sensor readout







Organic solvent detection

Palinski *et al.*, under review

National Aeronautics and Space Administration

Advanced Space Radiation Instrumentation Research

Problem:

- Awareness of space radiation critical in missions beyond LEO (i.e., Moon, Mars, NEOs, etc.) requiring:
  - Embedded instrumentation to provide feedback for "smart", adaptive shielding systems
  - Precision instrumentation to provide better data to space radiation modeling efforts
  - Compact instrumentation for more complete, real-time environmental awareness to crew and critical assets
- Current technology limiters are radiation hardness, noise floor, thermal stability, and detector geometry.

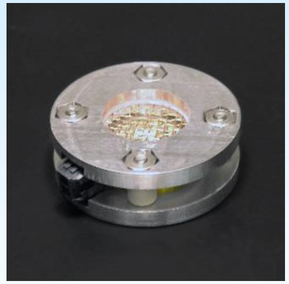
Solution:

- Compact integrated detectors with low noise, solid state components allowing spherical geometry

Approach:

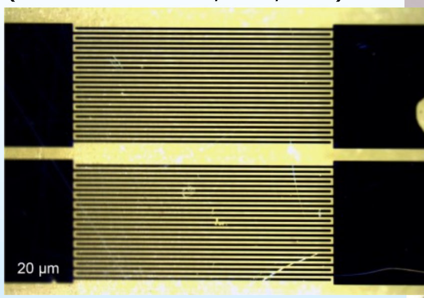
- GRC Expertise and Facilities in:
  - Harsh Environment Thin Films
  - SiC Devices & Harsh Environment Packaging
  - Micro-Optics
  - Flight Electronics
- These strengths are combined into GRC's Advanced Space Radiation Instrumentation Research effort

Compact Full-field Ion Detector System (CFIDS) Concept (US Patents 7,872,750 and 8,159,669)

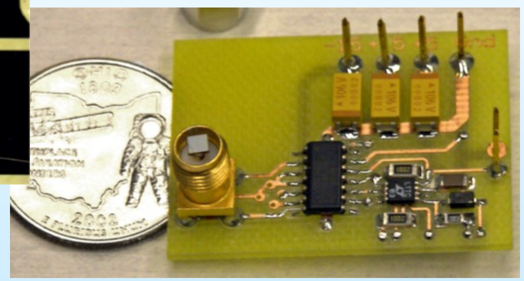


Large Area SiC LET Detectors

Low power charged particle counter (U.S. Patent 10,429,521)



Fast, Large Area, Wide Band Gap UV Photodetector (U.S. Patent 10,054,691)



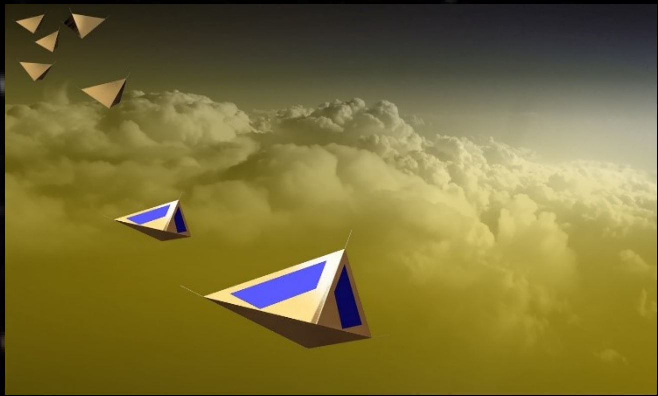
ETDD SiC Dosimeter Prototype

Example Activity

Lofted Environmental Venus Sensors (LEAVES)

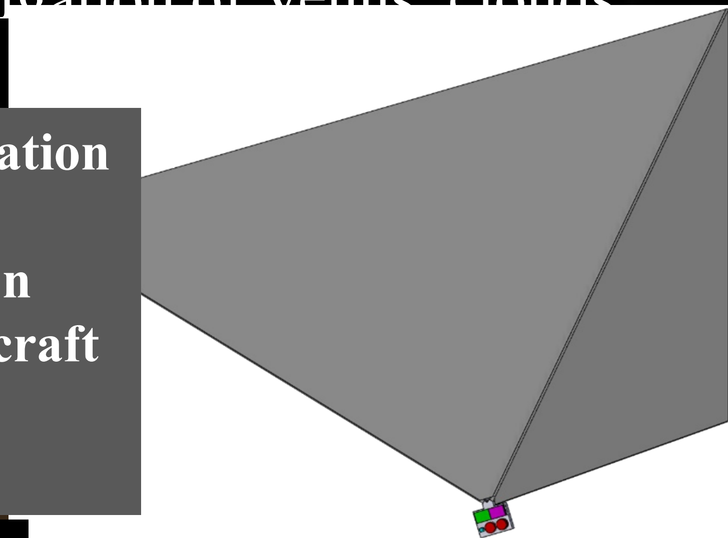
Jeffrey Balcerski
Ohio Aerospace Institute

Anthony Colozza (Vantage Partners, LLC), Gary Hunter (Glenn Research Center), Maciej Zborowski (Vantage Partners, LLC), Darby Makel (Makel Engineering, Inc.)

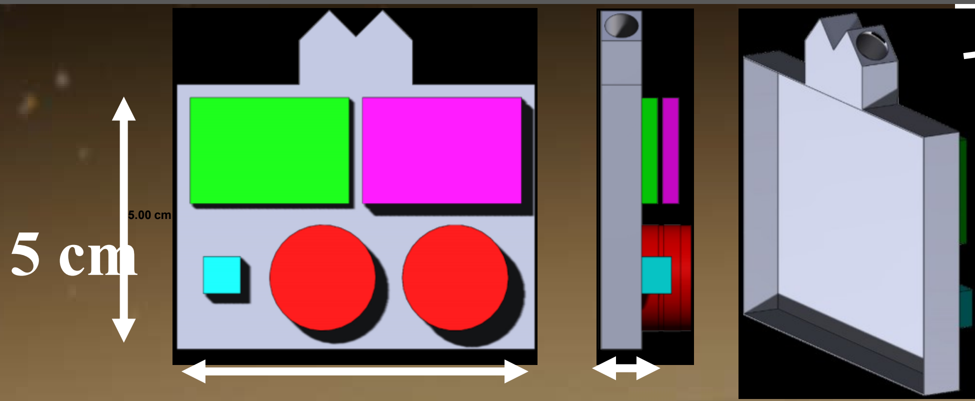


Lofted Environmental Venus Sensors (LEAVES)

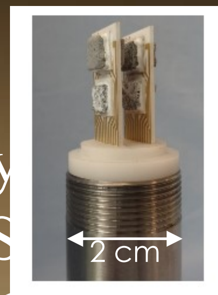
a swarm investigation of Venus' clouds



- Concept study for Venus atmosphere exploration
- Each "leaf" is 120 g with ~ 20 g payload
  - Chemical species, pressure, temp, motion
- 100 units deployed from orbit by host spacecraft
- Carried 1000s of km by the winds
- ~ 9 hour operational lifetime of slow freefall



Enabled by MEMS chemical sensors



NIAC NASA Innovative Advanced Concepts

NASA

MAKEL ENGINEERING

OAI Ohio Aerospace Institute

NANO DIMENSIONAL CONTROL PREVALENT IN CHEM/BIO SENSOR DEVELOPMENT

- Nano Control Of Chemical Sensor Structures Strongly Preferred Even If Sensor Isn't Labeled A "Nano Sensor"
  - We Are Measuring Varying Numbers Of Molecules
- If Nanotechnology Already Present In Chem/Bio Sensor Development, Then:
  - What Stays The Same And What's New?
  - What Are The Challenges In Nanotechnology Development?
  - What Is The Role/Advantage Of Nano Technology

Same

- Applications Don't Care That Is Nano, Need Improved Capabilities
- Standard Sensor Technology Requirements, Potential, And Directions Set By The Advent Of Microtechnology Remain Constant
- Sensitivity, Selectivity, Stability, Response Time, Tailor For The Application, "Lick And Stick", Etc.
- Packaging Still Significant Component Of System
- As With Micro, Can Only Go As Far As The Supporting Technologies
- Multiple Sensor Platforms May Still Be Necessary Depending On The Application/Environment

Metal Oxide Nanostructures for Chemical Sensor Development

Move Towards Nanostructure e.g. Tubes, Rods, Ribbons

- **Develop Basic Tools To Enable Fabrication Of Repeatable Sensors Using Nanostructures**
- **Approach 3 Basic Problems In Applying Nanostructures As Chemical Sensors**

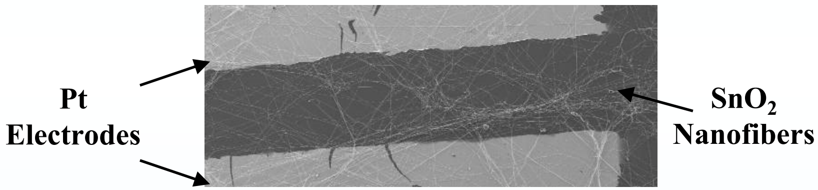
▶ ***Micro-Nano Contact Formation***

▶ ***Nanomaterial Structure Control***

▶ ***Range Of Nano Structured Oxides Available***

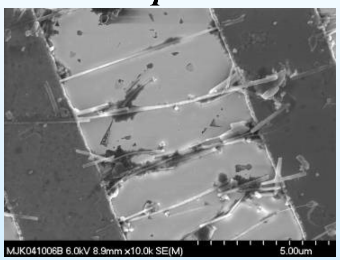
IMPROVE NANOSTRUCTURE TO MICROELECTRODE CONTACTS

Electrospinning



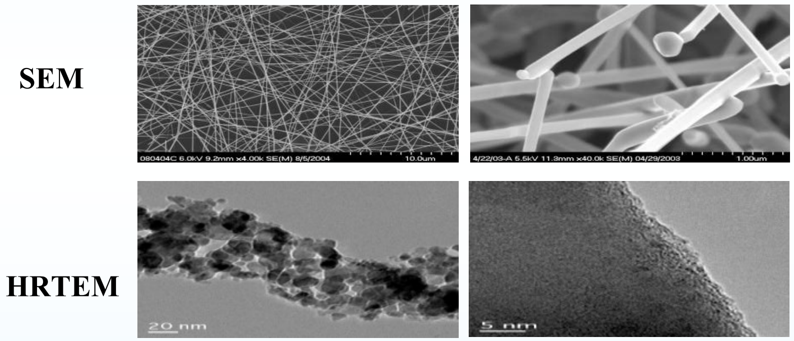
Bridging of electrospun SnO_2 nanofibers across electrodes.

Dielectrophoresis



TiO2 Nanorods aligned by dielectrophoresis across interdigitated electrode patterns.

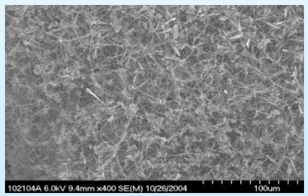
NANOMATERIAL STRUCTURE CONTROL



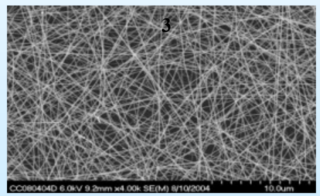
Different Processing of nanostructures produces different crystal structures

EXPAND RANGE OF NANOSTRUCTURES AVAILABLE

ZnO



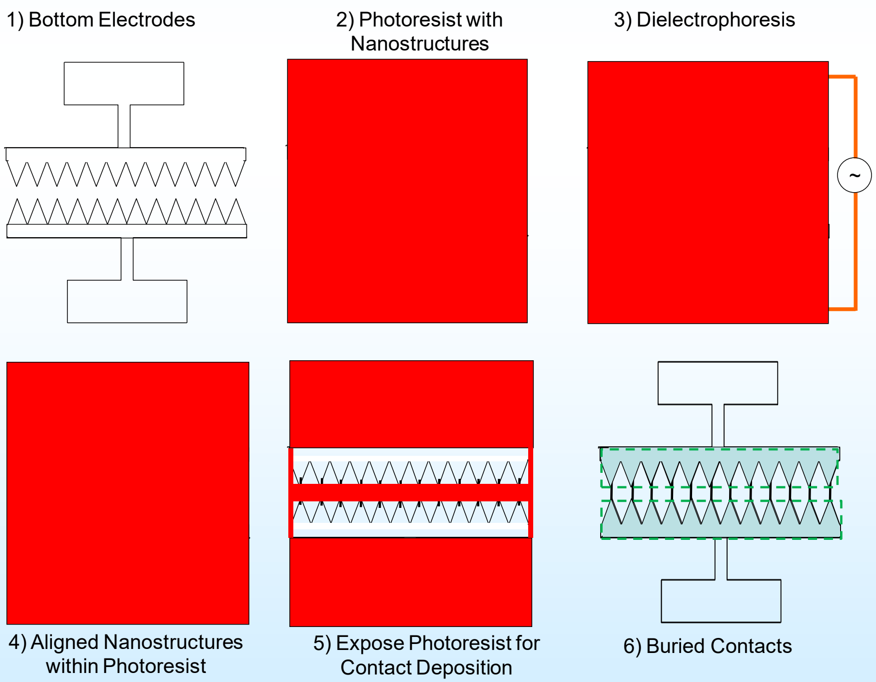
In_2O_3



Multiple oxide nanostructured materials fabricated

Microfabrication Techniques Applied To Nanotechnology

- Integration of standard microfabrication techniques with the alignment of nanostructures
- Core of the approach is to Mix Nanomaterials into the Photoresist Standardly Used for Microfabrication, Followed By Dielelectrophoresis for Alignments
- Implies that Nanostructures Can Be Integrated into Standard Microfabrication Processing At Multiple Stages in Sensor/Device Processing

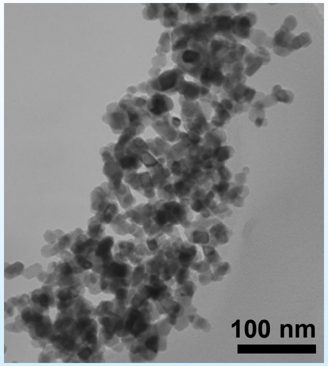


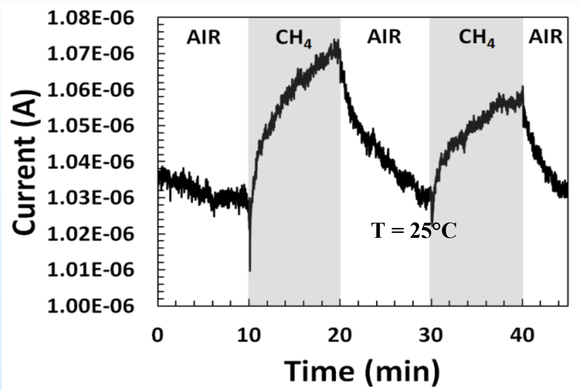
1) Deposit opposing sawtooth patterns on a substrate using standard photolithographic techniques.
2) Coat the electrodes with a photoresist mixture containing nanostructures.
3-4) Use the sawtooth electrodes and dielectrophoresis to align the nanostructures.
5) Expose the electrodes while the nanostructures are held in place with photoresist.
6) Deposit the top metallic layer over the bottom sawtooth electrode pattern leaving nanostructures buried in the electrodes and complete photoresist removal. The dotted line is an alternate pattern for the top metallic layer that broadly covers the bottom electrodes in a rectangle, rather than the sawtooth electrode pattern.

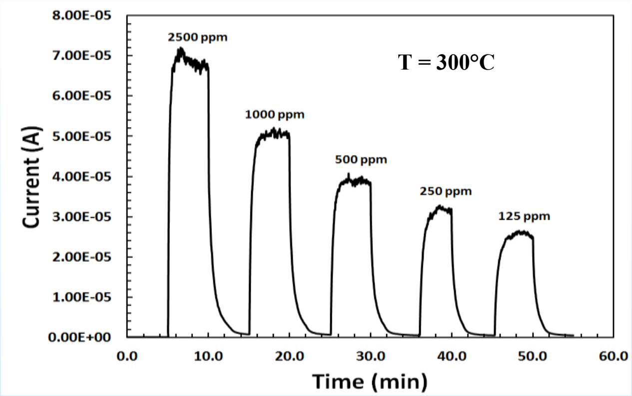
G.W. Hunter, et.al. Nanostructured Material Sensor Processing Using Microfabrication Techniques, Sensor Review 32/2 (2012) 106-117. (Paper of the year) Patent US 8,877,636 B1

Templated Approach To Sensor Fabrication

- Template Approach
  - Carbon Nanotube as a Template Coated with Tin Oxide
  - Burn Off Carbon Leaving Only Tin Oxide
  - Resulting Tin Oxide Has Sensing Properties More Similar to Carbon than Tin Oxide
- Porous SnO_2 nanorods via templated approach
  - Integrated into Micro Sensor Platform Using Micro Techniques
  - Room temperature methane detection
  - High temperature methane detection (up to 500°C)
- Can Be Used for Other Templates e.g., biological materials







A. Biaggi-Labiosa, et.al. A Novel Methane Sensor Based on Porous SnO2 Nanorods: Room Temperature to High Temperature Detection, Nanotechnology 23 (2012) 455501. Patent to be issued.

Example Possible Collaboration Approaches

- NASA Space Act Agreement (SAA)
  - Similar to CRADA in the DOD
  - Reimbursable SAA (Funds Exchanged)
  - NonReimbursible SAA (No Funds Exchanged)
- NASA Proposals
  - If There Is Not An Existing Agreement or In-House Capability, Then Partners Are Sought
  - Reply To Notice NASA Announcement Of Opportunity (AO) Related To A Partnership Opportunity
  - Typically, The Partnership Opportunity Would Note The Proposal Call And Outside Capabilities Sought
- Proposals To Other Sources Including Other Government Agencies
  - Contact Relevant NASA Technical POC Long Before The Proposal Is Due
  - Some Proposal Calls Do Not Allow Funding to Other Government Organizations

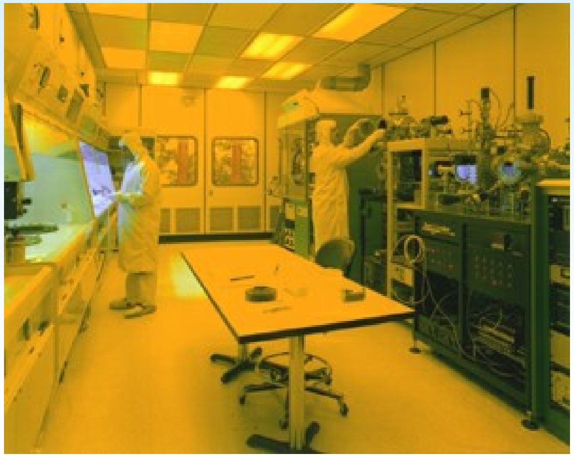
SUMMARY AND LONG-TERM VISION

- One of the Fundamental Suggestions Implied By This Presentation Is That Multiuse Micro/Nano Sensor Technology Combined With A Basic Hardware Platform (E.G. "Lick And Stick" Technology) Can Enhance The Viability Of Implementing Smart Sensor Systems
- Revolutionary Changes In A Range Of Applications Can Be Enabled By Intelligent Micro/Nano Systems
- A Range Of Systems Under Development; Begin With A Smart Core And Adapt To The Application
- Future Vision: Designer Diagnostics/Monitoring Systems Tailored To Optimize The Measurement Down To The Individual Application Environment for Distributed, Localized Care
- Part Of Full Field Diagnosis System Which Could Also Be Enabled With Intelligent Micro/Nano Systems
    - Ideally A Range Of Non-invasive Diagnostic Measurements
    - Diagnostics Systems Which Can Smell, Hear, See, Feel, Process Information And Communicate, And Self-reconfigure All In Miniaturized Field Applicable Systems
- Do Something With The Data: Diagnosis Combined With Treatment
- No Matter How Good The Technology, It Will Not Be Used Until It Proves Itself

A POSSIBLE VISION: A "SMART" SUIT ABLE TO PROVIDE COMPLETE DIAGNOSTICS AND HEALTH CARE

BACK UP

Facilities and Laboratories



Microsystems Fabrication Facility (Class 100 Cleanroom Facility)

Features:

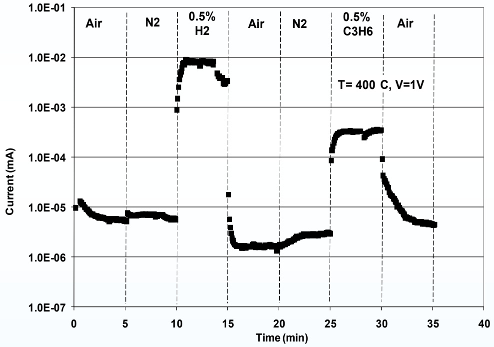
- 3000 square feet class 100 and class 1000 cleanroom space, Photolithography tools suitable for 2 micrometer linewidt Chemical work stations for substrate cleaning and wet etching
- Physical vapor thin film deposition systems, Plasma etchers, including deep reactive ion etcher for SiC micromachining
- Low pressure chemical vapor deposition system for silicon dioxide films
- Annealing and oxidation furnaces, Rapid thermal annealers

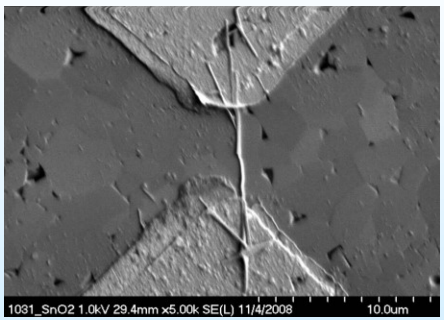
Research Projects:

- SiC electronic devices –worlds first 500°C integrated circuit
- High temperature wireless sensors using 500°C SiC electronics
- Thin film sensors in-situ monitoring of high temperature processes
- Chemical sensors for active emissions control and health monitoring
- High temperature SiC pressure sensors for active combustion control
- SiC microactuators for control of fuel flow to minimize combustion instability

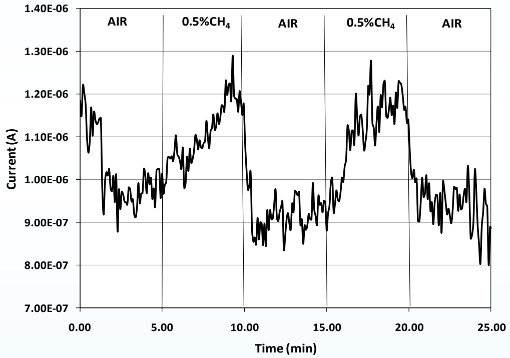
Microfabrication Techniques Applied To Nanotechnology

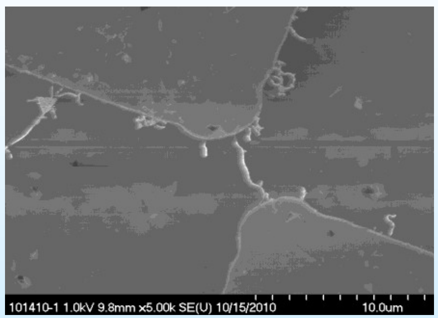
- Integration of standard microfabrication techniques with the alignment of nanostructures
- Length of nanostructures are affected by AC frequency used for alignment
- Core of the approach is to Mix Nanomaterials into the Photoresist Standardly Used for Microfabrication, Followed By Dielelectrophoresis for Alignments
- Implies Nanostructures Can Be Integrated into Standard Microfabrication Processing At Multiple Stages in Sensor/Device Processing



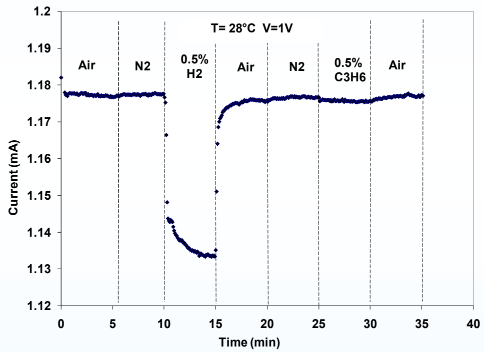


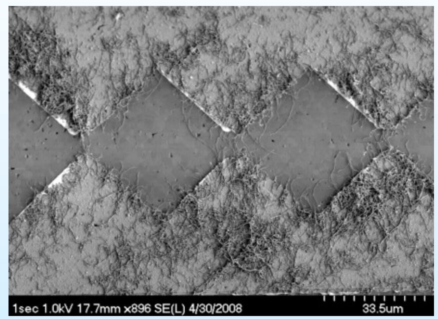
Tin Oxide Operational at 400°C Measuring Hydrogen and Hydrocarbons





Templated Tin Oxide Measuring Methane at Room Temperature
New capabilty





Carbon Nanotubes Operational at Room Temperature