Miniaturized Sensor Systems for Aerospace Fire Detection Applications

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OUTLINE

- INTRODUCTION

- SENSOR PLATFORMS AND SYSTEMS
  - HYDROGEN SENSOR/SCHOTTKY DIODE
  - "LICK AND STICK"

- FIRE DETECTION SENSOR DEVELOPMENT
  - CO
  - CO2
  - PARTICULATE

- FAA TESTING
  - FALSE ALARMS
  - FIRE DETECTION

- SUMMARY AND FUTURE PLANS

MICROFABRICATED GAS SENSORS

- COLLABORATIVE EFFORT BETWEEN NASA GRC, CASE WESTERN RESERVE, and OHIO STATE UNIVERSITY

- SENSOR DEVELOPMENT RESULTING FROM:
  - IMPROVEMENTS IN MICROFABRICATION AND MICROMACHINING TECHNOLOGY
  - NANOMATERIALS
  - DEVELOPMENT OF SiC-BASED SEMICONDUCTOR TECHNOLOGY

- GAS DETECTION IN:
  - HARSH ENVIRONMENTS
  - APPLICATIONS BEYOND CAPABILITIES OF COMMERCIAL SENSORS

- TECHNOLOGY DEVELOPS PLATFORMS FOR A VARIETY OF MEASUREMENTS
  - SCHOTTKY DIODE
  - RESISTANCE BASED
  - ELECTROCHEMICAL

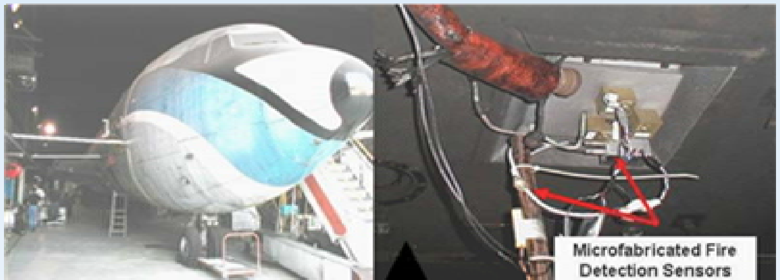
- TARGET DETECTION OF GASES OF FUNDAMENTAL INTEREST
  - HYDROGEN (H_2)
  - HYDROCARBONS (C_xH_y)
  - NITROGEN OXIDES (NO_X) AND CARBON MONOXIDE (CO)
  - OXYGEN (O_2)
  - CARBON DIOXIDE (CO_2)

BASE PLATFORM SENSOR TECHNOLOGY

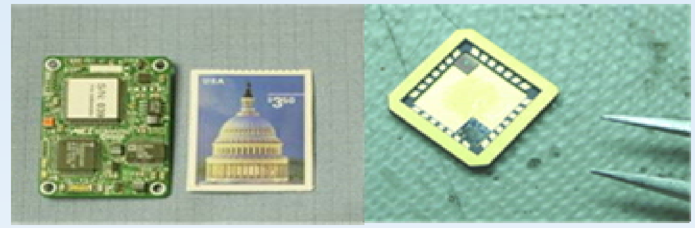
Integration of Micro Sensor Combinations into Small, Rugged Sensor Suites

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

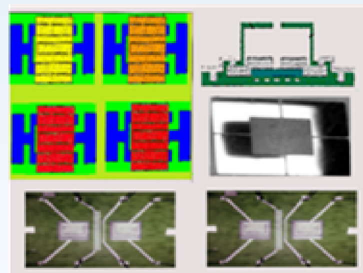
Multi Species Fire Sensors
for Aircraft Cargo Bays

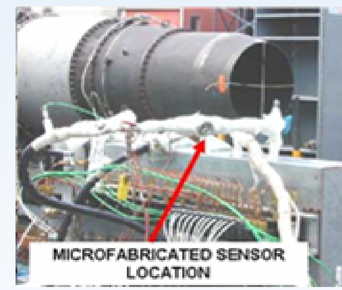


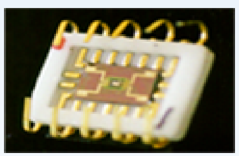
"Lick and Stick" Space Launch Vehicle
Leak Sensors with Power and Telemetry



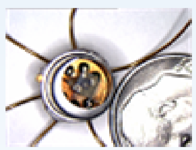
Aircraft Propulsion Exhaust High
Temperature Electronic Nose



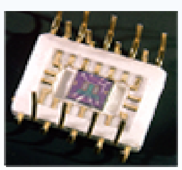




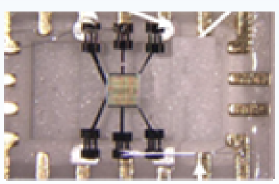
Oxygen Sensor



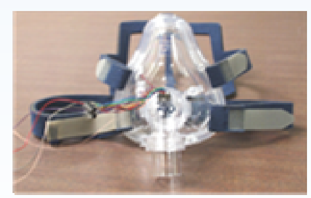
SiC Hydrocarbon
Sensor



H2 Sensor



Nanocrystalline Tin
Oxide NOx and CO
Sensor

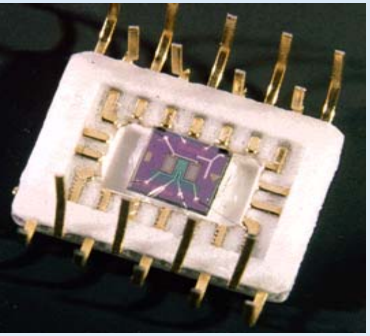


Sensor Equipped
Prototype Medical
Pulmonary Monitor

Hydrazine EVA Sensors
(11 ppb Detection)

CWRU

MEI Makel Engineering Inc.



HYDROGEN LEAK SENSOR TECHNOLOGY

- MICROFABRICATED USING MEMS-BASED TECHNOLOGY FOR MINIMAL SIZE, WEIGHT AND POWER CONSUMPTION
- HIGHLY SENSITIVE IN INERT OR OXYGEN-BEARING ENVIRONMENTS, WIDE CONCENTRATION RANGE DETECTION

1995 R&D 100 AWARD WINNER

NASA 2003 TURNING GOALS INTO REALITY SAFETY AWARD

Shuttle

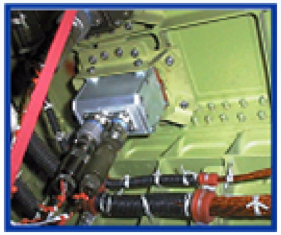
X33

X43

Helios

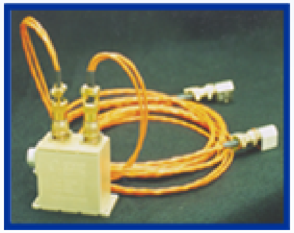
IIS

Model U

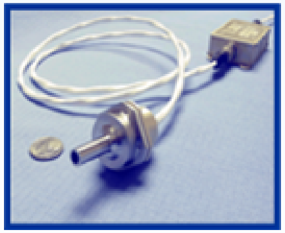


Aft Compartment Hydrogen Monitoring

Hydrogen Safety Monitoring

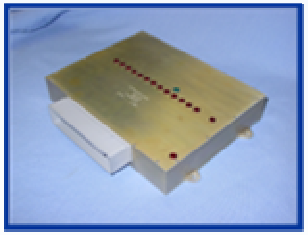


Hydrogen Safety Monitoring



Fuel Cell Safety and Process Monitoring

Life Support Process and Safety Monitoring



Vehicle Safety Monitoring

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SENSOR SYSTEM DEVELOPMENT

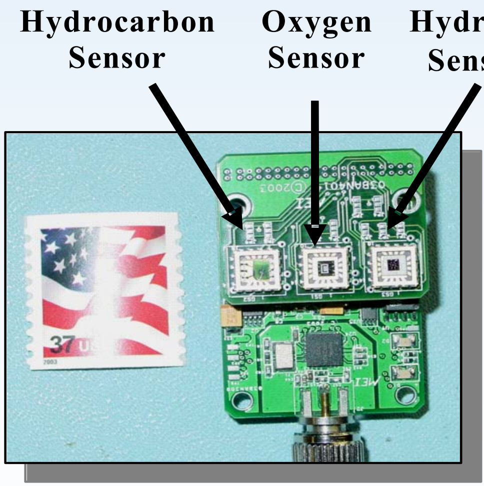
- EACH SENSOR PLATFORM PROVIDES QUALITATIVELY VERY DIFFERENT TYPES OF INFORMATION ON THE ENVIRONMENT
- SENSOR ARRAY VARIES WITH APPLICATION/MICROFABRICATION TECHNIQUES MANDATORY
- BASIS CHEMICAL SENSOR FEATURES:
  - RESPONSE TIME, SENSITIVITY, SELECTIVITY, STABILITY
  - BATCH FABRICATION, PROCESSING REPRODUCIBILITY, CONTROL OF STRUCTURE
  - TAILOR SENSOR SYSTEM FOR THE APPLICATION
- SUPPORTING TECHNOLOGIES NECESSARY
  - PACKAGING (OFTEN UP TO 70% OF OVERALL SENSOR COST)
  - SIGNAL CONDITIONING AND PROCESSING
  - SOFTWARE (E.G. NEURAL NET PROCESSING, MODELING)
  - POWER AND COMMUNICATION

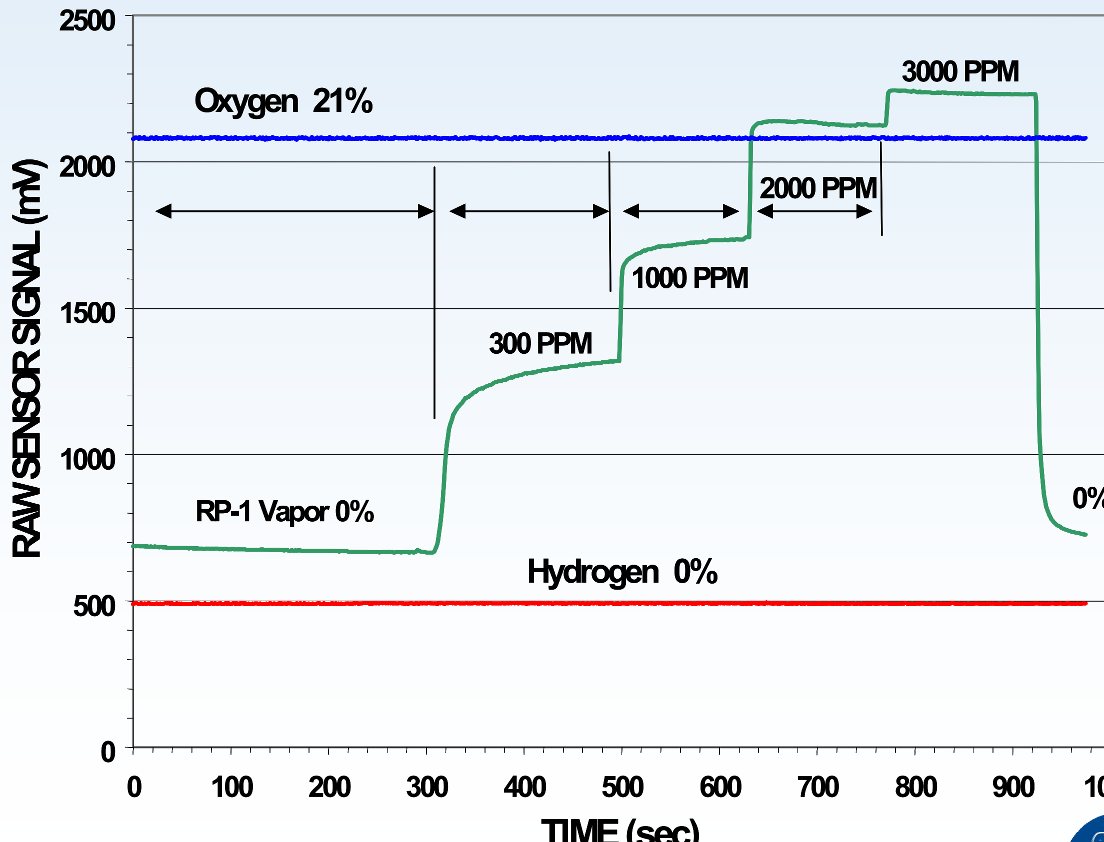
See for example: G. W. Hunter, C.C. Liu, D. Makel, Microfabricated Chemical Sensors For Aerospace Applications, MEMS Handbook, CRC Press LLC, ed. M. Gad-el-Hak, Ch. 22, 2001.

- POSSIBLE STEPS NEEDED FOR BROAD INCLUSION OF SENSORS INTO INTELLIGENT SYSTEMS
  - “LICK AND STICK” TECHNOLOGY (EASE OF APPLICATION)
  - RELIABILITY
  - ORTHOGONALITY
  - CROSS-CORRELATION
  - REDUNDANCY

"LICK AND STICK" LEAK SENSOR SYSTEM DEMONSTRATION

- MULTIPLE SENSORS IN ONE POSTAGE STAMP SIZED SYSTEM WITH POWER, SIGNAL PROCESSING, AND TELEMETRY
- COMBINE FUEL (HYDROGEN, HYDROCARBON) WITH OXYGEN IN AN ARRAY:
  - DECREASE SIZE AND POWER OF SENSORS/ELECTRONICS
  - VERIFY SYSTEM COMPATIBILITY WITH SPACE APPLICATIONS
- MEANT FOR BROAD COVERAGE OF REGION TO DETERMINE EXPLOSIVE CONCENTRATIONS OF FUEL/OXYGEN





Micro-Fabricated Gas Sensors for Low False Alarms

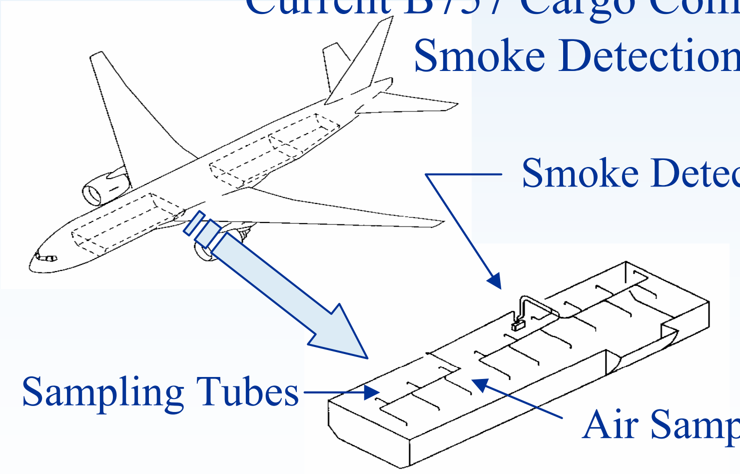
FEATURES

- MICROFABRICATED CO/CO_2 GAS SENSOR ARRAY
  - ➢CENTRAL TO APPROACH
  - ➢NANOCRYSTALLINE MATERIALS (IN CO SENSOR) PRODUCE MORE SENSITIVE, STABLE SENSORS
  - ➢TWO APPROACHES TO CO2 DETECTION
  - ➢MINIMAL SIZE/WEIGHT/POWER
- CHEMICAL GAS SENSORS PROVIDE GASEOUS PRODUCT-OF-COMBUSTION INFORMATION
  - ➢SENSOR ARRAY CAN DETECT RANGE OF GAS SPECIES
  - ➢TO BE COMBINED WITH INTELLIGENT SOFTWARE FOR PATTERN RECOGNITION
- BENEFITS

➢DISCRIMINATE FIRES FROM NON-FIRES

➢POTENTIAL SPIN-OFF TO HIGH-TEMPERATURE ENGINE MULTI SPECIES EMISSION CONTROL

Current B757 Cargo Compartment Smoke Detection

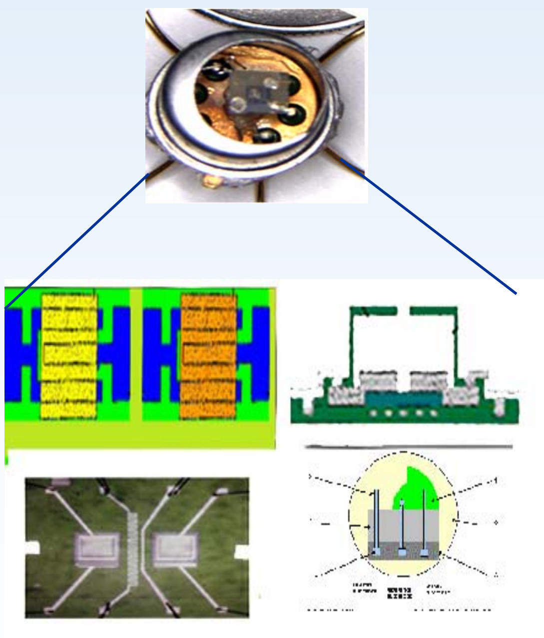


FAA Technical Center   MEI Makel Engineering Inc.   CWRU   The Ohio State University   NASA

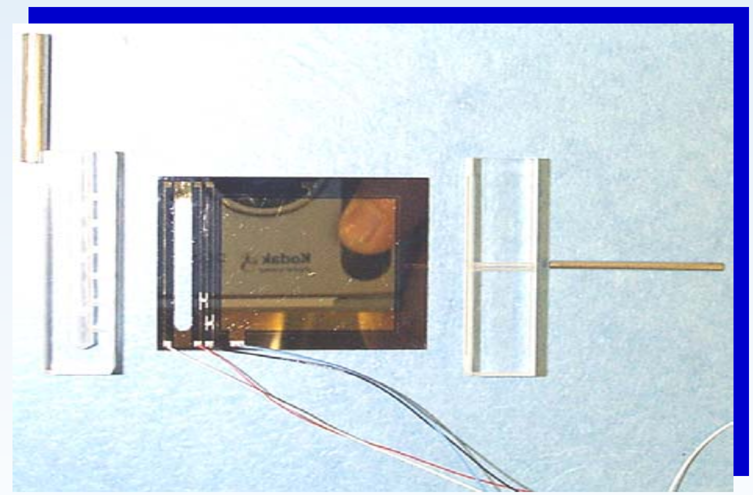
OVERALL FIRE DETECTION APPROACH

- **COMBINED MEMS-BASED CHEMICAL SPECIES AND PARTICULATE**
- **ORTHOGONAL DETECTION AND CROSS-CORRELATION SIGNIFICANTLY REDUCES FALSE ALARMS**

MEMS-Based Chemical Species Detection



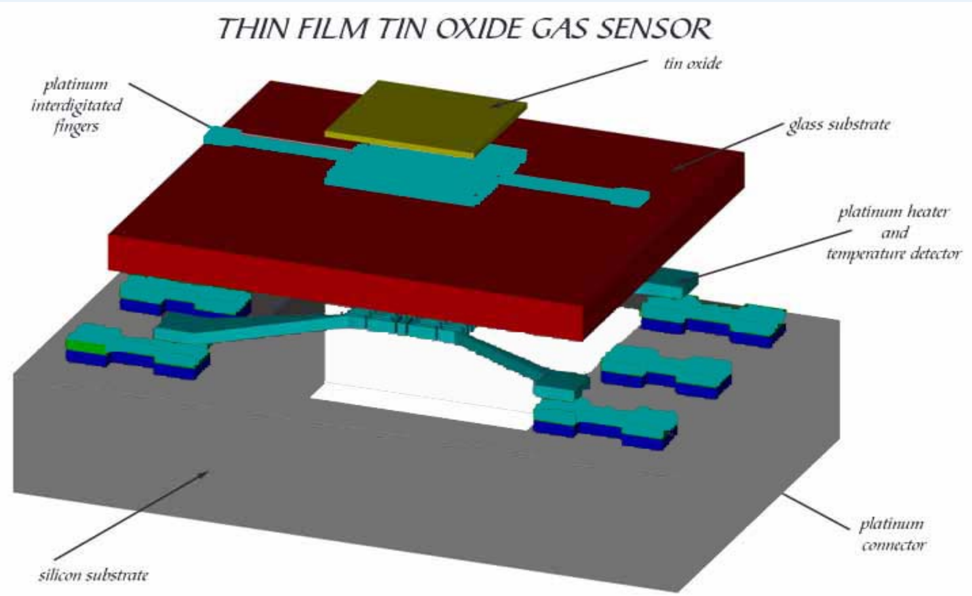
MEMS-Based Particulate Detector

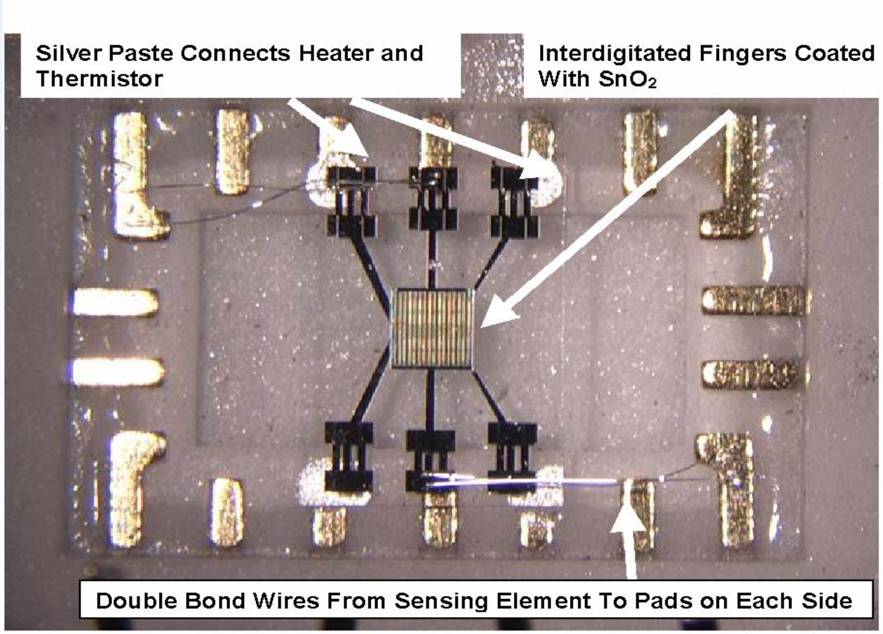


MICROFABRICATED NANOCRYSTALLINE TIN OXIDE NOx AND CO SENSOR TECHNOLOGY

A MIXTURE OF MICRO AND NANO TECHNOLOGY

- **MICROFABRICATED FOR MINIMAL SIZE, WEIGHT AND POWER CONSUMPTION**
- **MICROMACHINED TO MINIMIZE POWER CONSUMPTION AND IMPROVE RESPONSE TIME**
- **TEMPERATURE DETECTOR AND HEATER INCORPORATED INTO SENSOR STRUCTURE**
- **NANOFABRICATION OF TIN-OXIDE TO INCREASE SENSOR STABILITY**





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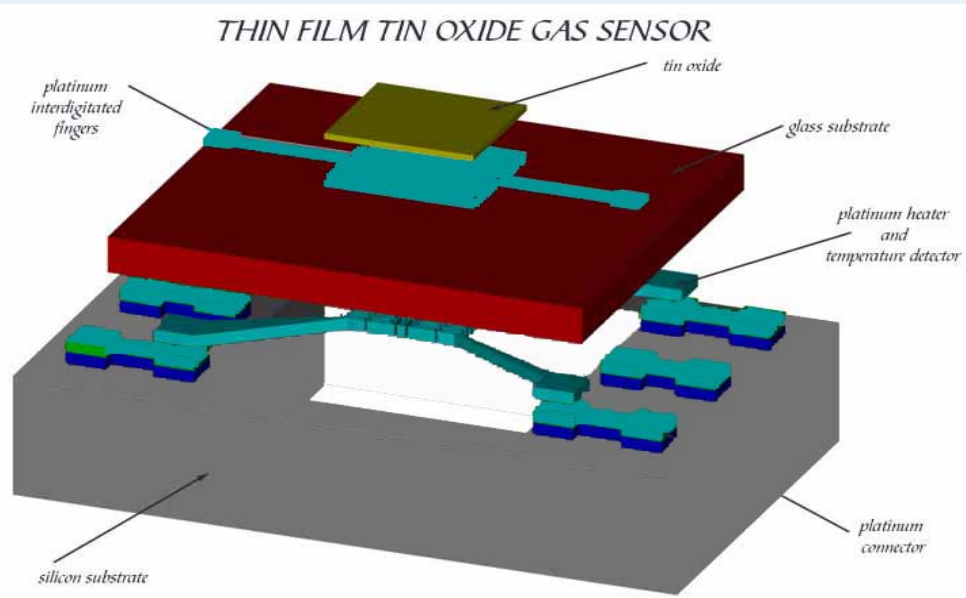
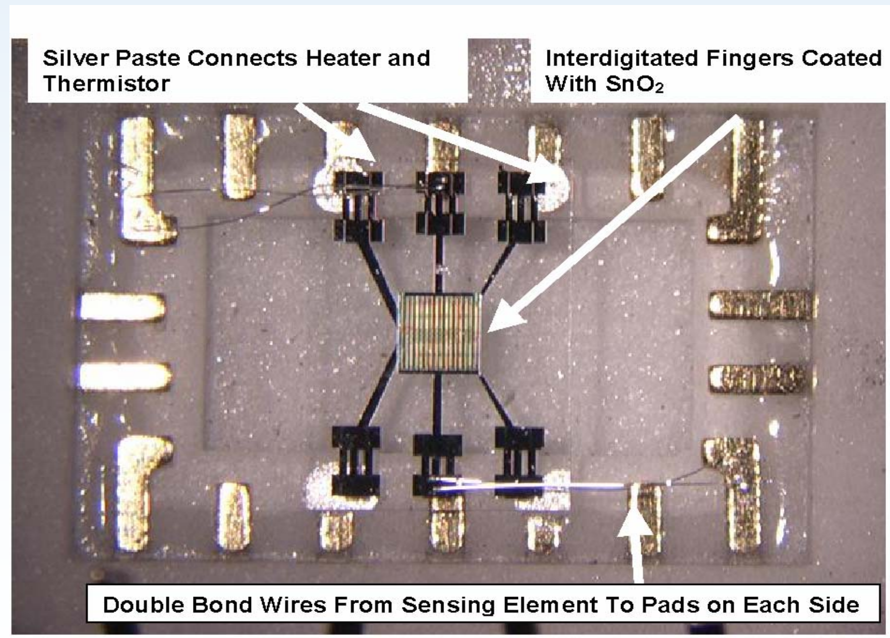
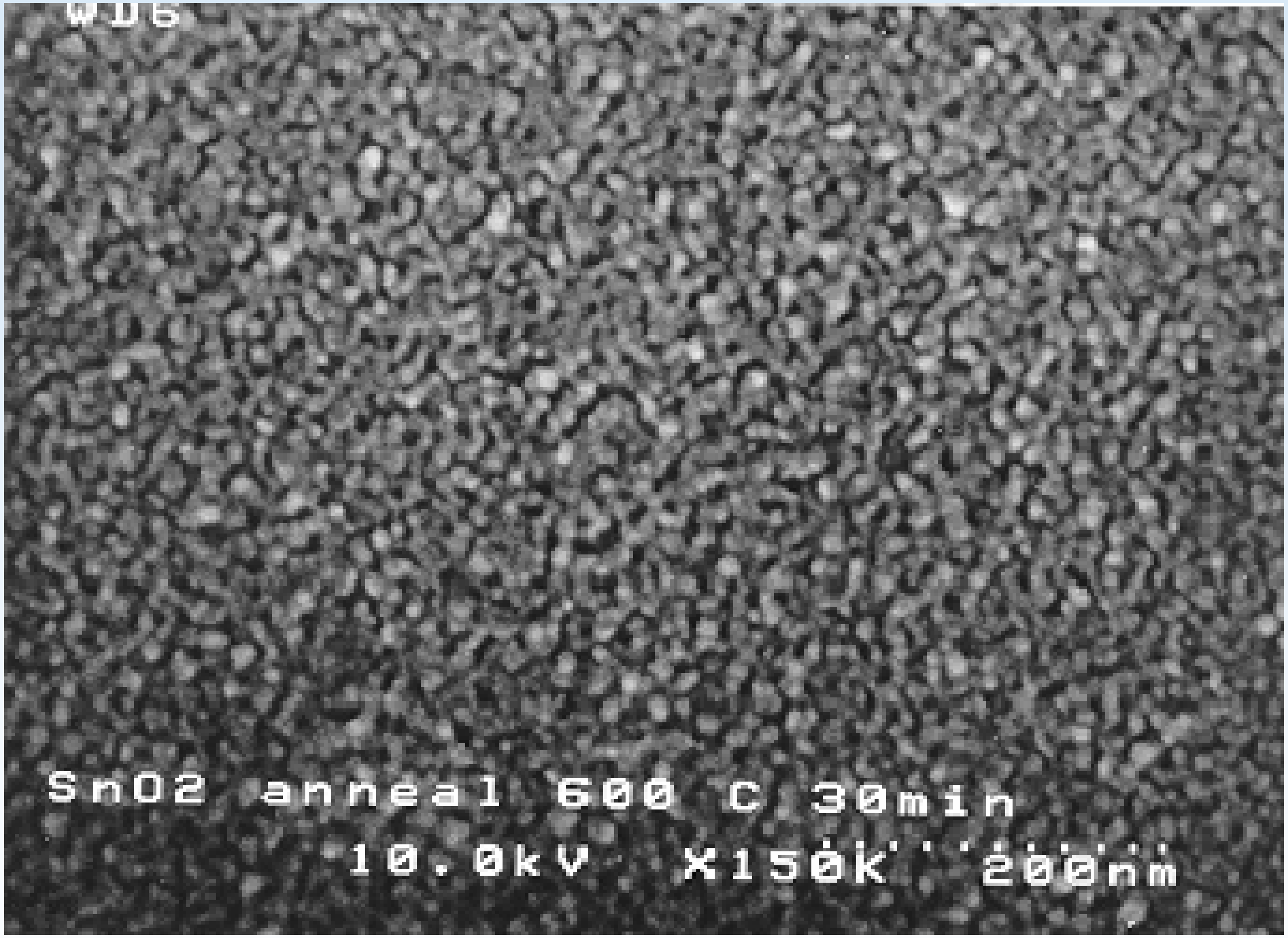
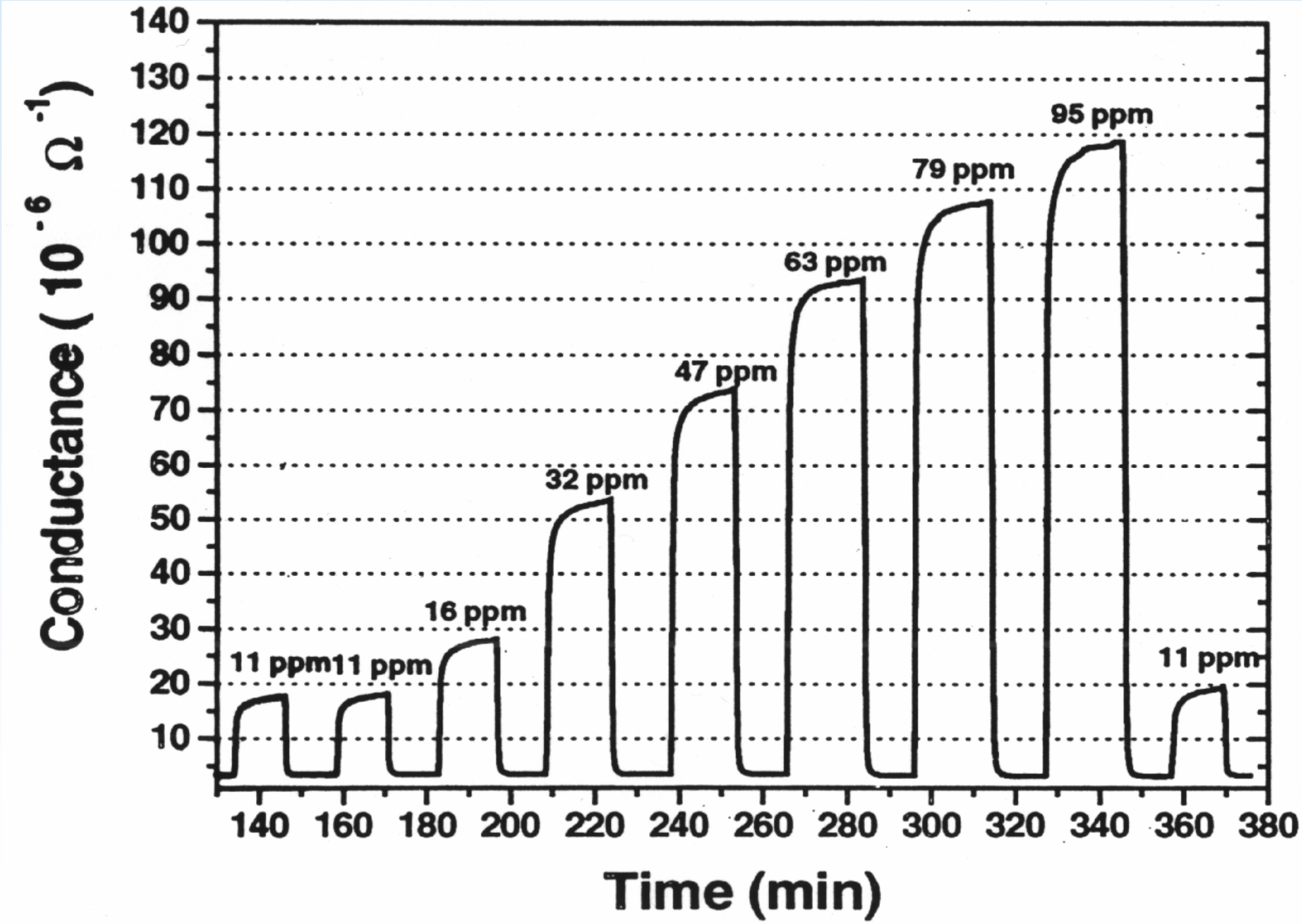






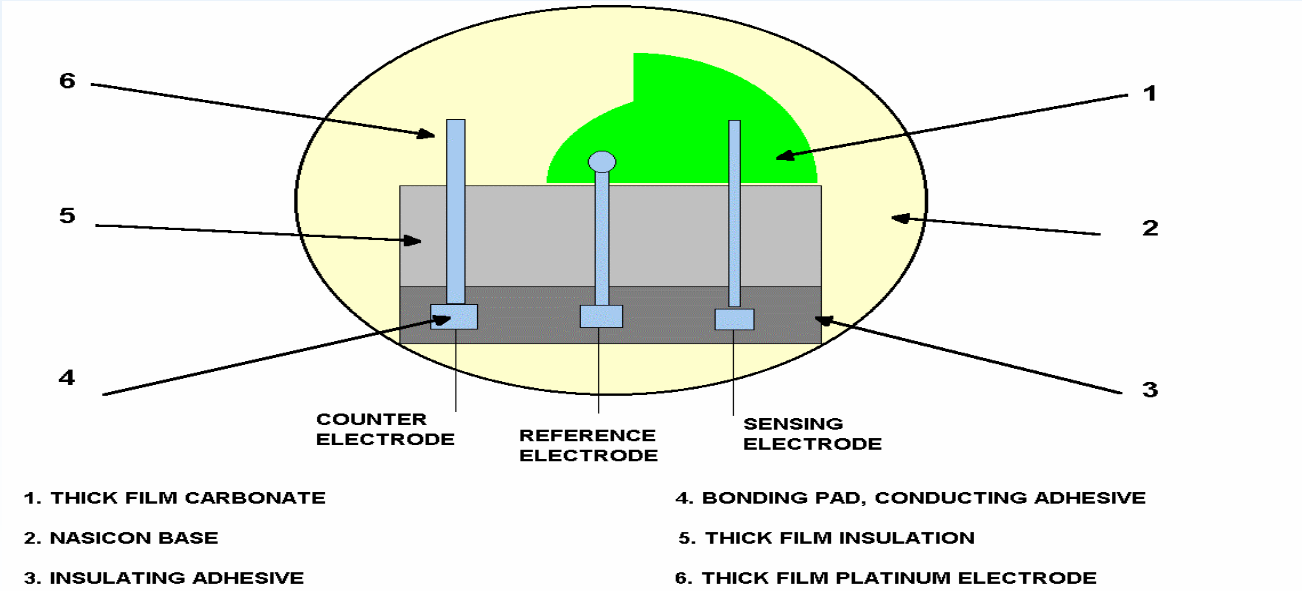
Nanocrystalline SnO2 after annealing at 600°C for 30 minutes.

THE RESPONSE OF A DOPED SNO_2 SENSOR TO CYCLED CONCENTRATIONS OF CO



MICROFABRICATED NASICON BASED CO2 SENSOR TECHNOLOGY

- MICROFABRICATED FOR MINIMAL SIZE, WEIGHT AND POWER CONSUMPTION
- ELECTROCHEMICAL CELL DESIGN USING PROTON CONDUCTING NASICON AS ELECTROLYTE TO DETECT A RANGE OF CO2 CONCENTRATIONS
- TEMPERATURE DETECTOR AND HEATER TO BE INCORPORATED INTO SENSOR STRUCTURE
- SENSOR TO BE COMBINED WITH CO SENSOR FOR SIMULTANEOUS CO/CO2 DETECTION

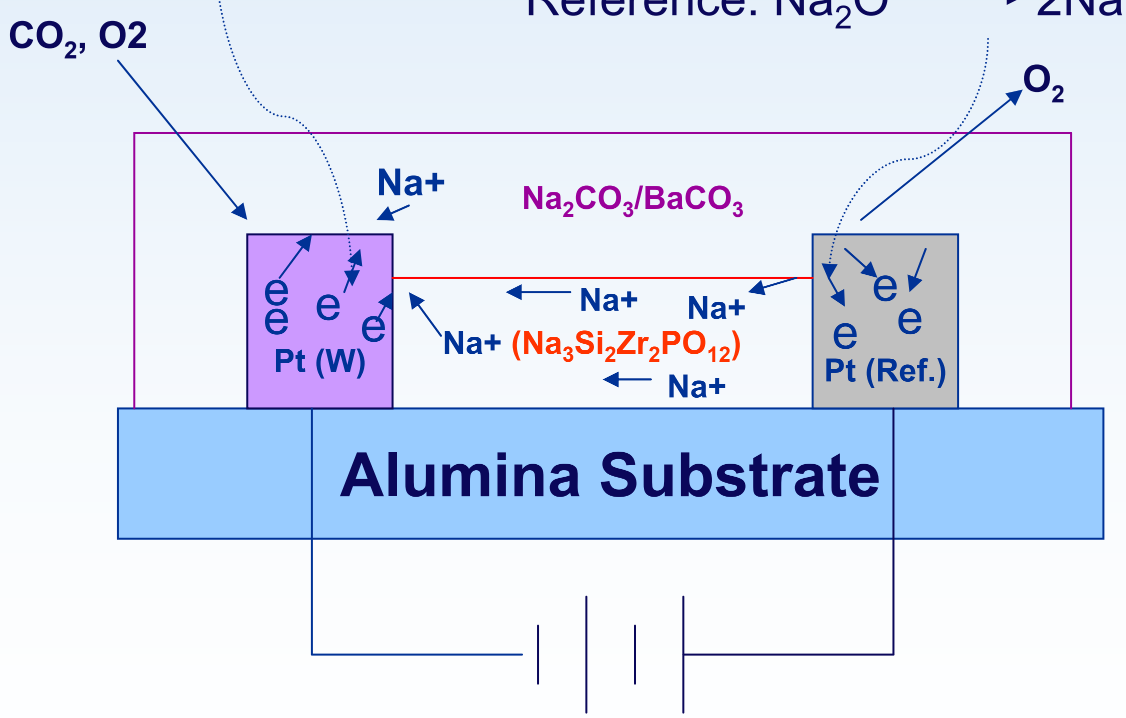


STRUCTURE OF A NASICON-BASED ELECTROCHEMICAL CELL CO2 SENSOR

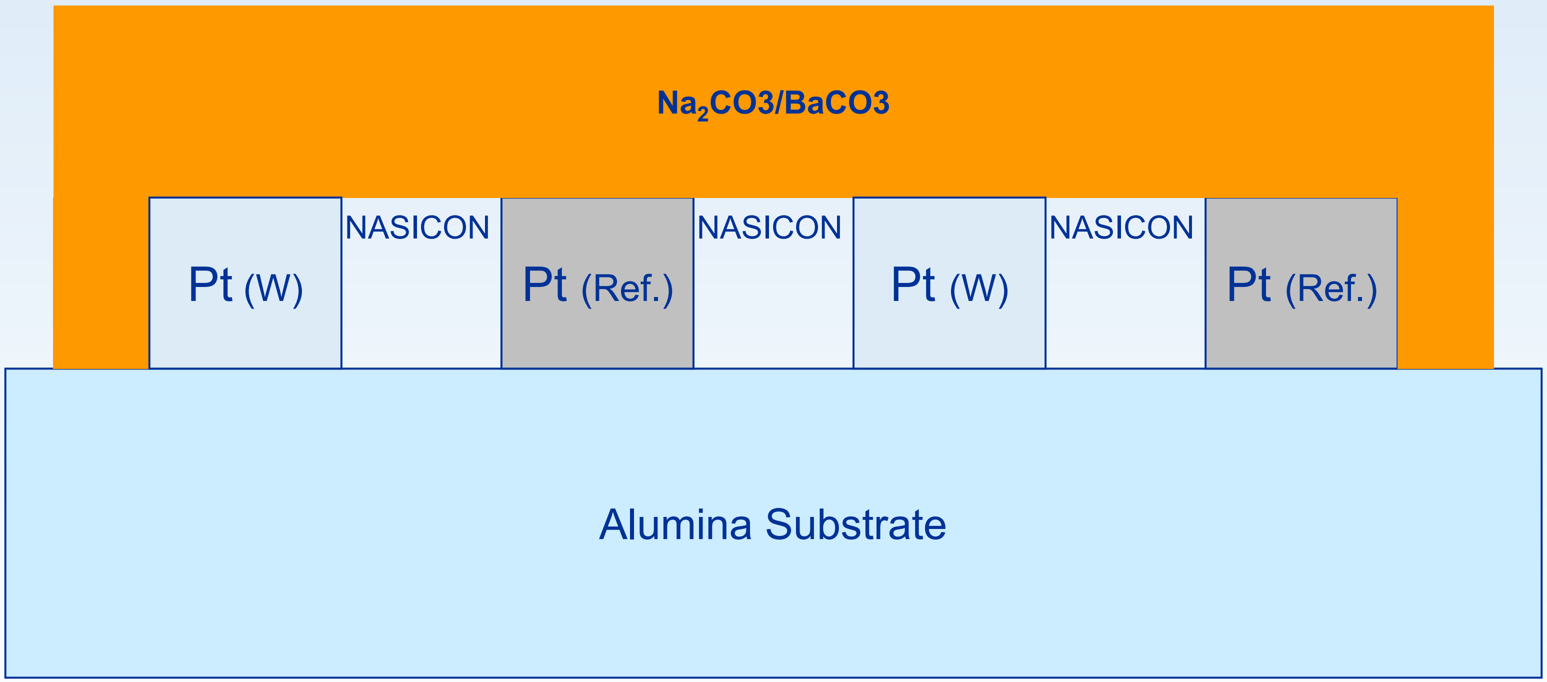
Sensing Mechanism of the Amperometric CO_2 Sensors

Working: $2Na^+ + CO_2 + 1/2\ O_2 + 2e \longrightarrow 2Na_2CO_3$

Reference: $Na_2O \longrightarrow 2Na^+ + 1/2O_2 + 2e$

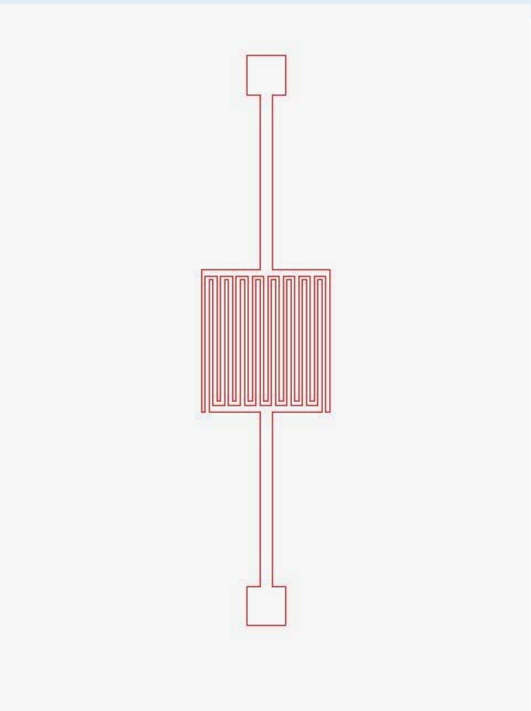


MICROFABRICATED AMPERIOMETRIC SENSOR SIDE VIEW

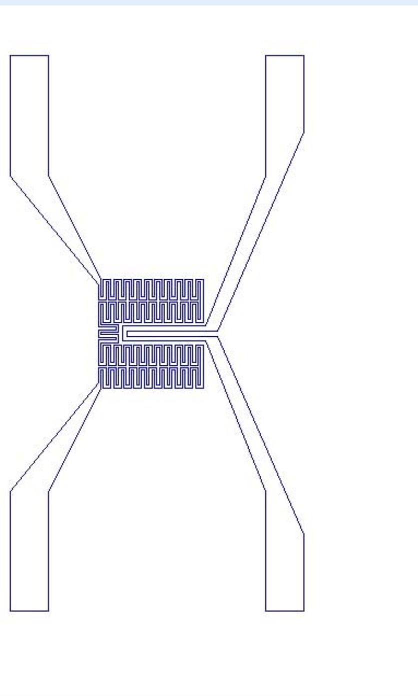


Amperometric CO_2 Sensor

SENSOR DESIGN

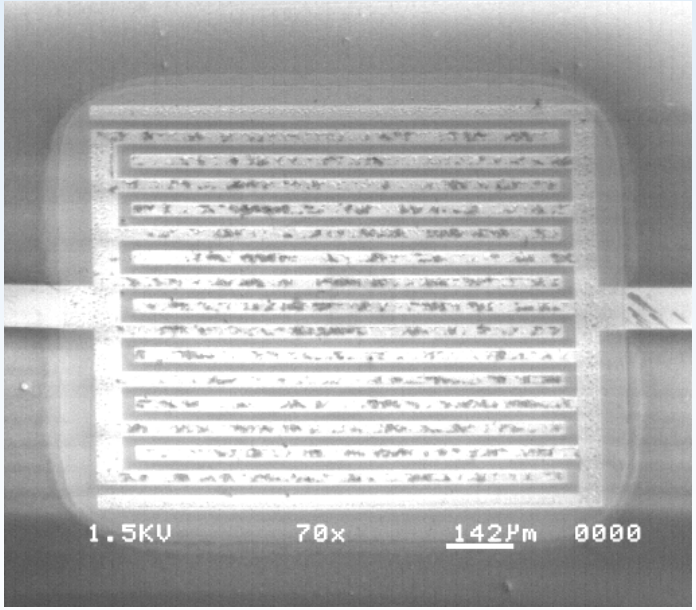


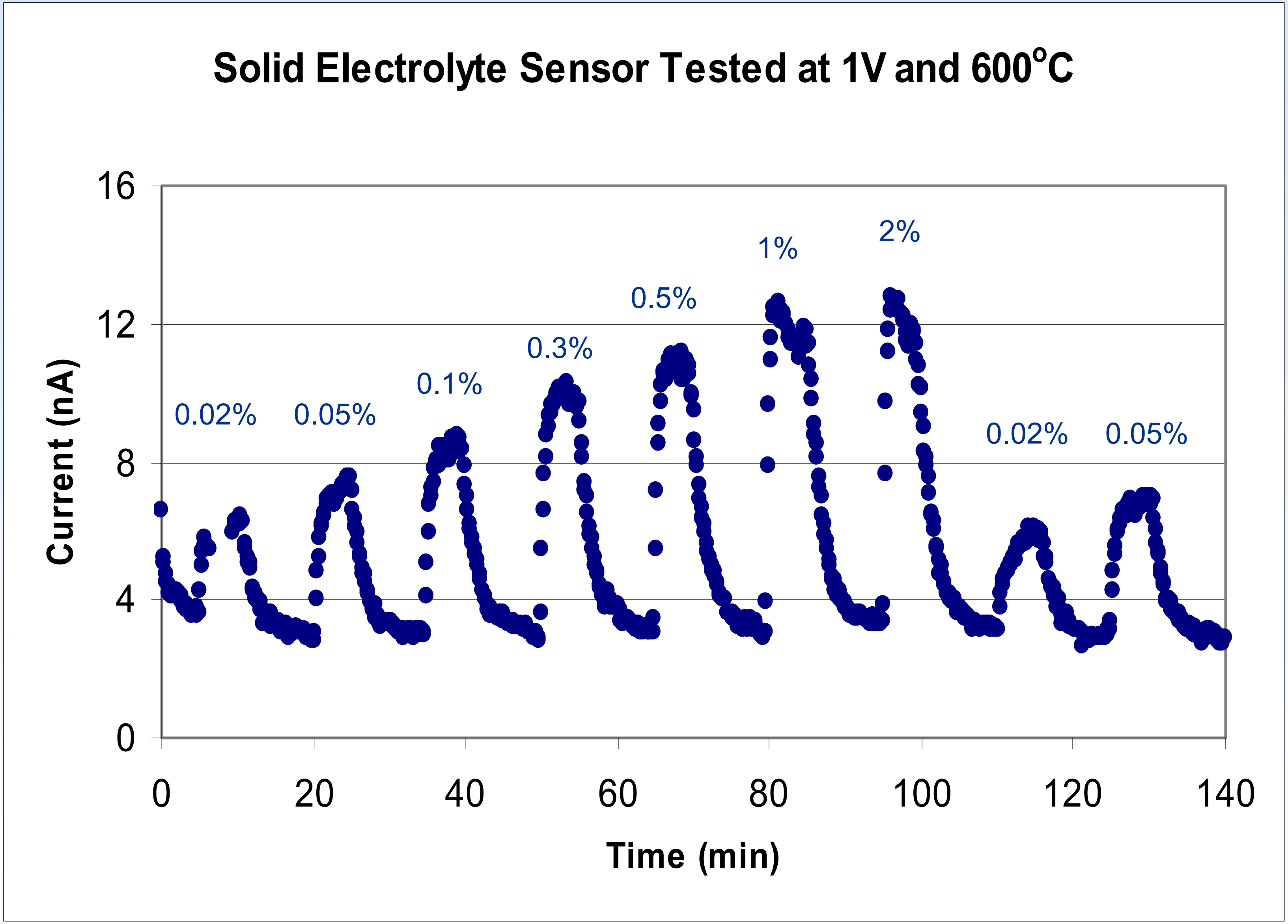
INTERDIGITATED FINGERS



TEMPERATURE DETECTOR AND HEATER

SEM OF SENSOR STRUCTURE



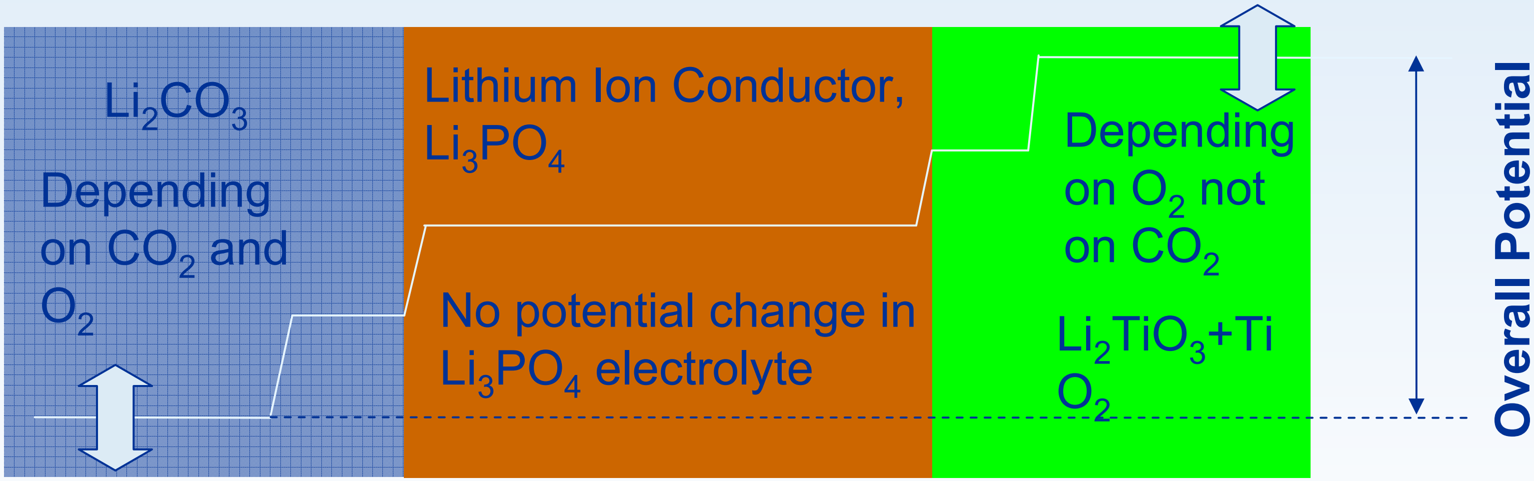


Solid Electrolyte Sensor Tested at 1V and 600°C
Current (nA)
Time (min)
16
12
8
4
0
0
20
40
60
80
100
120
140
0.02%
0.05%
0.1%
0.3%
0.5%
1%
2%
0.02%
0.05%

FUNDAMENTALS OF POTENTIOMETRIC CO2 SENSOR

$$2Li^{+} + CO_2 + \frac{1}{2}O_2 + 2e- = Li_2CO_3$$

$$2Li^{+} + TiO_2 + \frac{1}{2}O_2 + 2e- = Li_2TiO_3$$

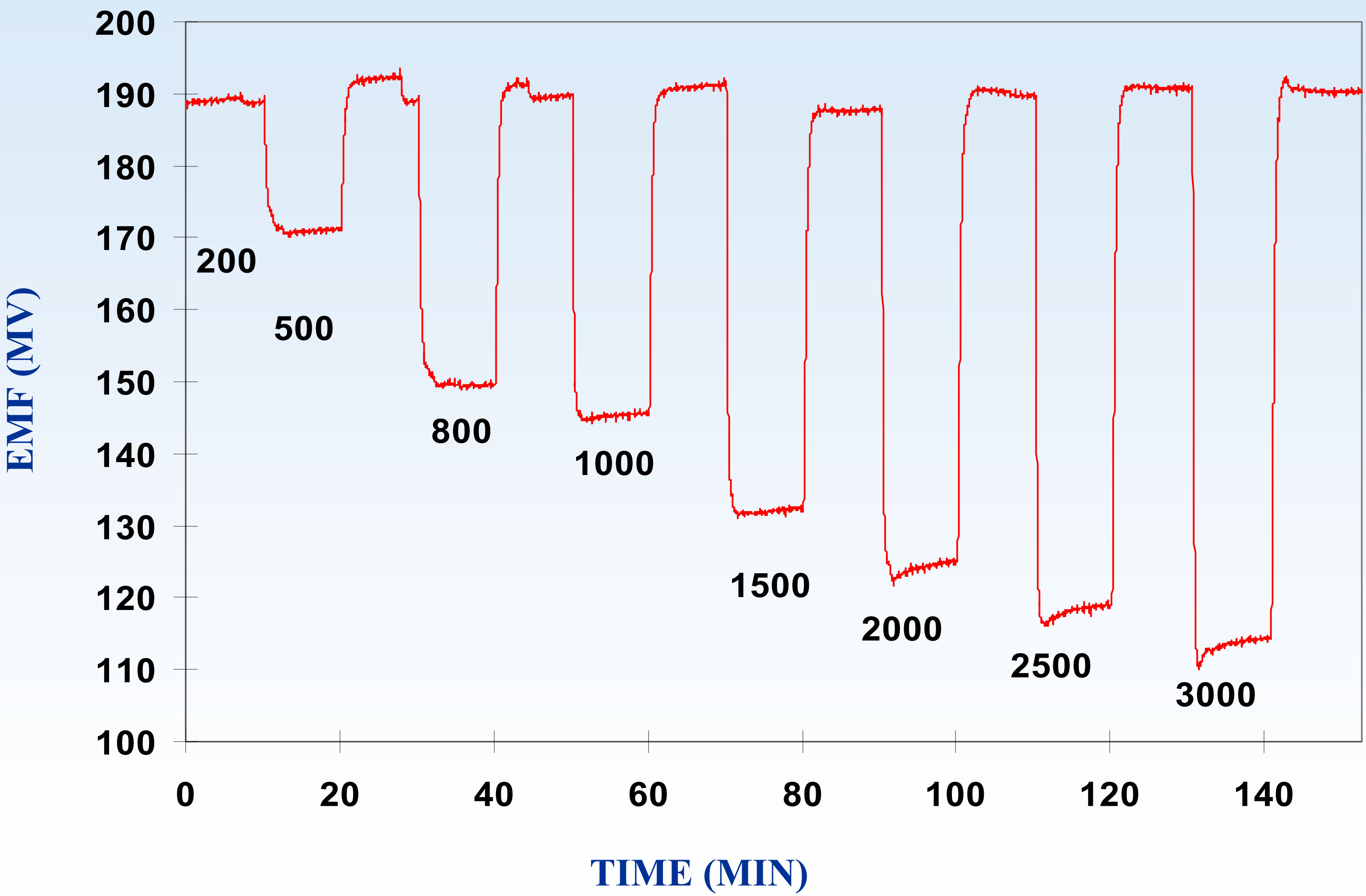


Overall Potential is determined by the Nernst Equation.

$$E_{cell} = -\frac{\Delta G^{o}}{2F} + \frac{RT}{2F}\ln P_{CO_2}$$

$$\Delta G^{o} = \Delta G^{\circ}_{f,TiO_2} - \Delta G^{\circ}_{f,Li_2TiO_3} - \Delta G^{\circ}_{f,CO_2} + \Delta G^{\circ}_{f,Li_2CO_3}$$

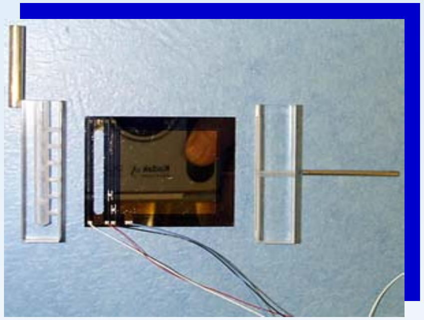
POTENTIOMETRIC CO2 SENSOR RESPONSE (500 C)



<u>OBJECTIVE</u>:

DEVELOPMENT AND DEMONSTRATION OF MICRODEVICES FOR THE CLASSIFICATION OF PARTICULATE SIZE AND CHARGE STATE DISTRIBUTION OF ATMOSPHERIC AEROSOLS.

MEMS sensor fabrication and assembly

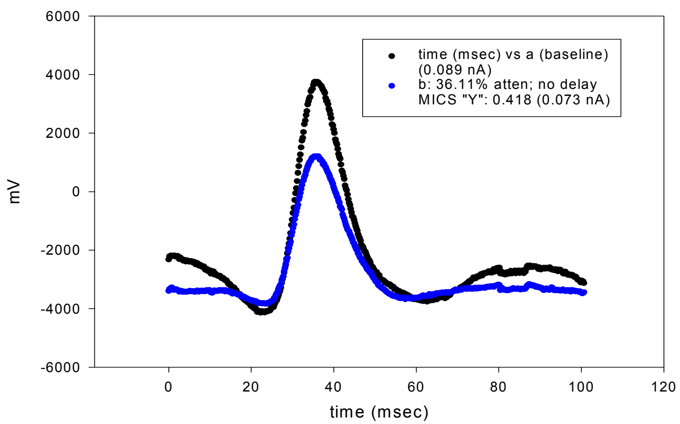


Completed wafer showing:
i) Micro-machined ion injection aperture
ii) Electric leads attached
iii) Integrated fluidic manifolds

Completed sensor contrast with traditional macroscale classifier.

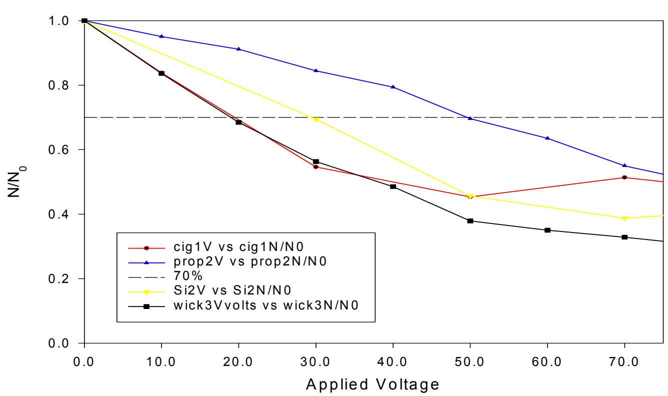
COMBINED CHEMICAL AND PARTICULATE SENSOR SYSTEM TESTED AT NIST PARTNERS: AVIATION SAFETY PROGRAM AND BIOASTRONAUTICS

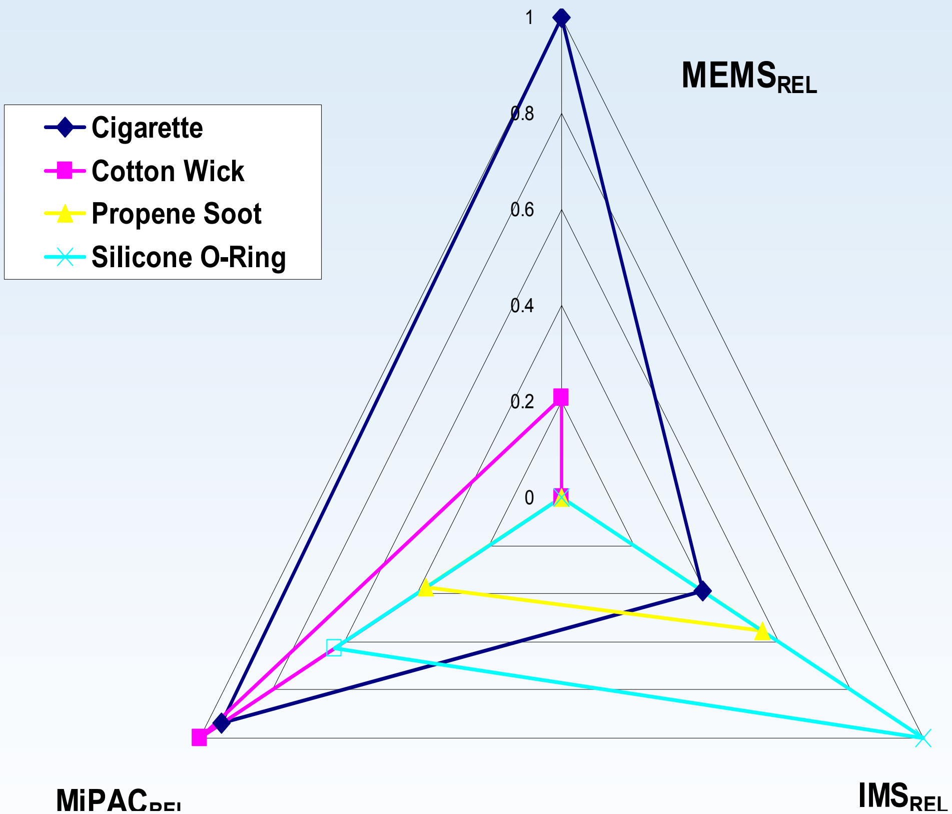
TOF Data: Pyrolizing Silicon Rubber



Classifier Data

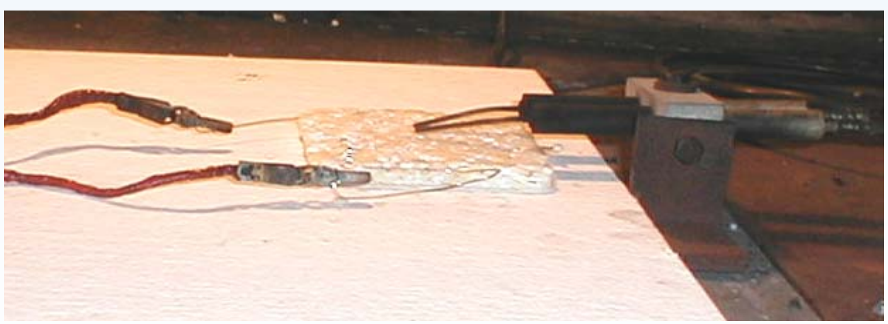
N/N_0 vs. Applied Voltage





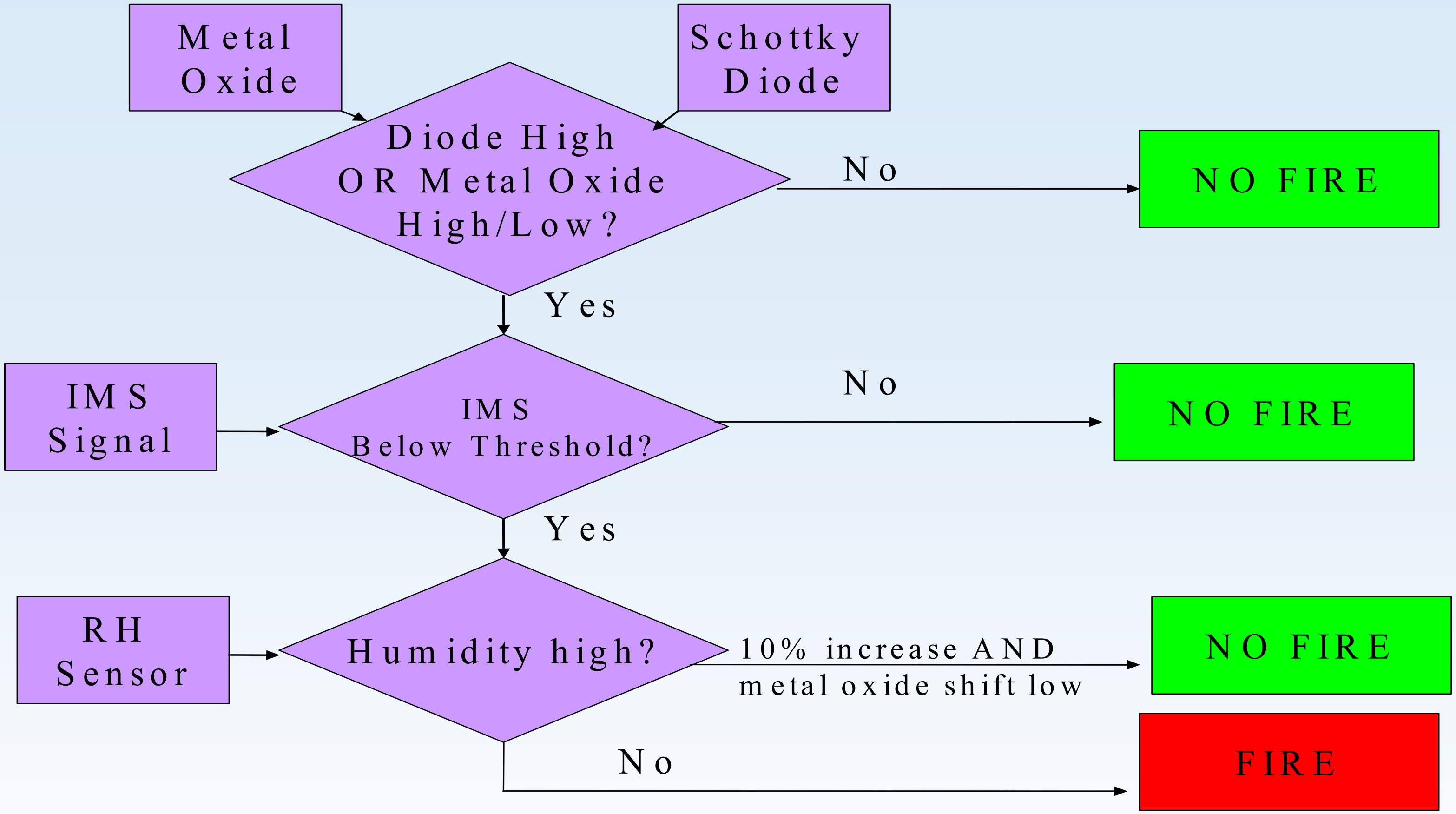
Response of 4 fire types - outputs relative to maximum signal from each detector

FAA Cargo Bay Fire Simulation Testing
Test False Alarm Rate and Ability to Detect Fires



Boeing 707 luggage compartment and the FAA "Biscuit"

SIMPLIFIED VERSION OF DETECTION ALGORITHM



	Δ MOS Sensor (Counts)	IMS Threshold	Max Δ RH
Algorithm X	100	0.6	10%
Algorithm Y	200	0.6	10%
Algorithm Z	100	0.8	10%

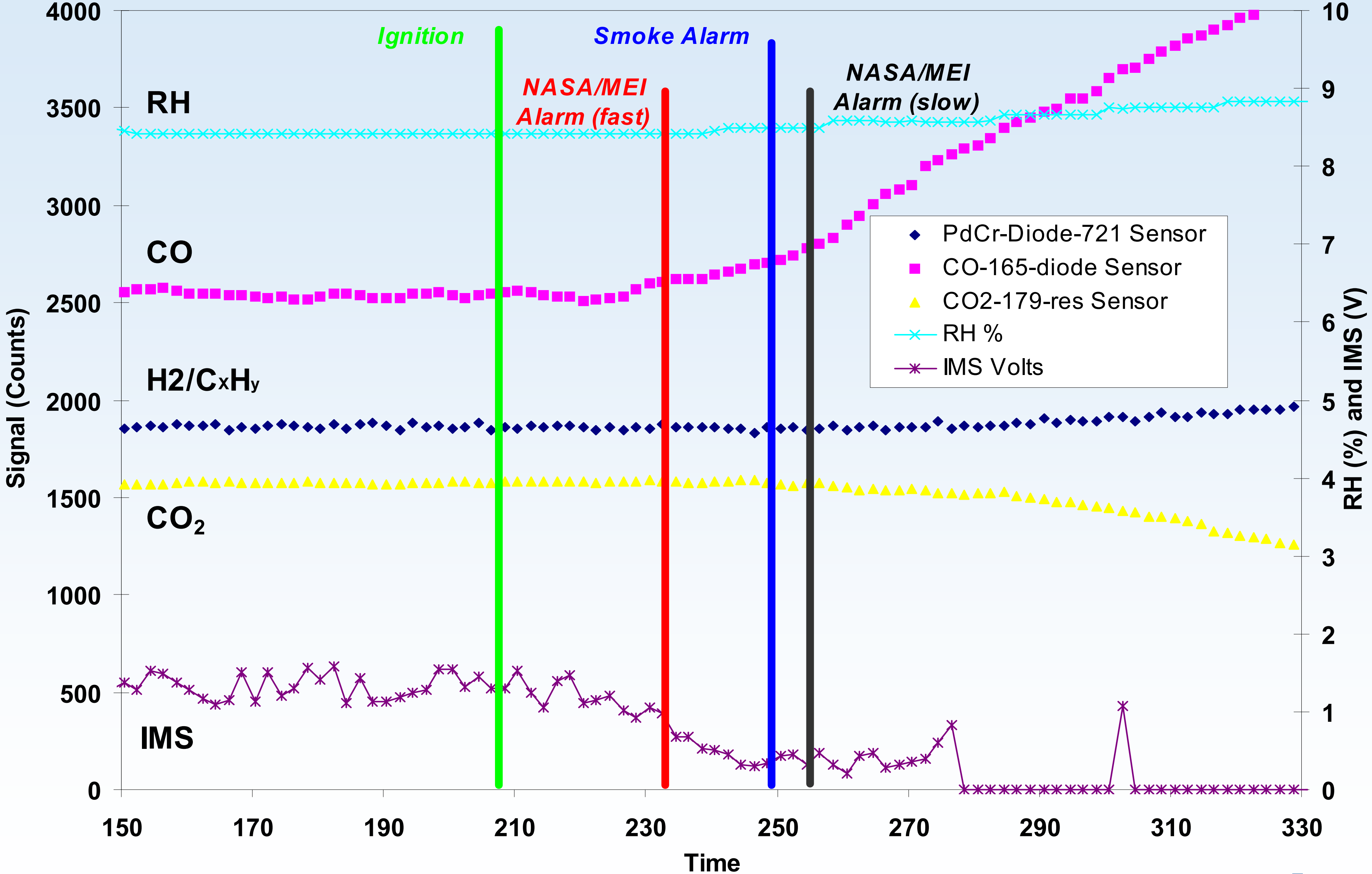
FAA Cargo Bay False Alarm Testing
No False Alarms

Test#	Detection System(s) Exposed	Exposed to	Test Duration (secs)	Generic Alarm Time (secs)	Alarm Time with Algorithm X (secs)	Alarm Time with Algorithm Y (secs)	Alarm Time with Algorithm Z (secs)
1	Generic/Makel	Dust		15	No Alarm	No Alarm	No Alarm
2	Generic/Makel	Dust		3	No Alarm	No Alarm	No Alarm
3	Generic/Makel	Dust		2	No Alarm	No Alarm	No Alarm
4	Generic/Makel	Dust		41	No Alarm	No Alarm	No Alarm
5	Generic/Makel	Dust		1	No Alarm	No Alarm	No Alarm
6	Generic/Makel	Dust		2	No Alarm	No Alarm	No Alarm
7	Generic/Makel	Dust		3	No Alarm	No Alarm	No Alarm
8	Generic/Makel	Dust		1	No Alarm	No Alarm	No Alarm
9	Generic/Makel	Dust		1	No Alarm	No Alarm	No Alarm
10	Generic/Makel	Dust		2	No Alarm	No Alarm	No Alarm
11	Generic	Water vapor	300	9			
12	Makel	Water vapor	340	N/A	No Alarm	No Alarm	No Alarm
13	Makel	Water vapor		N/A	No Alarm	No Alarm	No Alarm
14	Generic	Water vapor	20	3			
15	Generic	Water vapor	60	2			
16	Makel	Water vapor	60	N/A	No Alarm	No Alarm	No Alarm

FAA Cargo Bay Fire Testing
Consistent Detection of Fires

FAA Database Test #	Exposed to	Generic Alarm Time (secs)	Alarm Time with Algorithm X (secs)	Alarm Time with Algorithm Y (secs)	Alarm Time with Algorithm Z (secs)
147	Flaming Resin	38	34	45	34
148	Flaming Resin	42	36	41	36
149	Flaming Resin	35	36	45	36
150	Flaming Resin	39	33	39	33
151	Flaming Resin	37	46	57	46
152	Flaming Resin	47	50	55	50
174	Flaming Resin	33	30	42	30
175	Flaming Resin	35	37	42	37
176	Flaming Resin	40	34	45	34
177	Flaming Resin	36	29	42	27

FAA Cargo Bay Fire Testing



SUMMARY

- AEROSPACE APPLICATIONS REQUIRE A RANGE OF CHEMICAL SENSING TECHNOLOGIES
- NEW FAMILY OF GAS SENSOR TECHNOLOGY BEING DEVELOPED TO MEET THESE NEEDS USING:
  - MICROFABRICATION AND MICROMACHINING TECHNOLOGY
  - NANOMATERIALS
  - SiC-BASED SEMICONDUCTOR TECHNOLOGY
- SENSOR ARRAYS/SUPPORTING TECHNOLOGIES MANDATORY
- TECHNOLOGY BEST APPLIED WITH STRONG INTERACTION WITH USER/TAILOR SENSOR FOR NEEDS OF APPLICATION
- LONG-TERM: INTELLIGENT SYSTEMS
  - RELIABILITY
  - REDUNDANCY
  - ORTHOGONALITY
  - CROSS-CORRELATION

SUMMARY (CONT)

- FIRE DETECTION SENSOR DEVELOPMENT
  - CO: Tin Oxide Nanocrystalline
  - CO_2: Electrochemical Cell
  - PARTICULATE: IMS/Particle Classifier
- FAA TESTING
  - FALSE ALARMS
  - FIRE DETECTION
- NO FALSE ALARMS/100% FIRE DETECTION
- POSSIBLE FUTURE WORK:
  - FIRE IN HIDDEN AREAS
  - “LICK AND STICK”/MULTIFUNCTIONAL/ORTHOGONAL FIRE DETECTORS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