Online, In-Situ Monitoring Combustion Turbines Using Wireless Passive Ceramic Sensors

Xun Gong[1], Linan An[2,3] , and Chengying Xu[3]

1. School of Electrical Engineering and Computer Science (EECS)
2. Advanced Materials Processing and Analysis Center (AMPAC)
3. Department of Mechanical, Materials, and Aerospace Engineering (MMAE)

University of Central Florida
Orlando, FL 32816

Outline

- Motivation
- High-Temperature Sensors - State of the Art
- Technical Challenges and Proposed Solutions
- Project Management Plan
- State of the Project Objectives (SOPO)
- Conclusions

Motivation

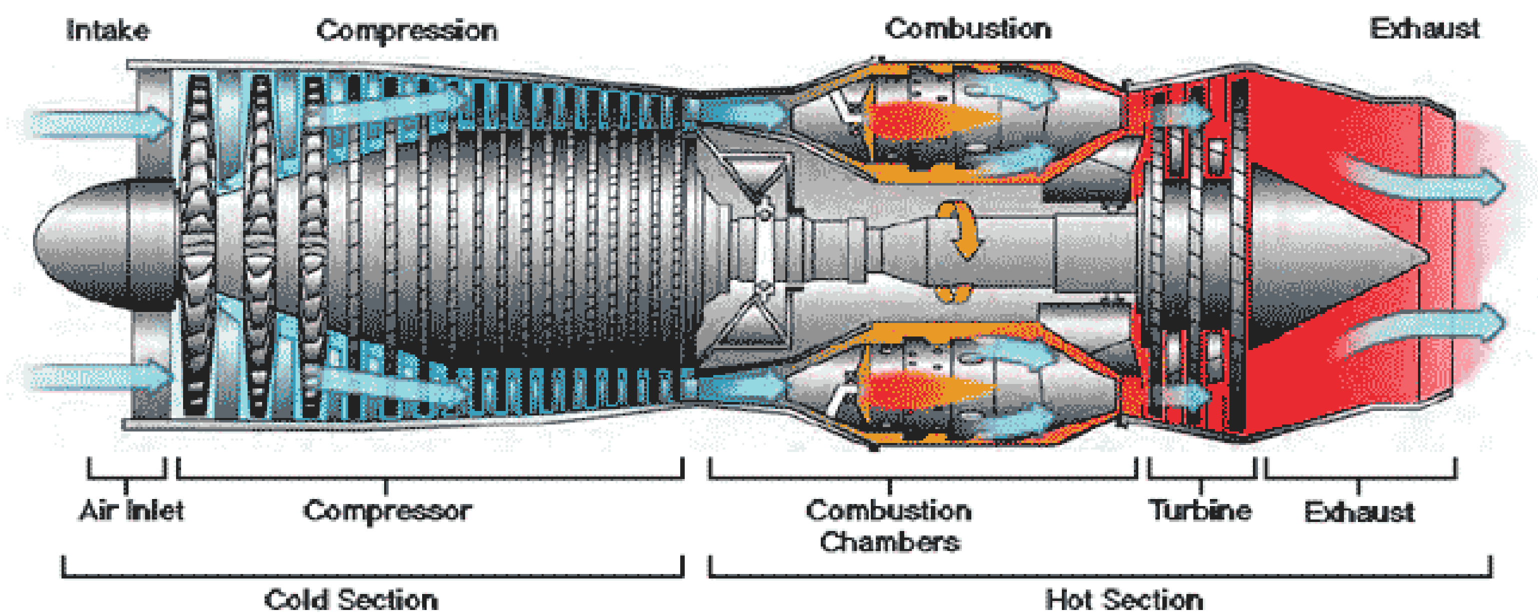
- Online combustion turbine monitoring
- Other high-temperature applications
- High-temperature (up to 1400^{o}C) sensing
- Sensing of pressure, temperature, and strain etc.

Description	2007
Net Generation (thousand megawatthours)	
Coal[1]	2,016,456
Petroleum[2]	65,739
Natural Gas	896,590
Other Gases[3]	13,453
Nuclear	806,425
Hydroelectric Conventional[4]	247,510
Other Renewables[5]	105,238
Wind	34,450
Solar Thermal and Photovoltaic	612
Wood and Wood Derived Fuels[6]	39,014
Geothermal	14,637
Other Biomass[7]	16,525
Pumped Storage[8]	-6,896
Other[9]	12,231
All Energy Sources	**4,156,745**

2007 Energy Generation Statistics (DOE)

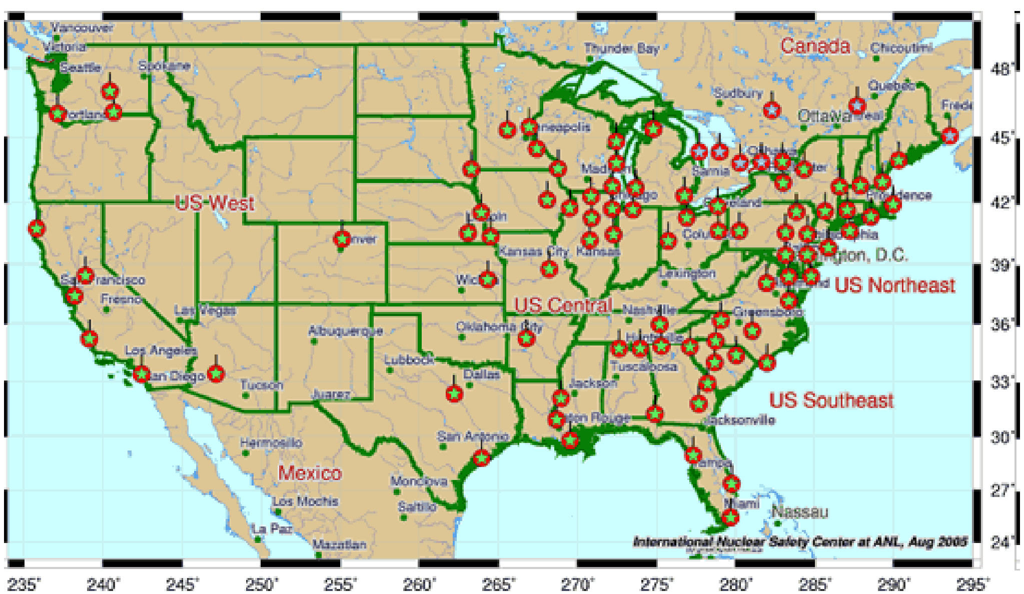
Online Turbine Monitoring

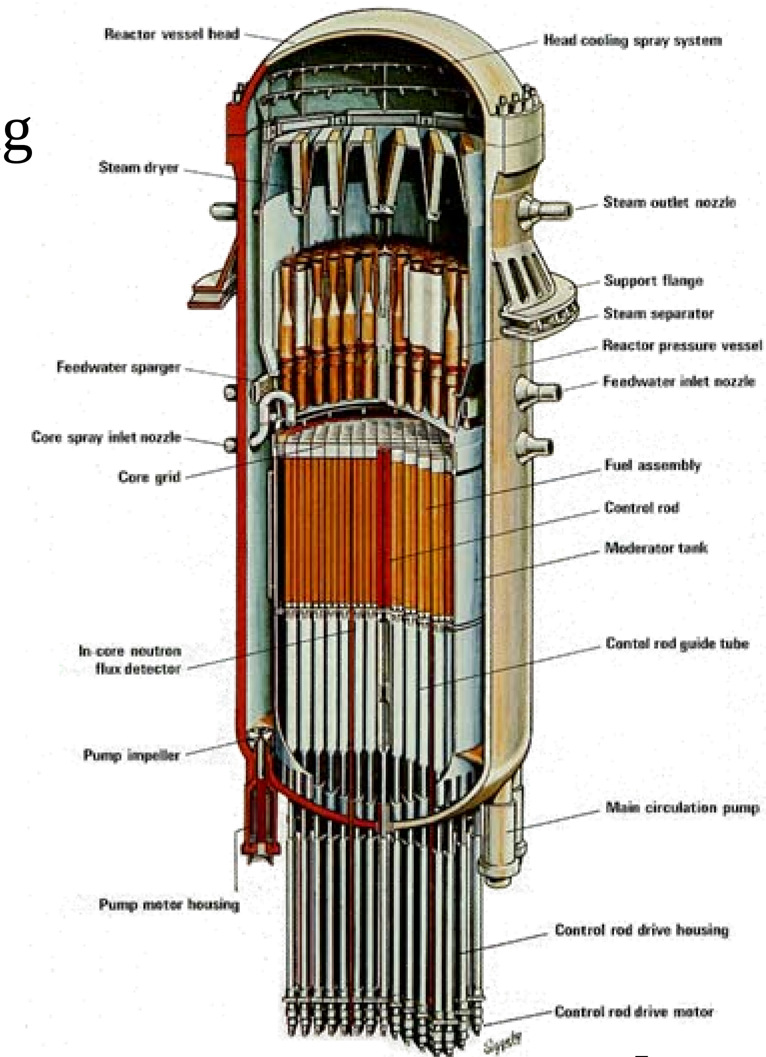
- Better efficiency
- Cleaner ("greener") emission
- More reliable turbines with real-time monitoring
- Benefit power generation, aviation, and military departments



Online Reactor Monitoring

- Better efficiency
- Safer operations with real-time monitoring
- Benefit nuclear power plants
- 104 units in U.S. (2007)
- ~ 806.5 billion KWh (2007)
- 20% of all electricity in U.S. (2007)

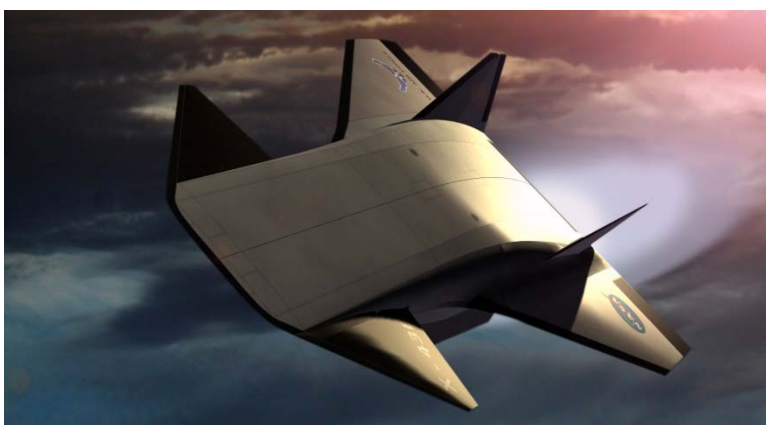


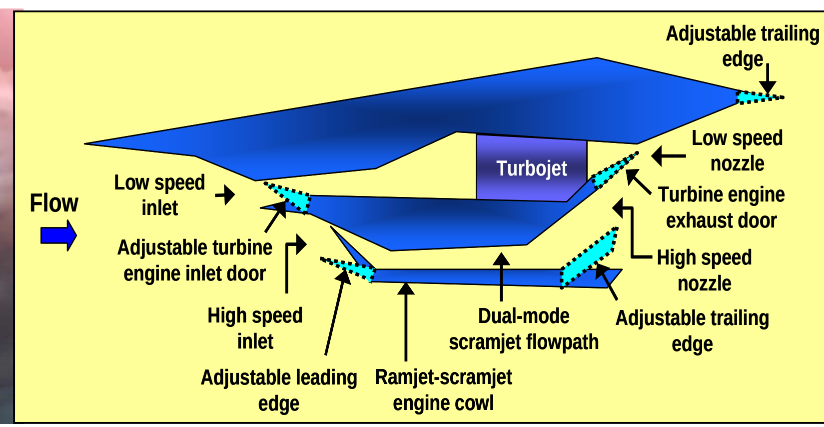


Other Applications

Military Aviation

Commercial Aviation





Next-Generation Scramjet – Turbine Monitoring, Flight Control

State of the Art

- Optical-Based Non-Contact Sensors
  - Lack of necessary accuracy
  - Not robust in harsh environments
- SiC/Si_3N_4-Based Micro-Sensors
  - Limited operation temperature range (< 600^{o}C)
  - Oxidation/corrosion associated degradation
  - Complicated wiring for sensor networks
  - Cannot access moving/rotating parts
- Wireless Sensors
  - Physical measurements (pressure, temperature, strain etc.) not readily available
  - No high-Q wireless micro-sensor available

Technical Challenges

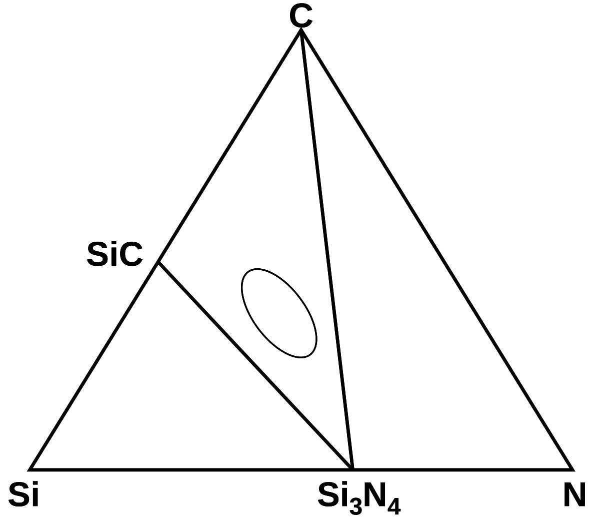
- ✓ Stable materials in harsh environments
- ✓ Functional materials at high temperatures
- ✓ Micromachining of high-temperature materials
- ✓ Wireless sensing for moving/rotating parts
- ✓ Robust and reliable sensing mechanisms

Proposed Solutions

- Develop functional ceramic materials at high temperatures
- Corrosion resistance
- Shape/strength retention
- Microfabrication of these ceramic materials
- Novel passive sensors (temperature, pressure, strain etc.)
- Wireless sensing for moving/rotation parts

High-Temp. Material - PDC

Starting materials → (Chemical synthesis) → Polymer precursor → (Cross linking) → Infusible preceramic network → (Pyrolysis 800-1000 ºC) → Amorphous Ceramics

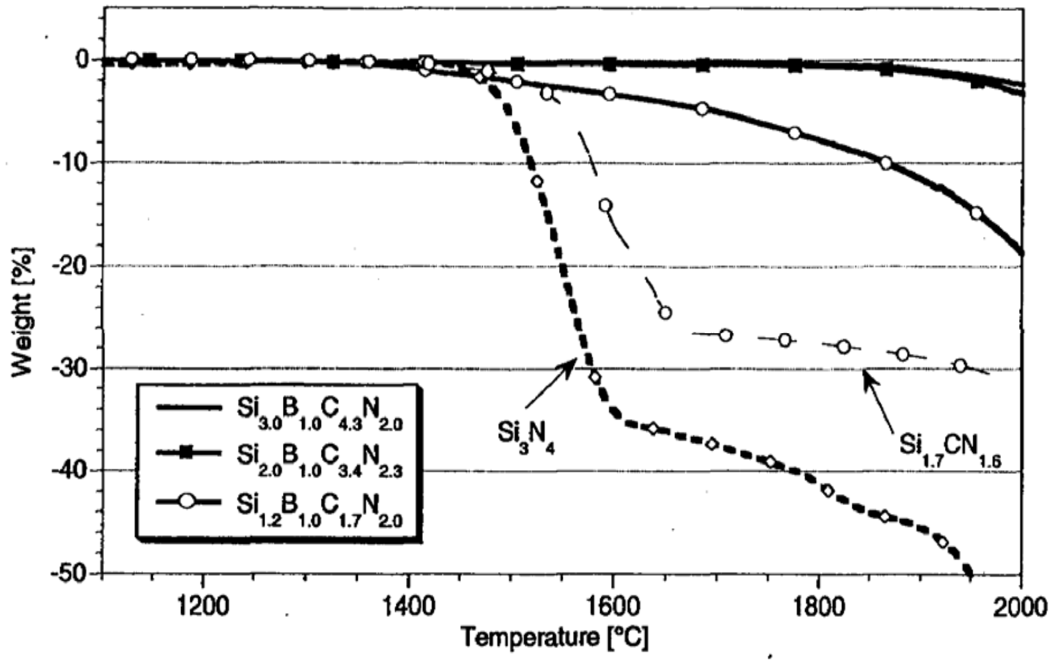


	PDC	SiC	Si_3N_4
Density (g/cm^3)	2.0-2.3	3.17	3.19
E-modulus (GPa)	100-150	400	320
Poisson's ratio	0.17	0.14	0.24
CTE ($x10^{-6}/K$)	~3	3.8	2.5
Hardness (GPa)	20	30	28
Strength (MPa)	1000	420	700
Thermal Shock FOM	~3000	250	880

Suitable for proposed micro-sensor applications:

- **High-temperature durability**
- **Micro-machining capability**
- **Multifunctionality (providing sensing mechanisms)**

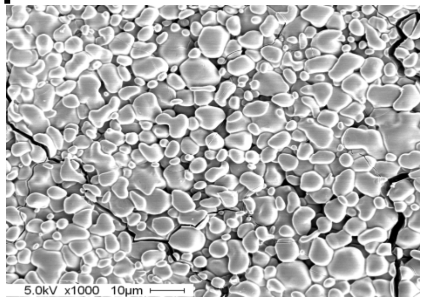
High Temperature Durability



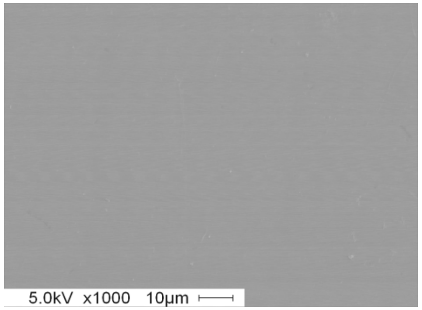
Excellent thermal stability up to 1800°C

Excellent oxidation/corrosion resistance

Typical Si-based materials



PDC



@ 1400 °C, Corrosion rate is 4 nm/hr

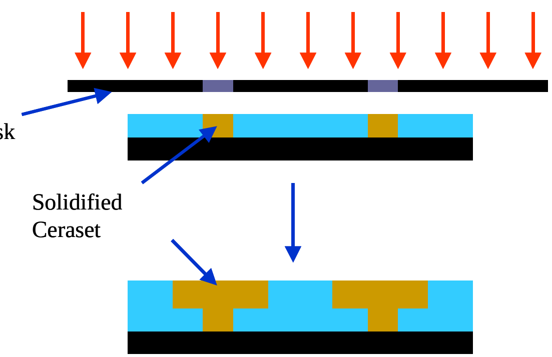
Microfabrication Capability

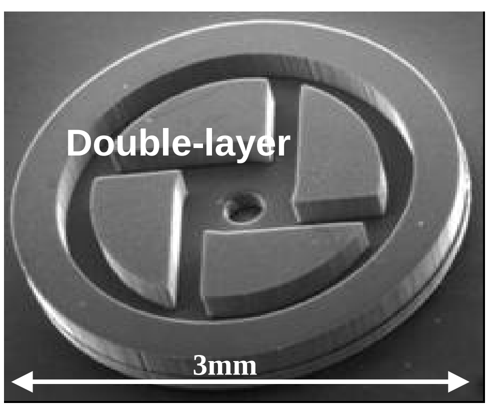
- US Patent 7,338,202

Precursor → Micro fabrication → **Polymer devices** → Pyrolysis → **Ceramic devices**

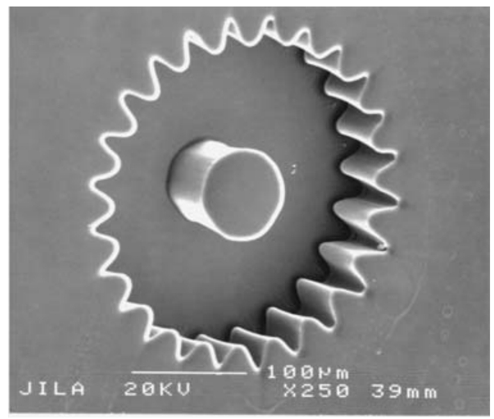
Lithography

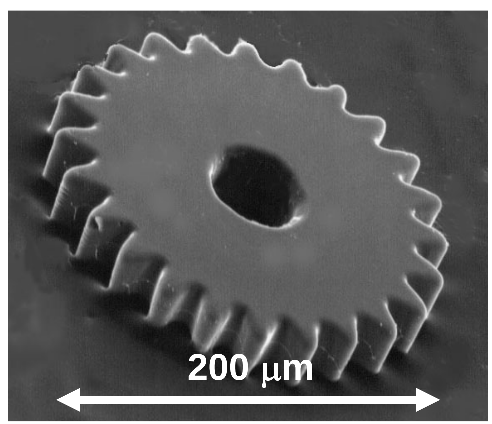
Single-layer



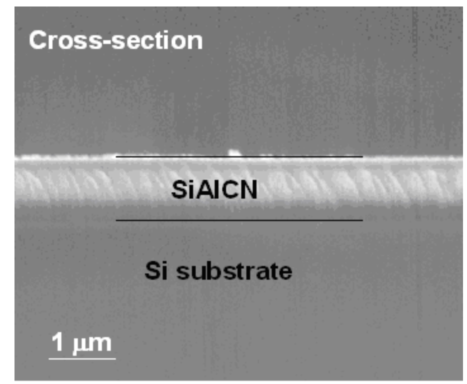


Micro-Injection Molding



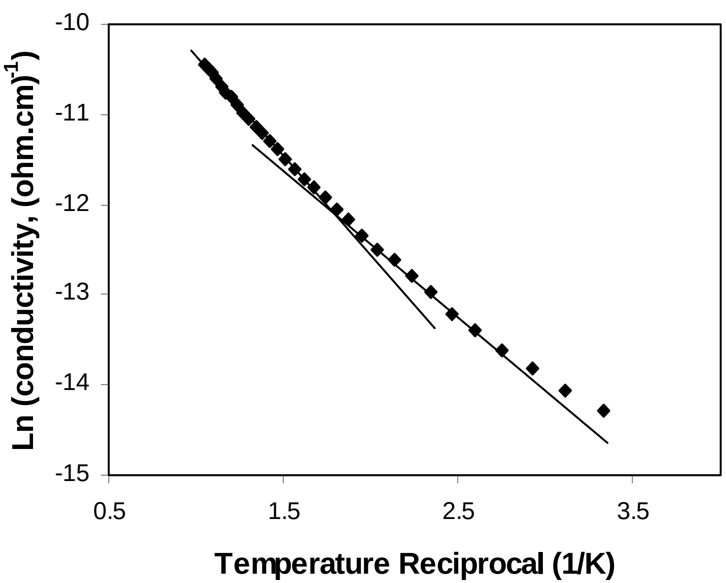


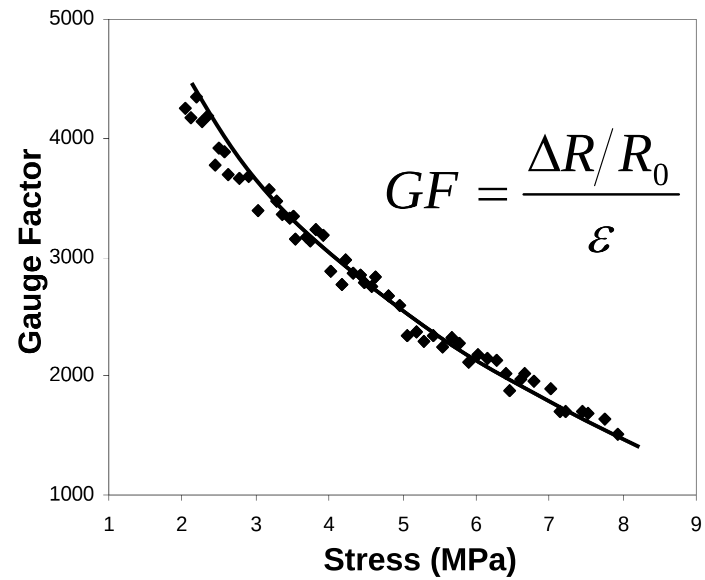
Spin-On



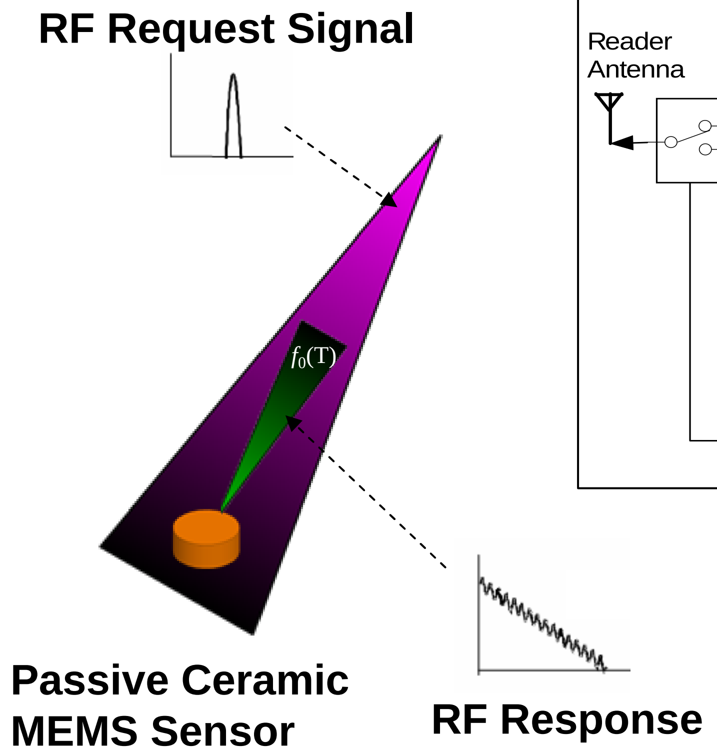
Electronic Properties for Sensing Mechanisms

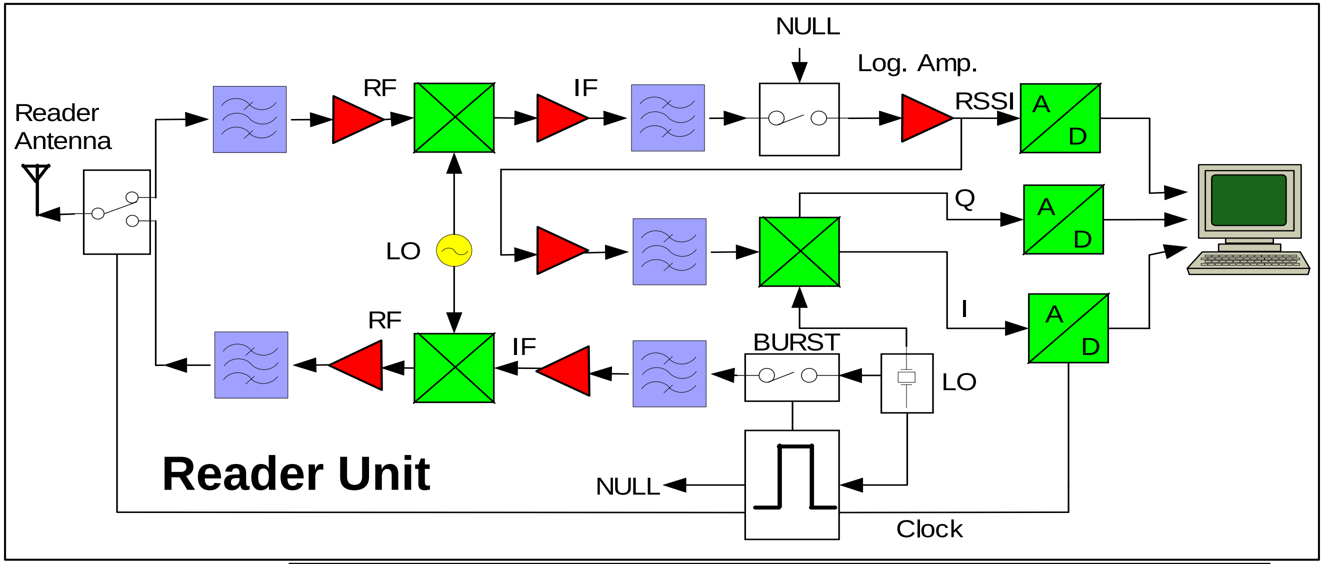
- Semiconducting behavior up to 1300°C – temperature/heat flux sensors
- Tunable conductivities – remove thermal mismatch
- Extremely high piezo-resistive coefficient – accurate, wide-range strain sensors
- Temperature-dependent dielectric constant – wireless temperature sensors



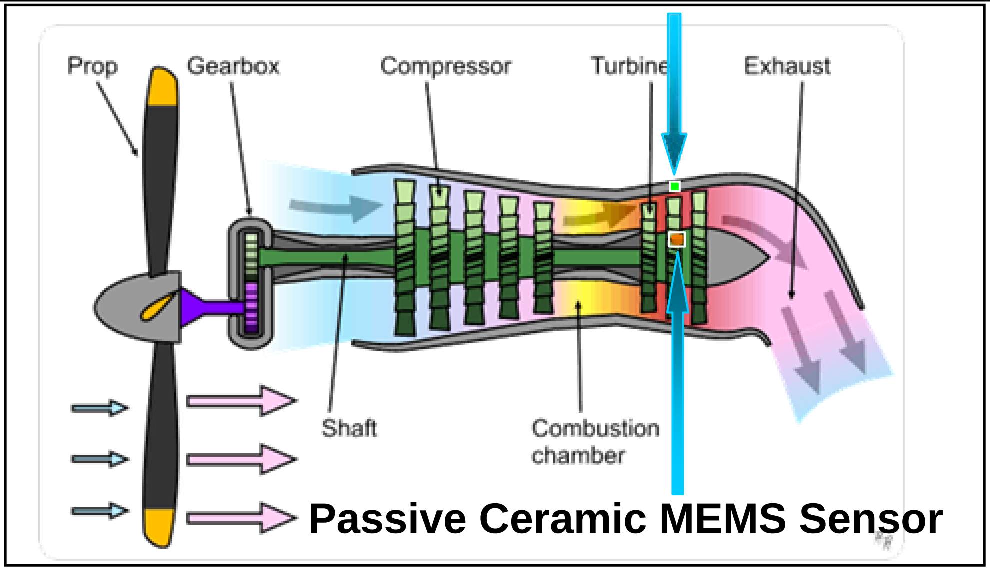


Passive sensors are necessary to survive harsh environments
High-Q resonators are needed for precise wireless sensing



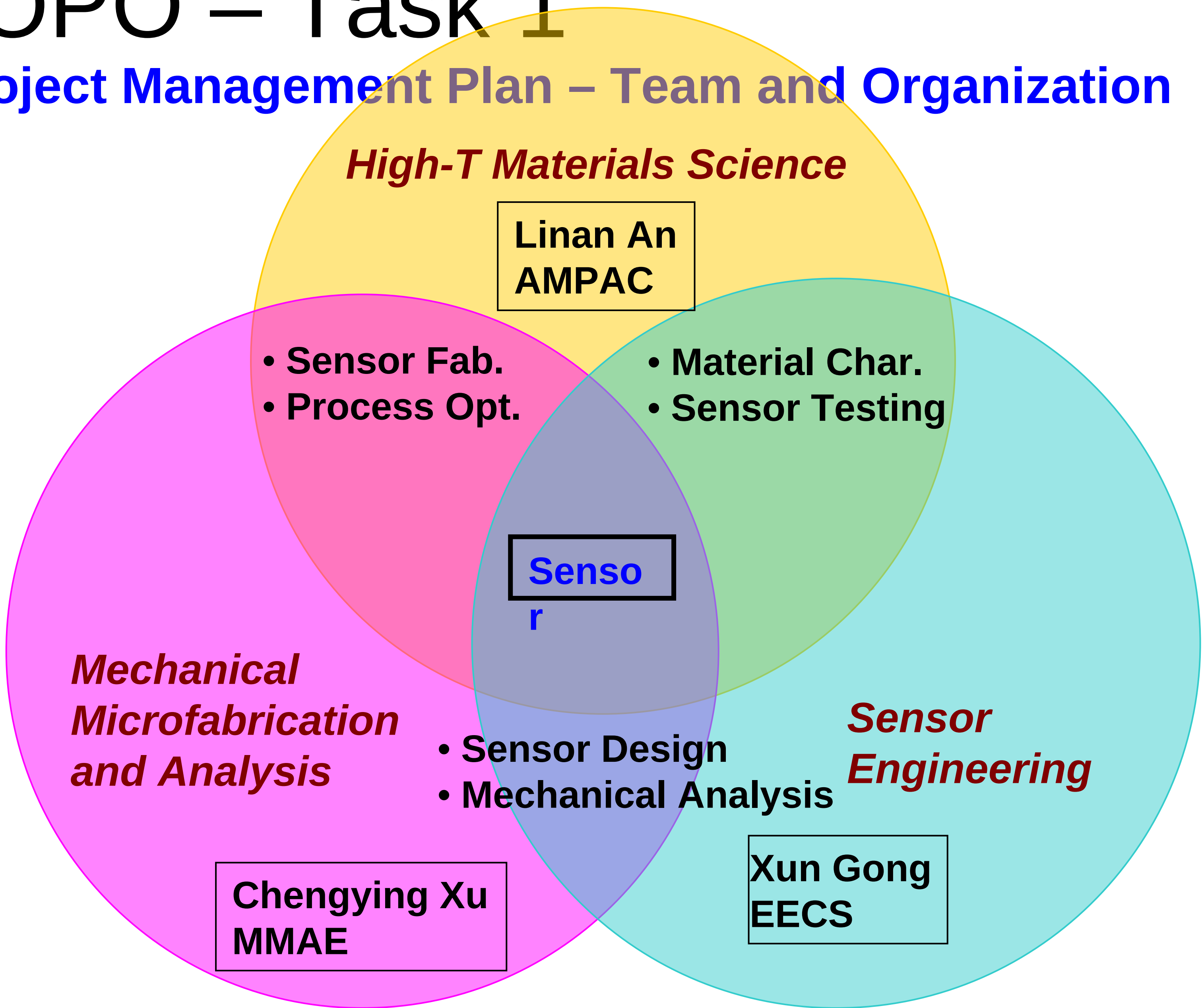


The sensed resonant frequency of the ceramic MEMS sensor contains the temperature or pressure information



SOPO – Task 1

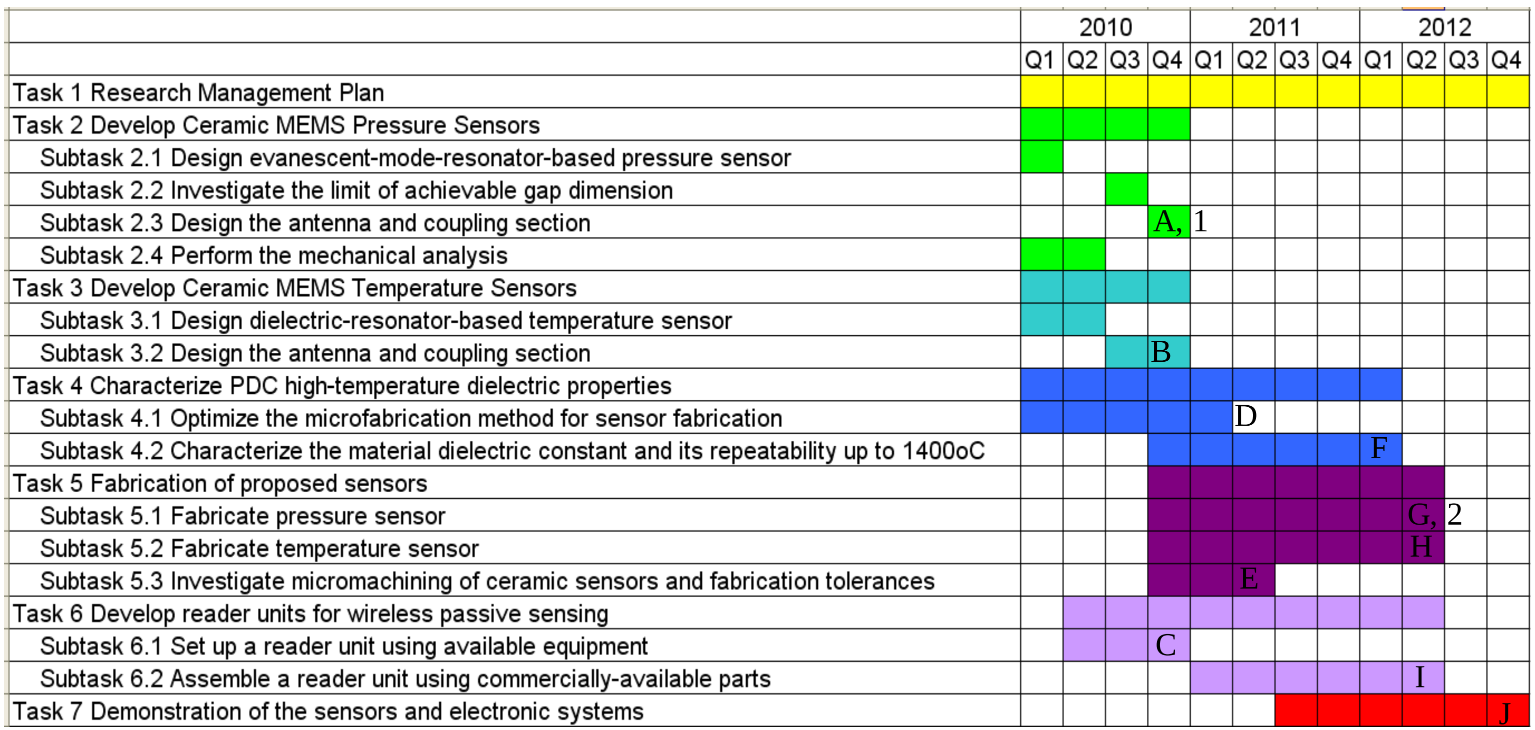
Project Management Plan – Team and Organization



SOPO – Task 1

Project Management Plan – Project Milestone & Timeline

	Milestone	Planned Completion Date	Verification Method
A	Design evanescent-mode-resonator-based pressure sensor	10/1/2010	Presentation
B	Design dielectric-resonator-based temperature sensor	10/1/2010	Presentation
C	Set up a reader unit using available equipment	1/1/2011	Presentation
D	Optimize the microfabrication method for sensor fabrication	4/1/2011	Show Fabricated Samples
E	Investigate micromachining of ceramic sensors and fabrication tolerances	4/1/2011	Presentation
F	Characterize the material dielectric constant and its repeatability up to 1400oC	1/1/2012	Presentation
G	Fabricate pressure sensor	4/1/2012	Show Fabricated Samples
H	Fabricate temperature sensor	4/1/2012	Show Fabricated Samples
I	Assemble a reader unit using commercially-available parts	7/1/2012	Presentation, demo
J	Demonstration of the sensors and electronic systems	10/1/2012	Presentation, demo



SOPO – Task 1

Project Management Plan – Success Criteria

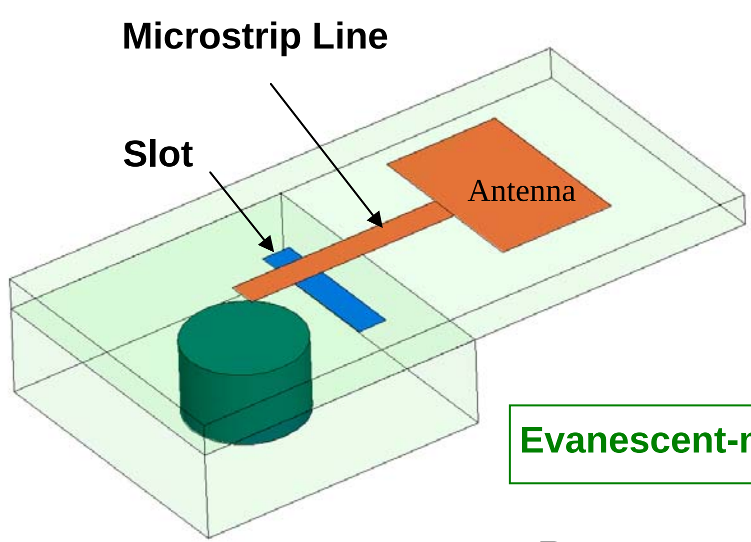
1. Successful Design
   - Design pressure and temperature sensors working at 10 GHz
   - Q factor of the resonator is > 200
   - The resonators can couple to antennas efficiently (better than 10-dB return loss)
   - A lab demo of wireless sensing using available equipment
   - Mechanical analysis will show the achievable gap dimension for the pressure sensor
2. Successful Fabrication
   - Fabricate the pressure and temperature sensors with good dimensional control
   - The dielectric constant of PDCs is characterized up to 1400^{o}C
   - There is no additional packaging or wired connections needed

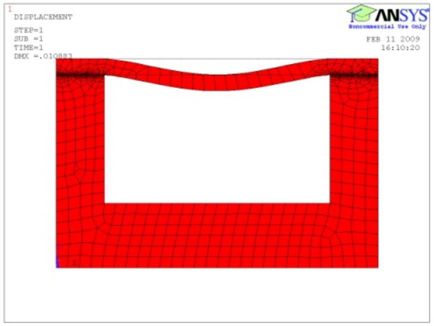
Project Management Plan – Risk Management

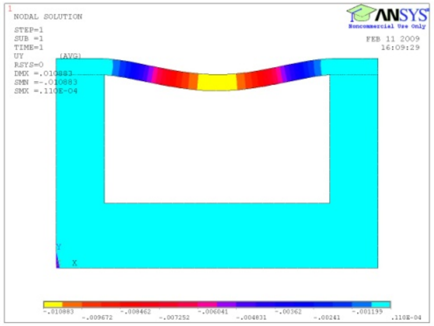
1. Electrical and mechanical properties of PDCs to satisfy the sensor requirement
2. Fabrication tolerances and challenges for high-temperature sensors
3. Tradeoffs between sensor size (which is closely related to operation frequency) and sensing range
4. Practical implementation of the proposed sensors in real turbine systems

SOPO – Task 2

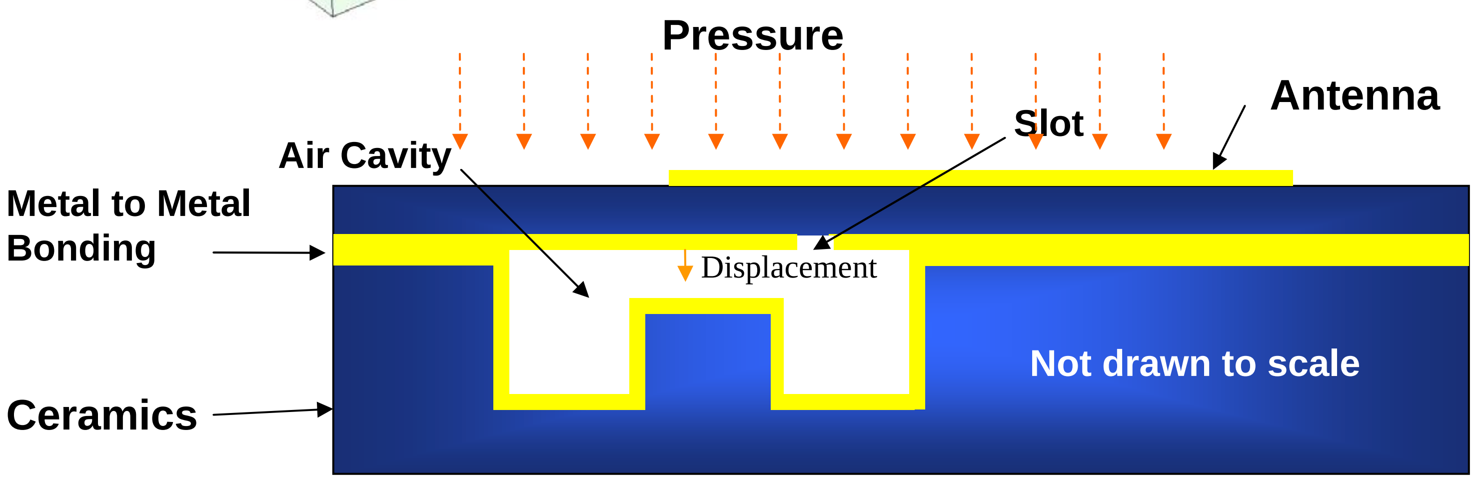
Wireless Pressure Sensor (Gong and Xu)





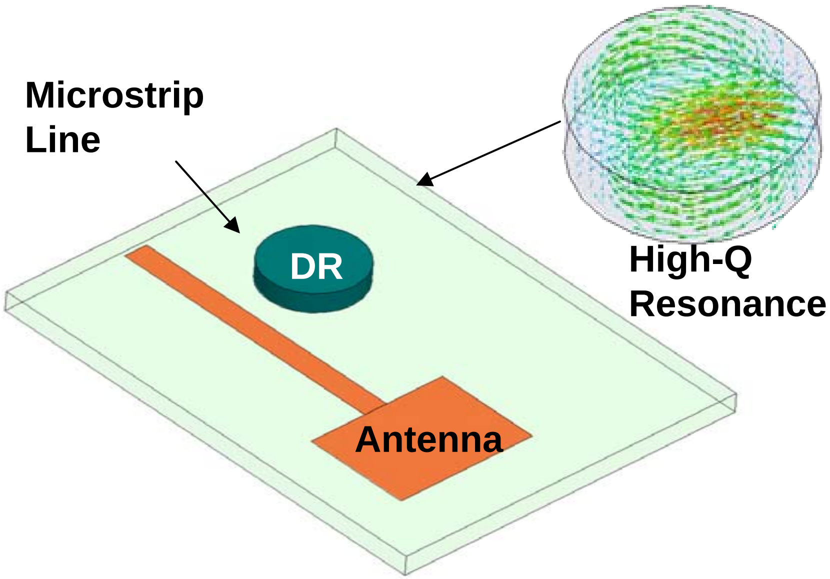


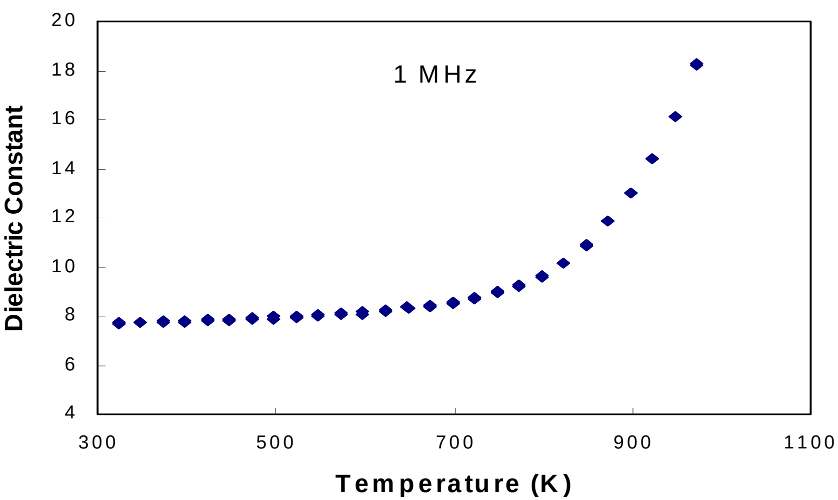
Evanescent-mode resonator pressure sensor



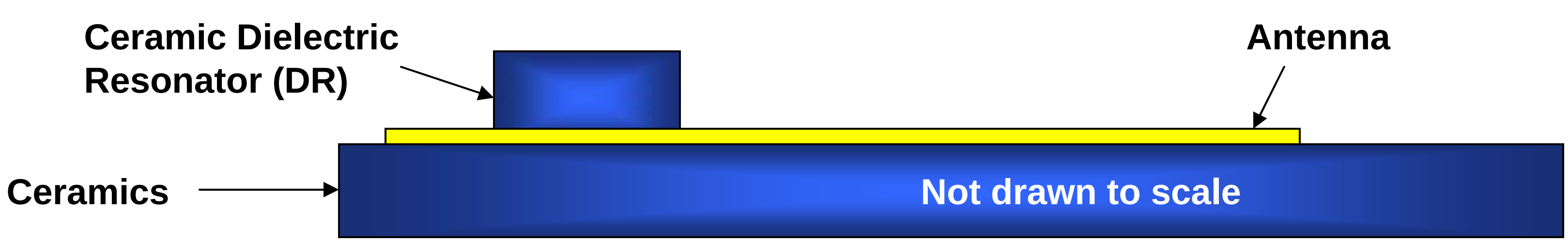
SOPO – Task 3

Wireless Temperature Sensor (Gong and An)





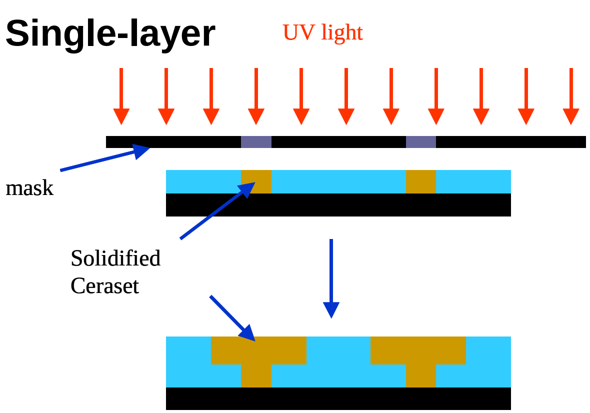
- Dielectric constant is strongly dependent on temperature
- Frequency is strongly dependent on dielectric constant
- High-Q resonator

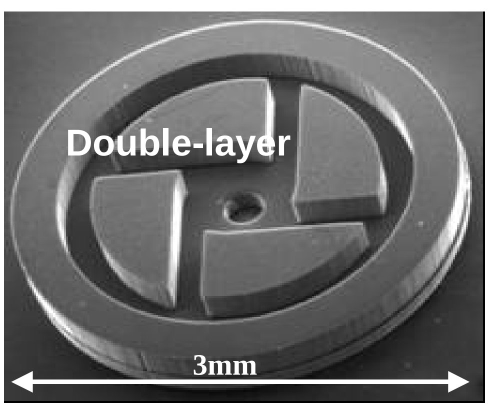


SOPO – Task 4

PDC Processing and Dielectric Properties (An and Gong)

Lithography

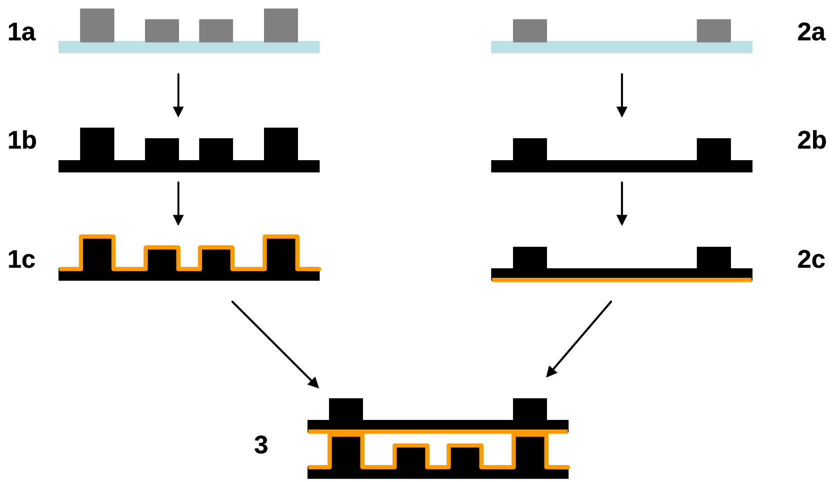




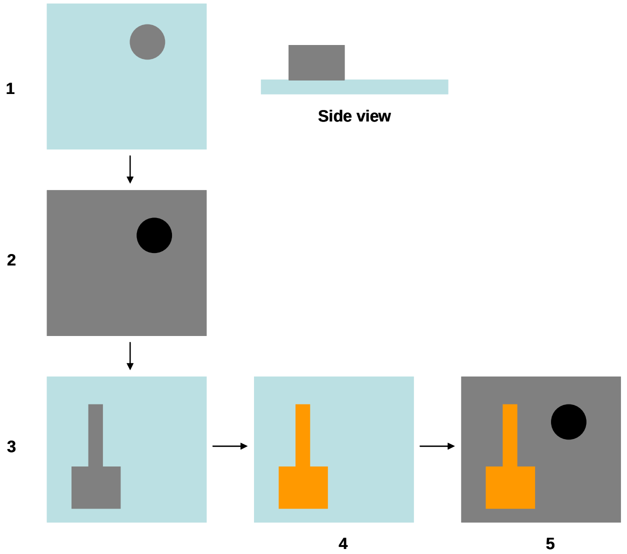
1. High-power UV curing
2. Dimensional accuracy and uniformity
3. Improve the photo-polymerization ability of the precursor
4. Characterize PDC dielectric constant at microwave frequencies and high temperatures

SOPO – Task 5

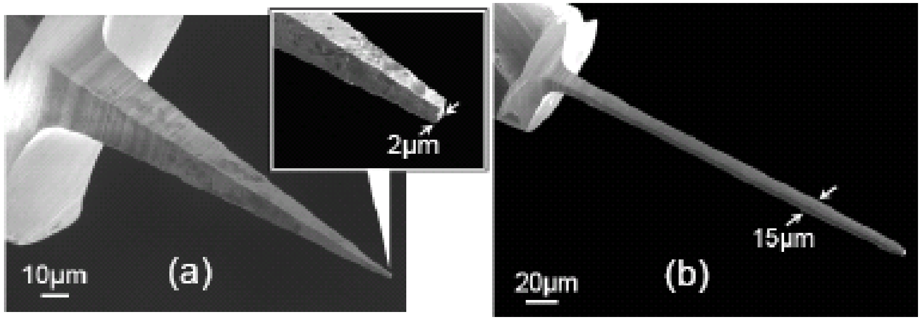
Sensor Fabrication (An and Xu)



Pressure Sensor



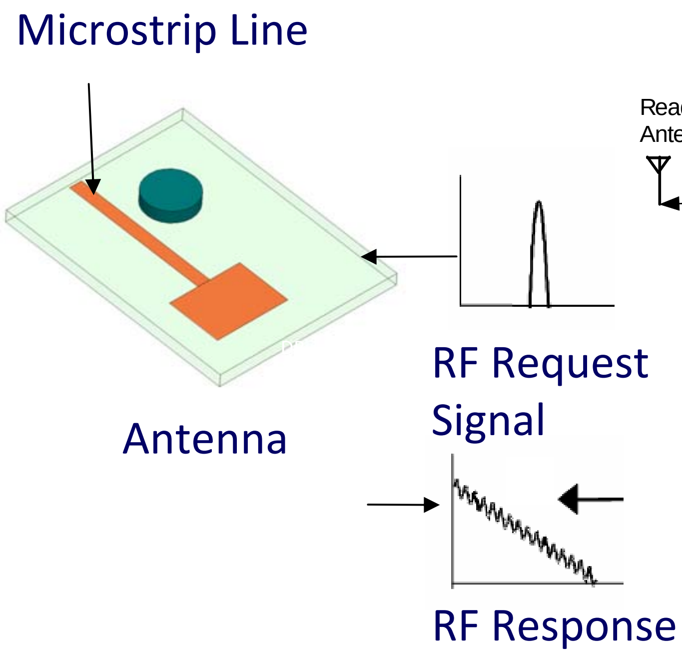
Temperature Sensor

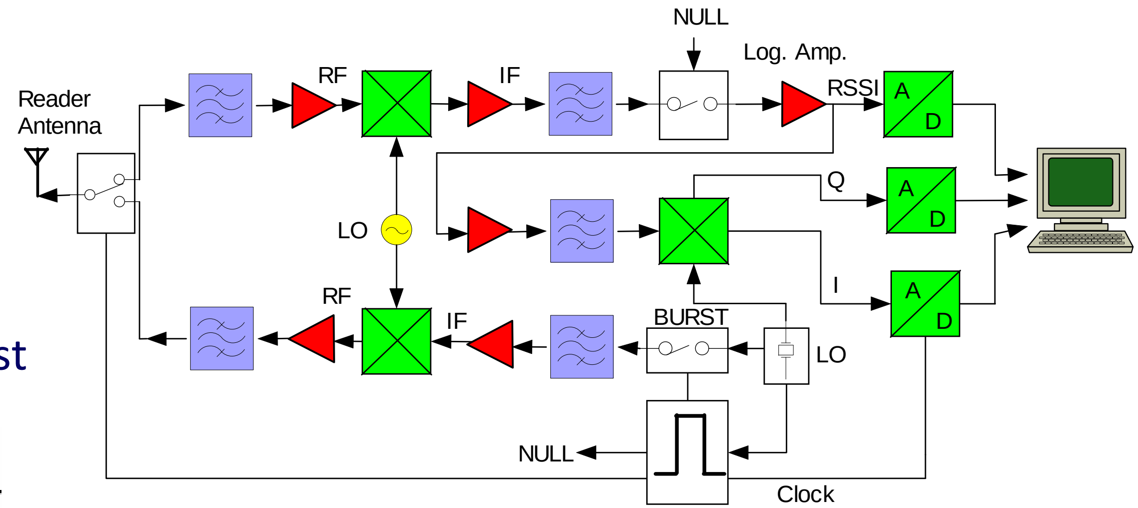


Mechanical micromachining to improve accuracy and uniformity

SOPO – Task 6

Reader Units (Gong)



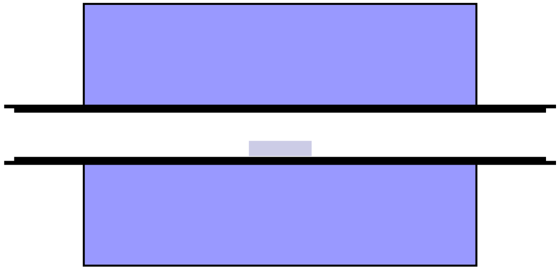


1. Set up a reader unit using available equipment
2. Assemble a reader unit using commercially-available parts

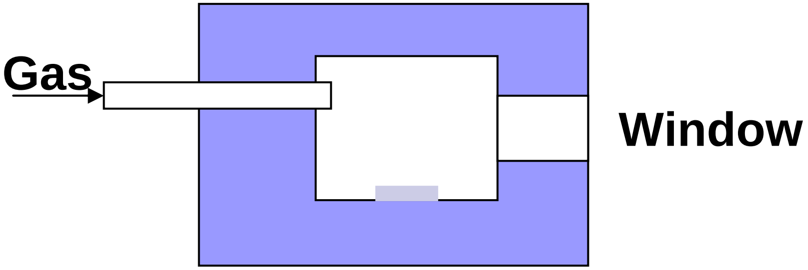
SOPO – Task 7

Sensor Testing (An and Gong)

Atmosphere	Pure oxygen	Water vapor + Air
1000°C	300 hr	300 hr



Tube furnace



High-temp/high-pressure Auto-clave

After successful testing of the developed sensors in the laboratories the team will provide the prototypes to the industrial partners

High temperature material characterization is also available

Conclusions

- PMP will be updated during the project period
- SOPO will be followed up based on the schedule
- Risks will be managed
- PIs will meet regularly to coordinate the research
- Success of this project will be transitioned to industry