Polymer-Derived Ceramics and Wireless, Passive Ceramic Strain Sensors

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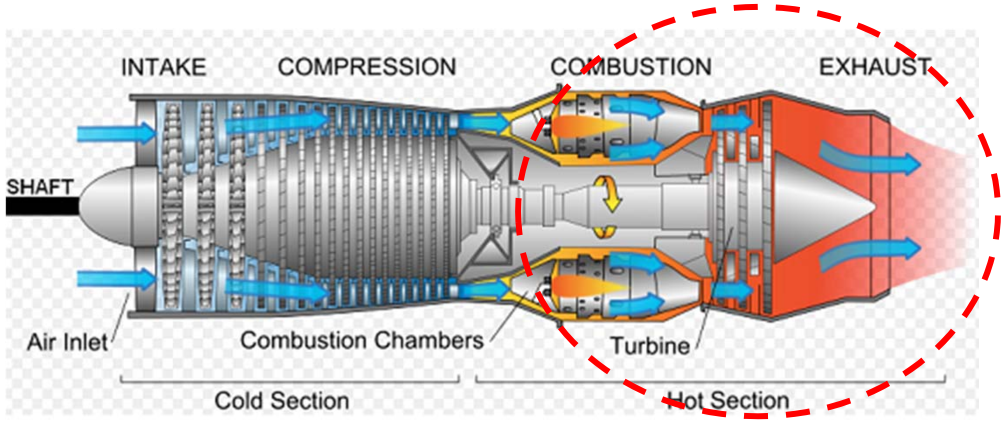
Outline

- Motivation
- Objectives
- Material development
- Sensor design and fabrication
- Sensor characterization (on going)
- Summary

Motivation – need for wireless strain sensors

- **Power generation**
- **Aero propulsion**



Turbine performance

- Optimal design
- Feedback control
- Health monitoring

→

- Temperature
- Heat flex
- Pressure
- Stress
- Strain
- Viscosity
- ....

→

Sensors

Motivation – wireless passive strain sensors

- Parts subjected to severe strain/stress in extreme environments

  High temperatures – need passive

  Moving parts/hidden areas – need wireless

Sensor Classification

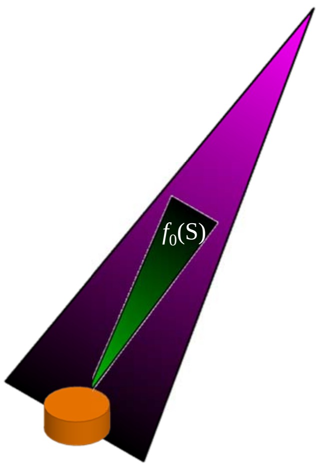
Senor Type	Single Transport	Sensing Mechanisms
Temperature-related sensing	Wired	Semiconducting
	Wireless	Temperature-dependent permittivity
Stress/strain-related sensing	Wired	Piezoresistivity
	Wireless	Piezodielectricity

Difficult to develop

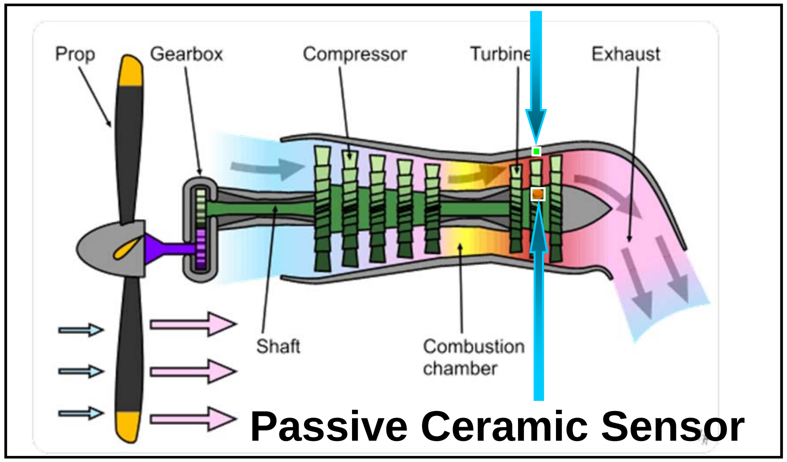
Objectives

- Overall Objective

  Develop RF resonator-based wireless passive polymer-derived ceramic strain/stress sensors



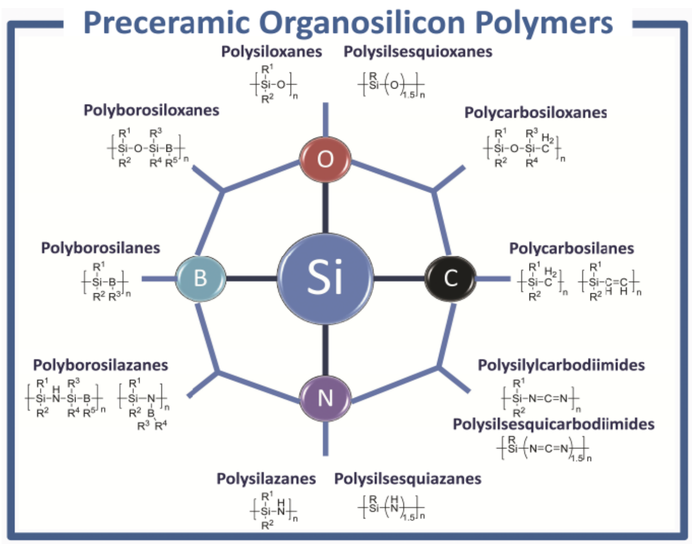
Passive Ceramic Sensor

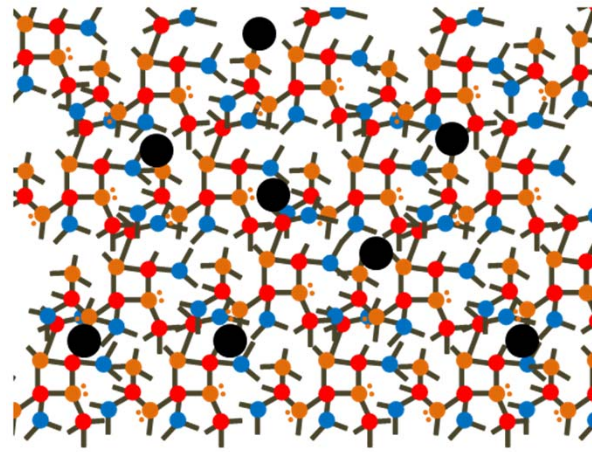


- Scientific Goals
  - Develop piezo-dielectric polymer-derived ceramics (pd-PDCs)
  - Design and fabricate resonator sensors
  - Characterize the sensors in extreme environments

Material development – polymer-derived ceramics

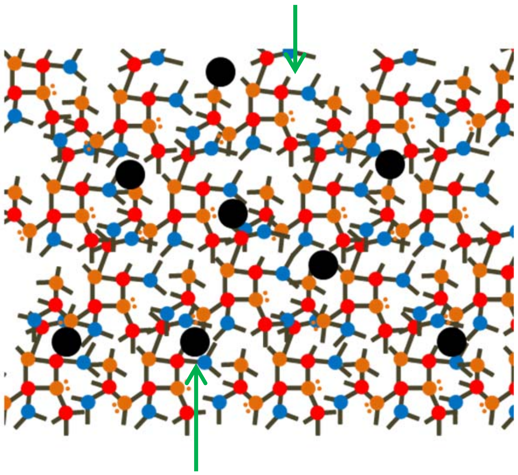
Starting materials → (Chemical synthesis) → Polymer precursor → (Cross linking) → Infusible preceramic network → (Pyrolysis 800-1000ºC) → Amorphous Ceramics





Fundamentally Different from Traditional Ceramics

- **Macro-scale amorphous**
  - **No X-ray diffraction**
- **Nano-scale heterogeneity – nanodomain structure**
  - **Two phases: amorphous matrix (AM) and disordered free carbon (FC)**
    - **Distribution of two phases:**
      - ✓ **Both continuous**
      - ✓ **AM continuous**
      - ✓ **FC continuous**
    - **Possible phase separation within AM phase**
  - **Interface (area) between different phases**
  - **Free volume**
- **Atomic/molecular scale**
  - **Large amount of point defects (dangling bonds)**
  - **Doping effect**
  - **Residue stresses**



Excellent high-temperature properties

❖ **Excellent thermal stability**

- **PDCs can be stable up to 1800-2200°C against decomposition and crystalization**

❖ **Excellent creep resistance**

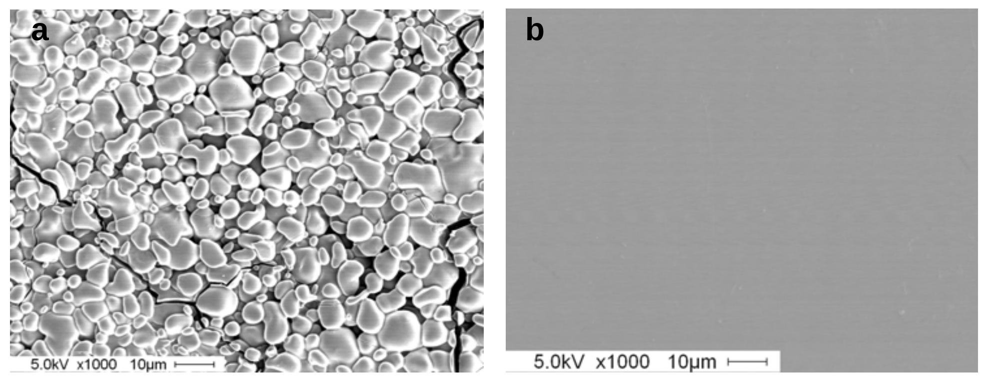
- **Creep resistance of PDCs can be higher than polycrystalline SiC/Si_3N_4**

❖ **Excellent oxidation/corrosion resistance**

- **Oxidation rate of PDCs is more than 10 times lower than conventional silicon based materials**

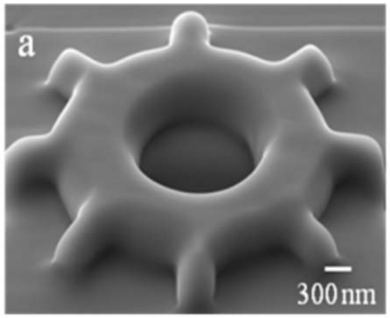
- **Corrosion rate of PDCs is about 10 times lower than silicon based materials**

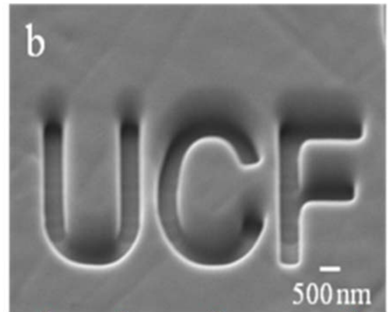
- **Excellent strength retention**

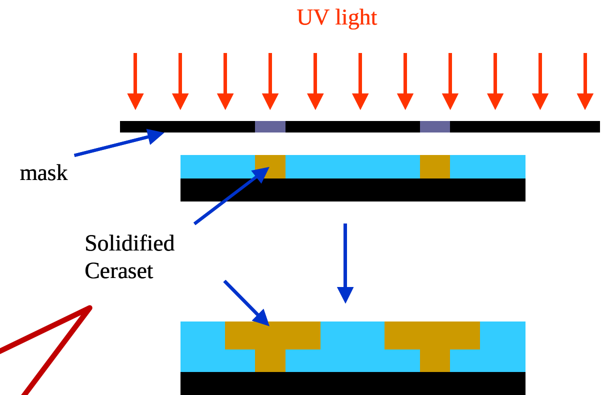


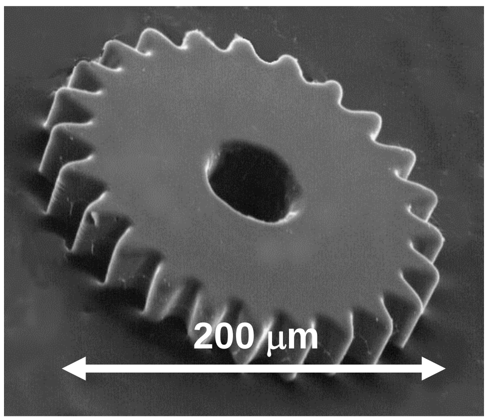
Suitable for high-temperature applications

- Flexible microfabrication capability

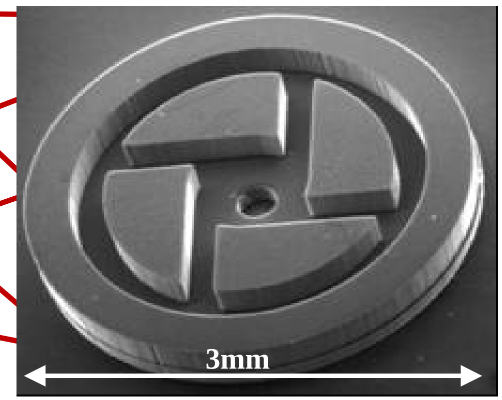


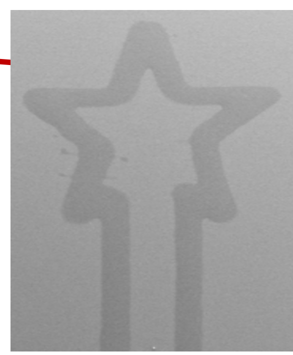


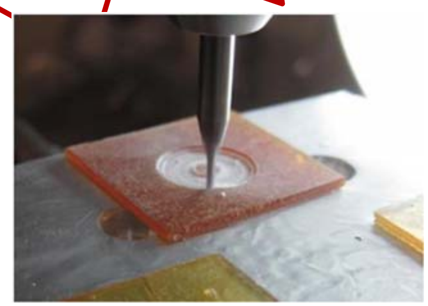


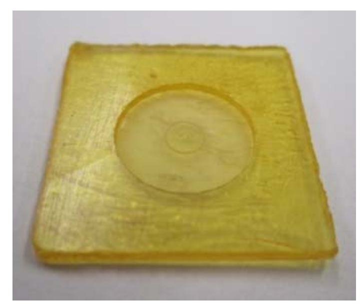


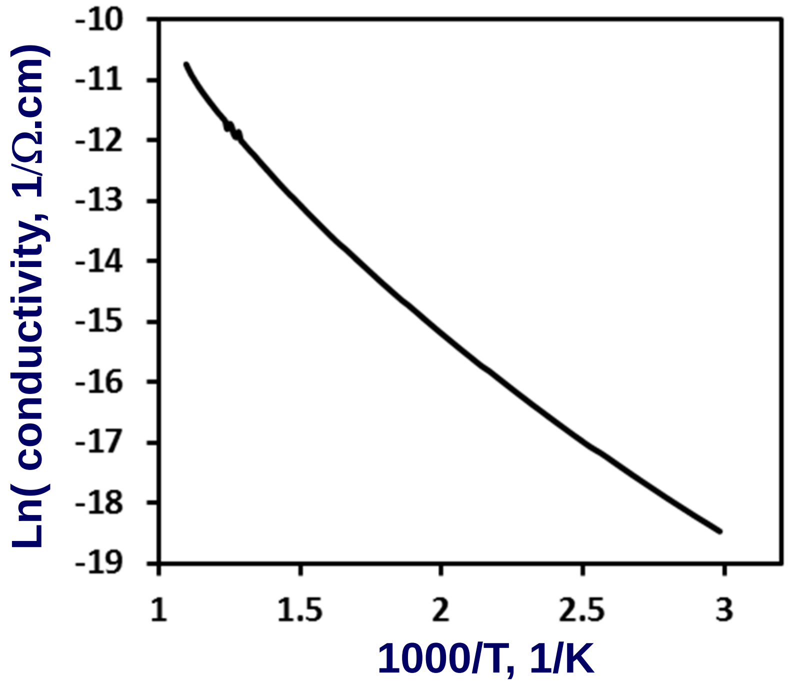
- **Lithography**
- **Micro-casting**
- **Direct writing/printing**
- **Spin-on thin/thick film**
- **Mechanical machining**
- **FIB nano-machining**





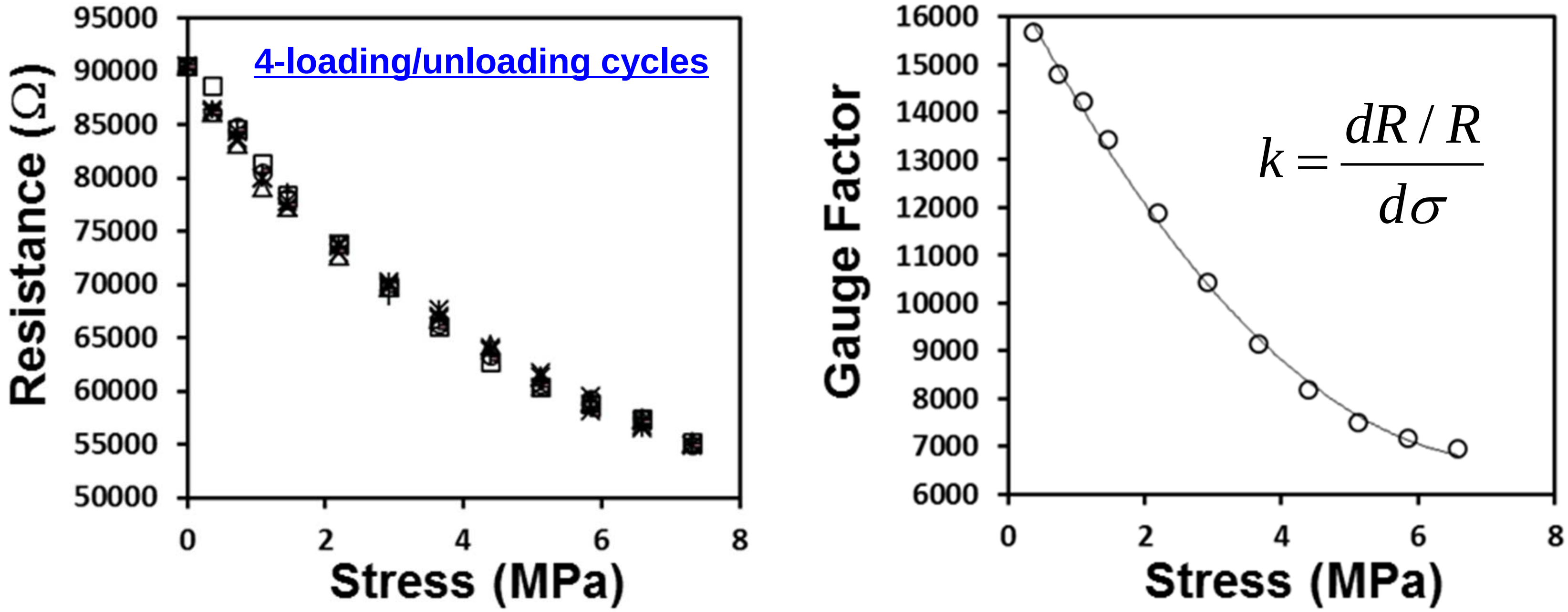




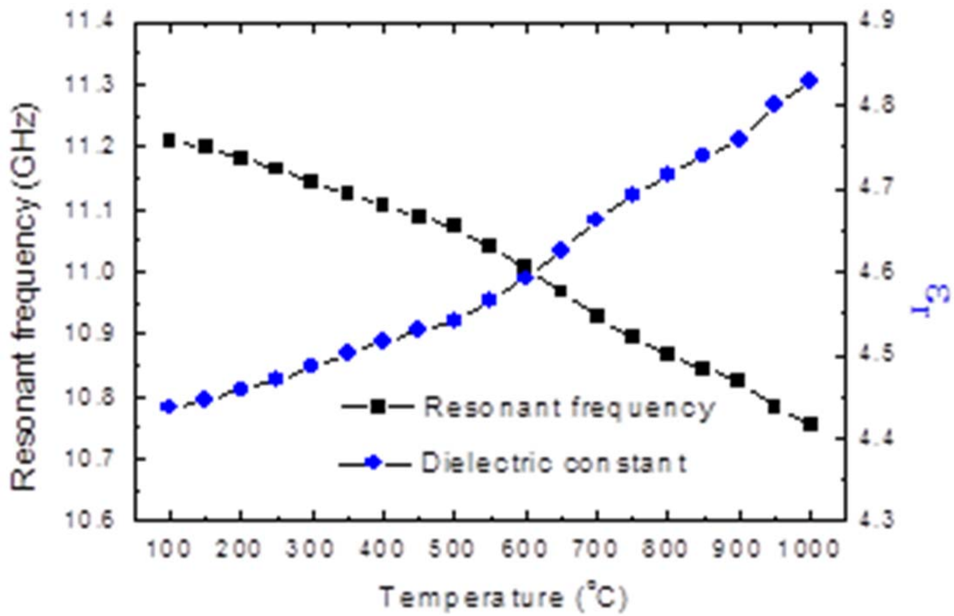


$$\sigma = \sigma_1 e^{-\frac{E_c - E_f}{KT}} + \sigma_2 e^{-\frac{E_A - E_f + w_1}{KT}} + \sigma_3 e^{-(\frac{T_o}{T})^{1/4}}$$

o Amorphous semiconducting behavior at high temperatures – excellent for wired temperature-related sensing



- **Huge gauge factor – excellent for wired stress/strain-related sensing**



oTemperature dependent permittivity – excellent for wireless temperature-related sensing

- Material system: SiAlCN

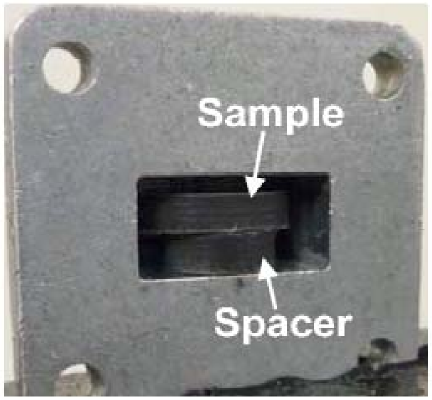
- **Polysilazane (VL20): main precursor**
- **Phenylbis (2,4,6-trimethylbenzoyl) phosphine oxide (819): the photon initiator for UV curing**
- **Aluminum-tri-sec-butoxide (ASB): source for Al**
- **Poly (melamine-co-formaldehyde) acrylated solution (PVN): additional source for N**
- **Methacrylic Acid (MA): for enhancing the effectiveness of UV curing**

- Material system: SiAlCN

Name	MA (wt%)	ASB (wt%)	819 (wt%)	VL20 (wt%)	PVN (wt%)
S-1	2	5	5	78	10
S-2	2	5	5	68	20
S-3	2	5	5	58	30
S-4	5	5	0	90	0
S-5	0	1	0	99	0
S-6	0	5	0	95	0
S-7	0	10	0	90	0
S-8	2	1	0	97	0

Key: lowest dielectric loss

- Dielectric properties of SiAlCN at ~ 10 GHz



(a)

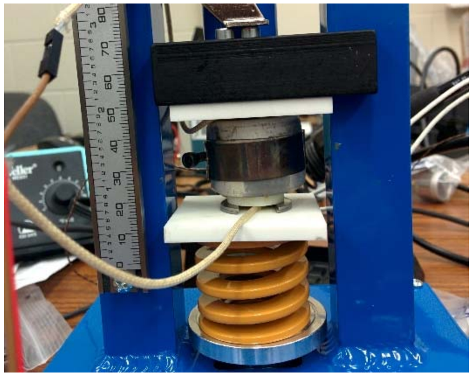
(b)

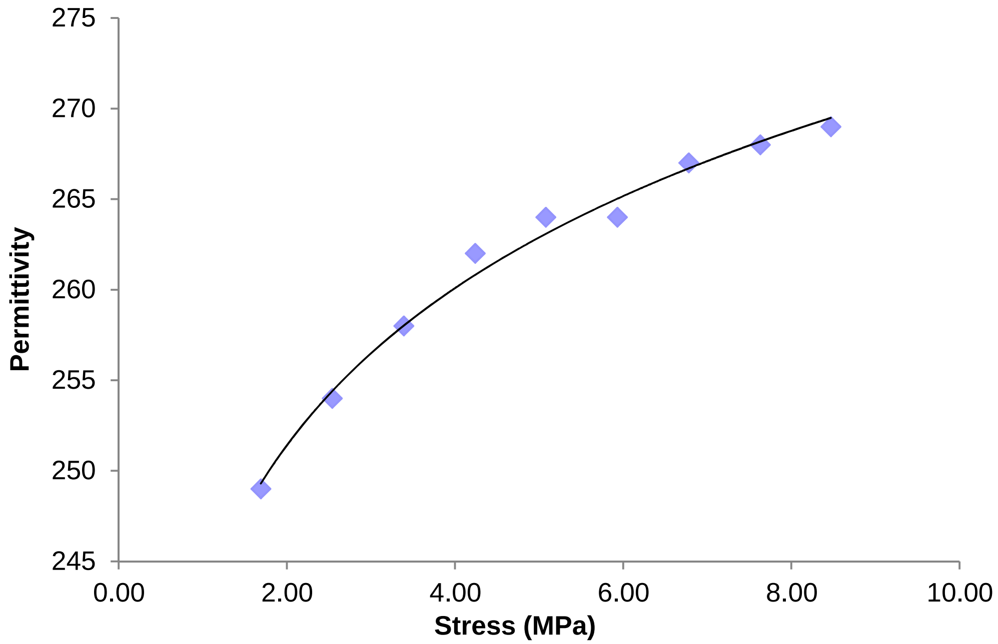
Name	Dielectric constant	Dielectric loss	Frequency (GHz)
S-1	4.87	0.042	9.767
S-2	6.66	0.083	9.743
S-3	7.40	0.21	9.718
S-4	4.45	0.0085	8.826
S-5	3.6	0.0045	9.028
S-6	3.55	0.0046	9.221
S-7	3.85	0.0046	9.337
S-8	4.8	0.0045	9.0035

✓ **819 can cause drastic increase in dielectric loss**

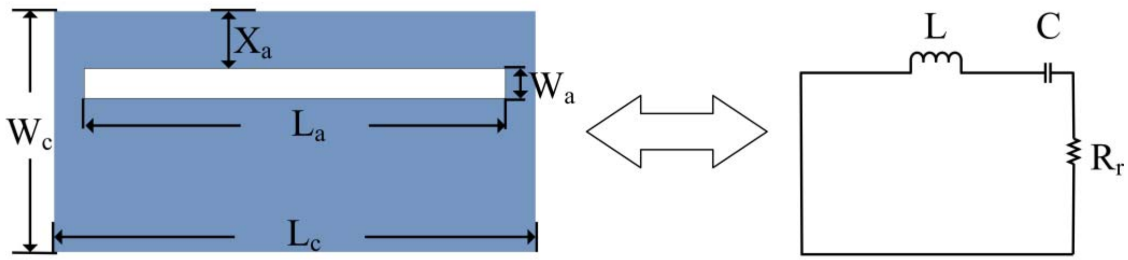
✓ **Other additives have less effect**

- Piezodielectricity at 1 MHz





Sensor design and fabrication



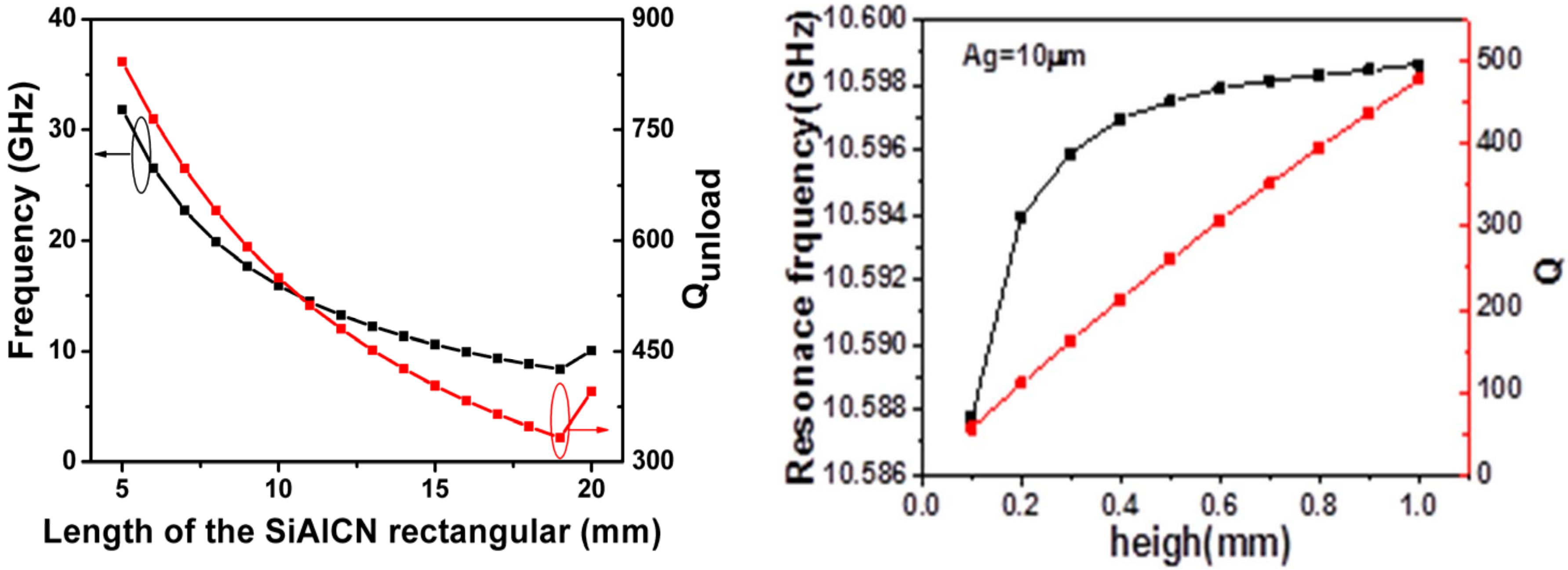
W_c: the width of the PDC rectangular
L_c: the length of the PDC rectangular

$$W_c = \frac{1}{2} L_c$$

H: the thickness of the PDC rectangular
W_a: the width of the slot
L_a: the length of the slot
X_a: the distance of the slot from the edge

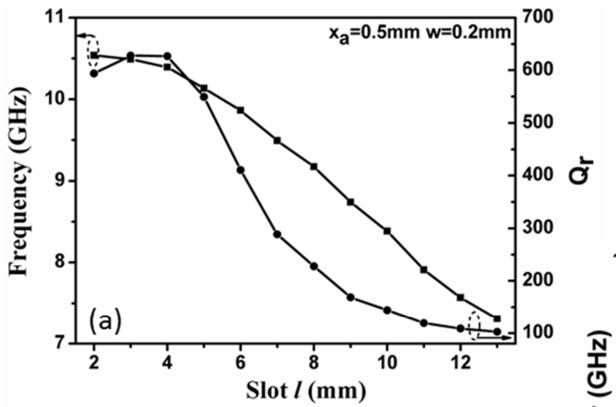
Low dielectric loss and high Q factor

❑ The effect of the rectangualar dimensions

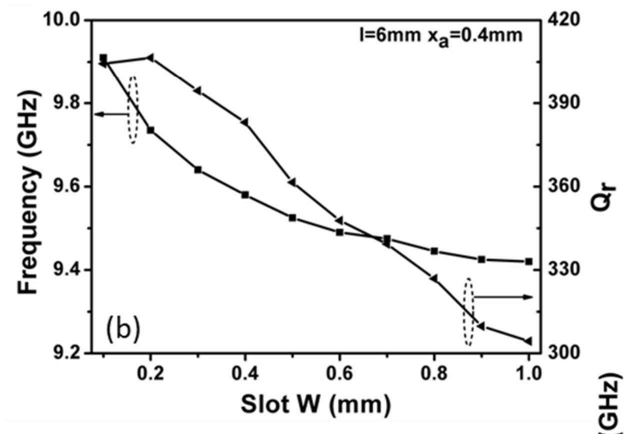


W_c = 8 mm; L_c = 16 mm; H = 1 mm

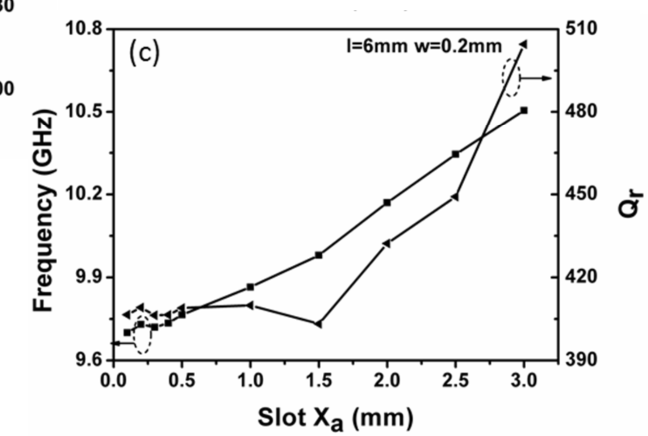
❑ The effect of the slot dimensions



L_a = 6 mm



W_a = 0.4 mm



X_a = 1.0 mm

❑ Sensor fabrication

Material: SiAlCN (1%ASB+2%MA+97%VL20)

Fabrication procedure:

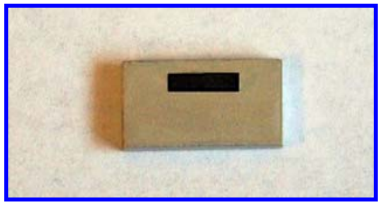
- Cross-link the precursor synthesized in our lab.
- Ball-milling the cross-linked precursor to a fine powder of ～1um scale
- Compress the powder into a disk of 1 inch in diameter and 2-3 mm in thickness using a die under a uniaxial pressure of 50 MPa.
- Further treat the disk under isostatic pressure of 200 MPa at room temperature.
- Pyrolyzed the disk at 1000°C for 4 hrs using a heating rate of 1°C/min.
- Machine the pyrolyzed ceramic disk into the final dimension of the sensor.
- Make electrode on the final sensor.

Final sensor feature:

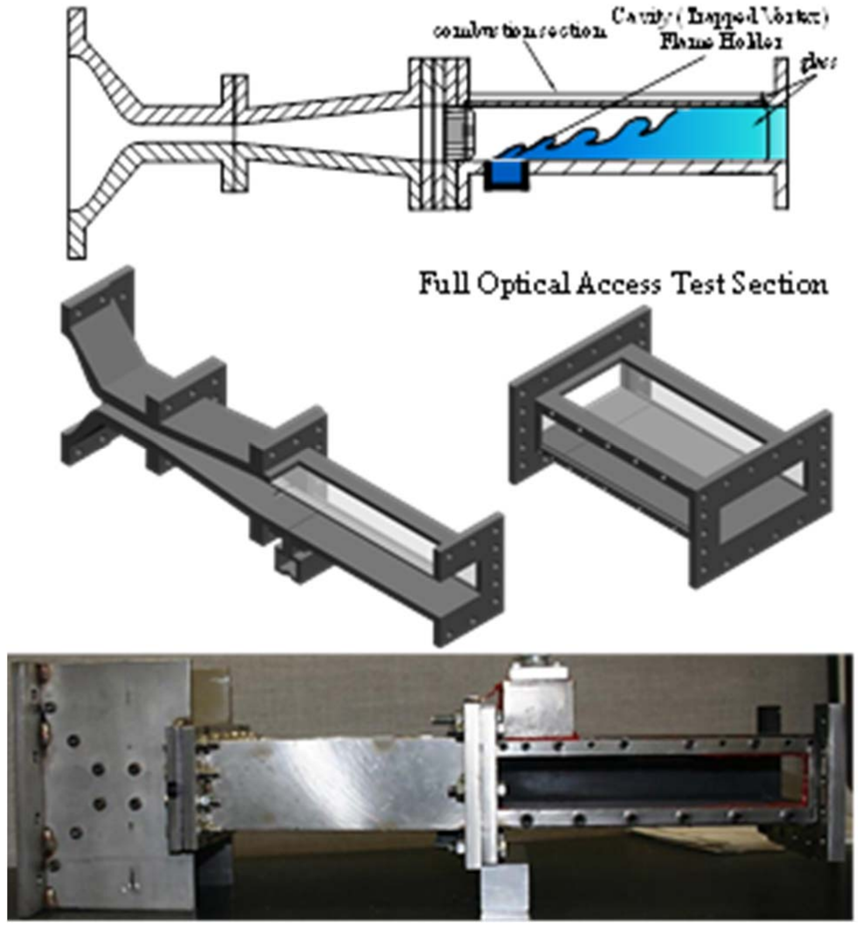
W_c = 8 mm; L_c = 16 mm; H = 1 mm; Pt thickness > 20 um
W_a = 0.4 mm; L_a = 6 mm; X_a = 1 mm

Calculated sensor feature:

- ✓ Resonant frequency = 9.58 GHz;
- ✓ Q-factor will be 383



Sensor characterization (on going)



Summary

- Polymer-derived ceramics possess necessary properties for making high-temperature sensors for turbine applications
- Developed piezodielectric SiAlCN ceramics for wireless passive strain/stress sensors for high-temperature applications.
- A wireless passive strain/stress sensor based-on RF cavity resonator has been designed and fabricated.
- The sensor testing is on going.

Thank you!