Passive Wireless Sensor Fabricated by Direct-Writing for Temperature and Health Monitoring of Energy Systems in Harsh-Environments

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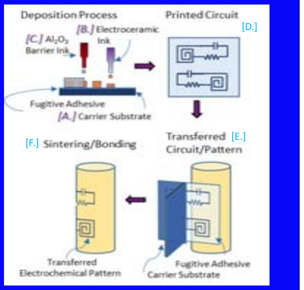
Background

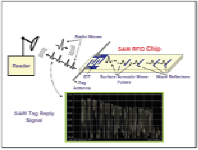
The objective of the work is to develop a wireless, high-temperature sensor system for monitoring the temperature and health of energy-system components. The active sensor and electronics for passive wireless communication will be composed entirely of electroceramic materials which are capable of withstanding the harsh-environments of fossil energy-based technologies.

This work will focus primarily on the direct-writing and testing of temperature (thermocouples and thermistors) and health (strain/stress and crack propagation sensors) that function between 500-1700ºC. A "peel-and-stick"-like transfer process to deposit the entire sensor circuit to various energy-system components will be developed.

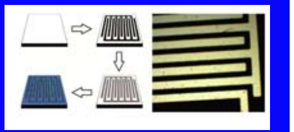
The specific project goals are as follows: 1) Investigate phase formation, sintering/grain growth, and electrical properties of polymer-derived ceramic composites between 500-1700ºC; 2) Define processes to direct-write through ink-jet and robo-casting the polymer-derived ceramic composites; 3) Develop methods to form monolithic "peel-and-stick" preforms that will efficiently transfer the sensor circuit to surfaces after thermal treatment; 4) Design passive RF wireless LCR circuits and reader antennas for high-temperature sensor communication and testing at temperatures up to 1700°C; 5) Investigate the passive wireless sensor system developed for temperature and stress/strain measurements on SOFC repeat units and gas turbine blade prototypes as example applications.

- **A.** Organic carrier film.
- **B.** Polymer Derived Preceramic (after heat treatment converts to electroseramic)
- **C.** Possible barrier layer
- **D.** Printed sensor circuit on the transfer paper
- **E.** Pattern being placed upon the energy-system component
- **F.** Pyrolysis of the organic carrier and bonding





Sound Acoustic Wave Sensor Operation [1]



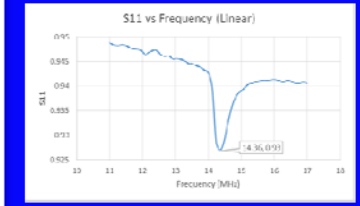
Interdigitated Capacitor (IDC) [2]

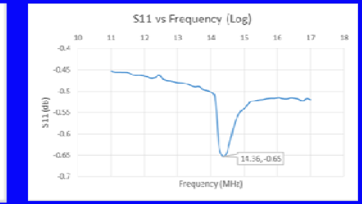
- Three passive wireless methods of using ceramic sensor systems to measure high temperatures in harsh environments are: Surface Acoustic Wave (SAW) sensors; Ring Resonator sensors; Inductor, Resistor, and Capacitor (LRC) sensors. All three of these designs rely on the sensor's environment changing physical or material features of the sensor to measure changes in temperature
- **Saw Sensors** can be used as temperature sensors because as the environment's temperature changes the sensor's surface changes. The changes in the surface causes variations in the SAW waves that are reflected back to the Inter-Digital Transducer (IDT). These variations in the reflected SAW waves cause the IDT to radiate RF signals that have variations reflecting the varied SAW waves. One can use the variations in the received RF signal from the SAW sensor to determine the temperature of the sensor's environment.
- **Ring Resonator Sensors** depend on shifts in the sensors resonate frequency to determine changes in the environments temperature. A reader antenna radiates an RF signal to the resonator sensor's antenna. The sensor's antenna transmits the signal to the sensor's resonating chamber which reflects the signal back to the sensor's antenna. The sensor radiates this reflected signal back to the reader antenna. The strongest reflections are at the sensor's resonant frequency.
- **LRC Sensors** can function as passive high temperature sensors because as the environment's temperature changes the dielectric constant of the circuit's material changes. This causes a change in the circuit's impedance which intern causes shifts in the circuit's resonant frequency. Thus the shifts in the circuit's resonant frequency can be used to infer changes in the environment's temperature

Impedance and Frequency Response Testbed for Sensor Experimentation

- Testbed Features:
  - ☐ Measures impedance characteristics of a sensor
    - ☐ Measures the sensor's impedance and the impedance mismatch between the sensor and RF components
    - ☐ This is critical for antenna design and performing impedance matching between a sensor and RF components
  - ☐ Measures the frequency response of a sensor
    - ☐ Signal generator sweeps through a frequency range
    - ☐ Spectrum analyzer measures the received spectrum
    - ☐ This is critical for finding the resonant frequency of the sensor

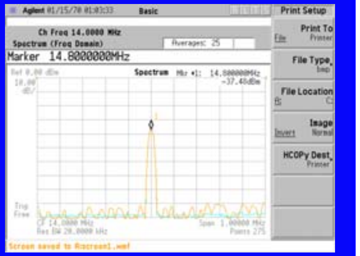
Test Sensor (NFC tag)





- A linearized S11 vs Frequency plot gives the reflection coefficient (Γ) between 0 and 1
- High Γ means poor impedance match
- Best impedance match at 14.36 MHz with Γ = 0.93
- Γ = 0.93 means that approximately 86% of the power is reflected by the sensor
- This sensor is poorly matched to 50 Ω RF components

- A Logarithmic S11 vs Frequency plot gives the return loss (RL) in dB
- Large RL values (those that approach 0 dB) have poor impedance matching
- The sensor had lowest RL of -0.65 dB at 14.36 MHz



- The Smith Chart gives sensor's impedance for the frequency span of 2 MHz – 26 MHz
- Sensor has closest impedance match at 14.4 MHz
- Sensor has 1.8 Ω of resistance and 9 Ω of reactance at 14.4 MHz
- Reactance is inductive as it lies above the horizontal resistance line
- The smith chart is very useful for performing impedance matching

- A signal generator was connect to one sensor and swept through 2 MHz – 26 MHz
- A spectrum analyzer was connected to an identical sensor and measured the received spectrum
- The greatest received signal strength occurs at the sensor's resonant frequency
- Above is a plot of the sensor's resonant frequency of 14.8 MHz

Acknowledgement and References

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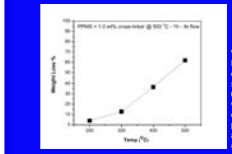
- [1] P. R. Hartmann, "A passive SAW based RFID system for use on ordnance," RFID, 2009 IEEE International Conference on, Orlando, FL, 2009, pp. 291-297
- [2] González, G.; Kolosovas-Machuca, E.S.; López-Luna, E.; Hernández-Arriaga, H.; González, F.J. Design and Fabrication of Interdigital Nanocapacitors Coated with HfO2. Sensors 2015, 15, 1998-2005.

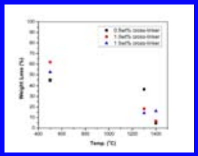
Fabrication and Characterization of Polymer-Derived Electroceramic Composites

Thermal Processing of Composite Compositions

Percentage of weight loss for poly-phenyl-methyl-siloxane (PPMS) polymer derived-ceramic after pyrolyzed until transformation from liquid to solid phase.



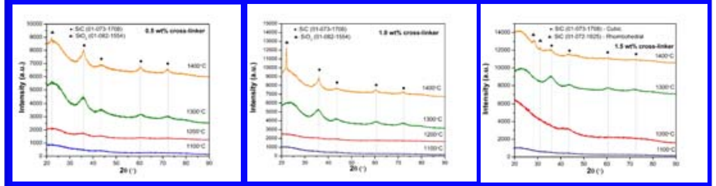
Weight Loss (%) for PPMS with 1.0wt% cross-linker fired at 500ºC for 1h, is 61.91%. Less weight loss (%) exhibited when pyrolyzed in Air atmosphere (45.05%)



Increasing pyrolyzed temperatures (500-1400ºC) indicates a decrease of weight loss in all samples. Grade decrease of samples' weight obtained in temperature from RT to 500ºC A weight loss decrease trend shown in samples with increase of percentage of cross-linker (0.5, 1.0, 1.5wt%) in PPMS precursor.

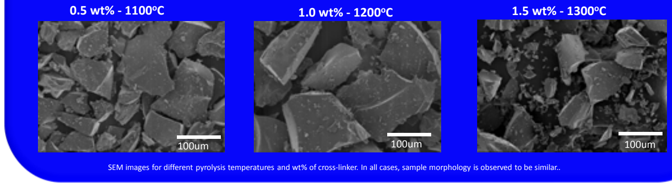
Composite Material Structural and Optical Characterization

X-ray diffraction (XRD) plots of Poly-Phenyl-Methyl-Siloxane (PPMS) in various concentrations (0.5, 1.0, and 1.5 wt%) of cross-linker (Di-cumyl-peroxide) are pyrolyzed at different temperatures (1100ºC-1400ºC) and pure Argon atmosphere.



- Samples in various concentrations of cross-linker pyrolyzed at lower temperatures than 1300ºC exhibit totally amorphous structures.
- Above 1300ºC and for all concentrations of cross-linker a polycrystalline cubic phase of SiC is exhibited.
- A mixture of polycrystalline cubic and Rhombohedral phase of SiC is found for 1.5 wt% cross-linker and 1400ºC firing conditions

SEM images of PPMS with 0.5, 1.0, and 1.5 wt% of cross-linker fired in various (1100ºC-1400ºC) and pure Argon atmosphere.



0.5 wt% - 1100ºC **1.0 wt% - 1200ºC** **1.5 wt% - 1300ºC**

SEM images for different pyrolysis temperatures and wt% of cross-linker. In all cases, sample morphology is observed to be similar..

Conclusion & Future work

- XRD patterns for the material at lower temperatures (<1200 °C) show no diffraction peak, suggesting that they are completely amorphous, while samples pyrolyzed at higher temperatures (>1300°C) show weak diffraction peaks, indicating presence of a small amount of crystalline phase. Indexed peak(s) suggest a mixture of cubic and rhombohedral phase of SiC.
- The Impedance and Frequency Response Testbed successfully measured the impedance characteristics and frequency response of the sensor. The Testbed is ready to be used to analyze the sensors manufactured for this project
- ANSYS HFSS High Frequency Electromagnetic Field Simulation software will be used to perform modeling and simulation analysis for sensor design. 3D models of the sensors will be built in HFSS and the physical parameters of the sensor circuit will be modeled and simulated. These physical parameters could include the design of the inductor (number of coils, width of the coils lines, spacing between the coils), interdigitated capacitor (number of fingers, width of fingers, spacing between the fingers), as well as changing the material properties of the sensor.