Near-Field Passive Wireless Sensors for High-Temperature Metal Corrosion Monitoring

Oğuzhan Bilaç [1], Noah Strader [1], Kevin M. Tennant[1], William Bullock [1], Jordyn Herter [1], Brian Jordan[1], Daryl S. Reynolds[2], Katarzyna Sabolsky[1], Edward M. Sabolsky[1]

[1] Department of Mechanical and Aerospace Engineering, West Virginia University
[2] Lane Department of Computer Science and Electrical Engineering, West Virginia University

October 8, 2024,
Advanced Materials for Harsh Environments
MS&T24 Conference, October 6-9, 2024, Pittsburgh, PA

WestVirginiaUniversity

OUTLINE

- INTRODUCTION
  - Harsh Environments
  - Corrosion
- AIM
- METHODOLOGY
- RESULTS AND DISCUSION
  - Corrosion Kinetics of Copper
  - LC Resonator Modelling and Simulation
  - Passive Wireless Temperature and Corrosion Sensing at High Temperature
  - Passive Wireless Sensing of Cracking and Spallation of Corrosion Layer
- CONCLUSIONS

Introduction- Harsh Environments

Accurate online monitoring of temperatures as well as other physical parameters is highly desirable inside various harsh environments:

Gas turbines [1]

Turbine engines [2]

Nuclear reactors [3]

Harsh environments;

- **High temperatures (500-1500 ⁰C)**
- **Corrosive gases (containing sodium, vanadium and sulfate)**
- **High pressures (up to 1000 psi) or nuclear radiation**

Ability to monitor:

- **Temperature**
- **Structural stability of systems components.**

Jun Zhang…..A Review of Passive RFID Tag Antenna-Based Sensors and Systems for Structural Health Monitoring ApplicationsJanuary 2017Sensors 17(2):265, 17(2):265
[1] https://www.dixonpilot.com/2022/04/05/gas-turbine-vs-steam-turbine-which-is-more-efficient/
[2] https://www.govconwire.com/2024/06/ge-books-1-1b-army-contract-for-t700-turbine-engines/
[3] https://www.investopedia.com/us-launches-its-first-nuclear-reactor-built-from-scratch-in-decades-7567525

Introduction- Metal Corrosion

Metal corrosion can be generally defined as a change of the initial metal chemistry (and phase) to an alternative compound, which typically includes the formation of an unwanted metal oxide phase (but may also include the formation of other metal compound phases)[1].

Corrosion types

Room temperature

- **Erosive**
- **Crevice**
- **Pitting**
- **Concentration**
- **Galvanic**

Multiple electrochemical reactions [1]

High temperature

Direct atmospheric oxidation: A less common and less complex form of metal corrosion which typically occurs at accelerated rates at high temperatures [2].

[1] F. Pettit, "Hot corrosion of Metals and Alloys," Oxid Met 76: 1-21 (2011).
[2]M. Iannuzzi and G. S. Frankel, Materials Degradation (2022) 6:101 ; https://doi.org/10.1038/s41529-022-00318-1

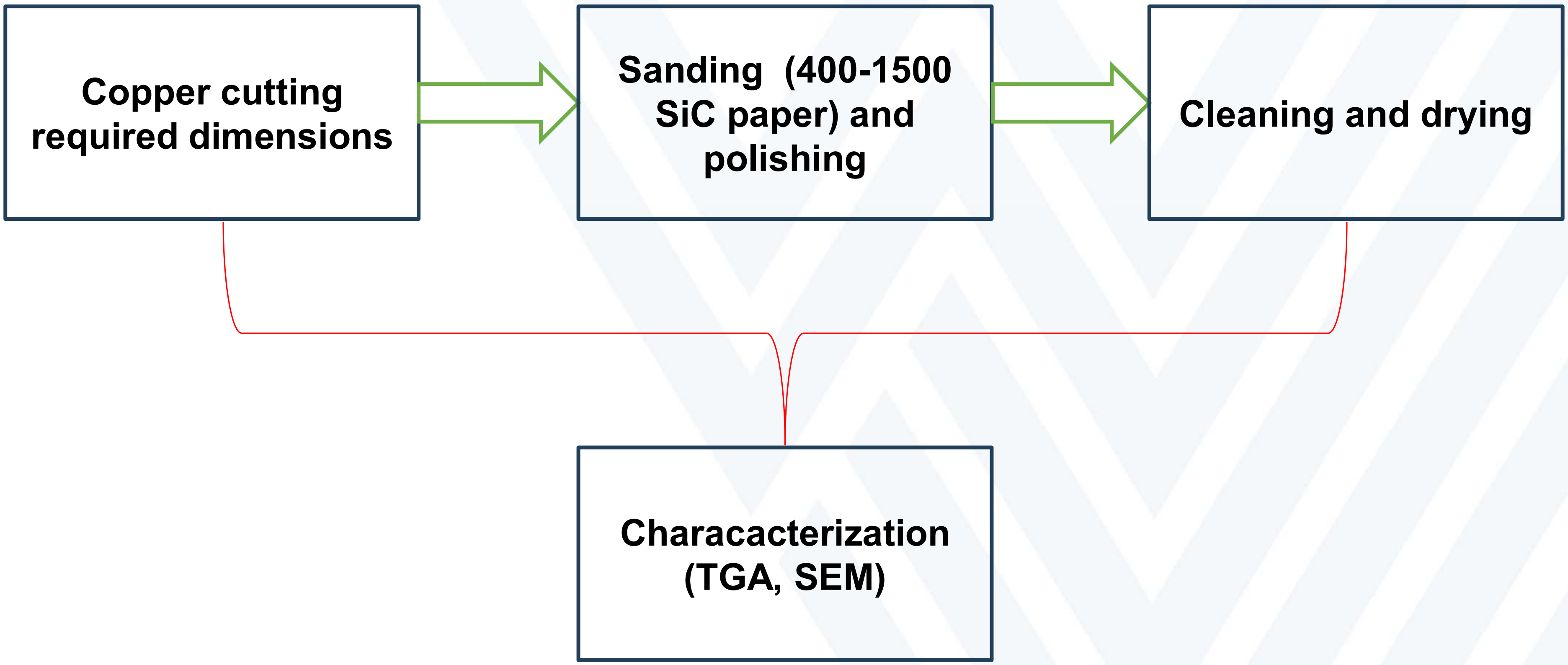
Objectives of This Study

- Designing LC passive wireless sensors operating at 70-100 MHz using ANSYS HFSS modeling package.

- To investigate the fabrication and evaluation of passive wireless LC sensors for high temperature and corrosion measurement.

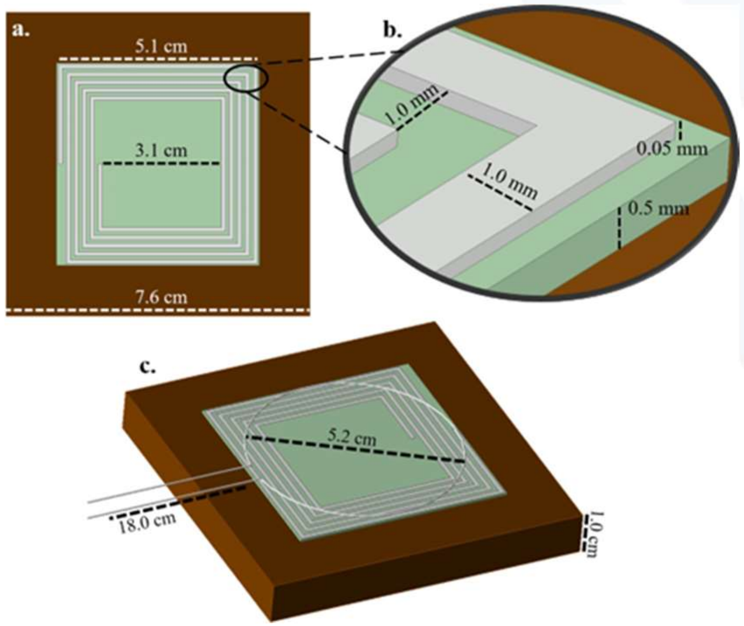
- To study and analyze the sensors' simultaneous temperature and corrosion measurements to be produced in real-time.
  - TGA
  - SEM

Methodology- *Copper Preparetion*



Methodology- LC Resonator Modelling and Simulation

Models and simulations were created using the ANSYS HFSS electronics software, produced by ANSYS.



3D Geometry of sensor design produced in the ANSYS HFSS software (a) sensor top-down view, (b) sensor close-up view of printed lines, (c) and the sensor isometric view.

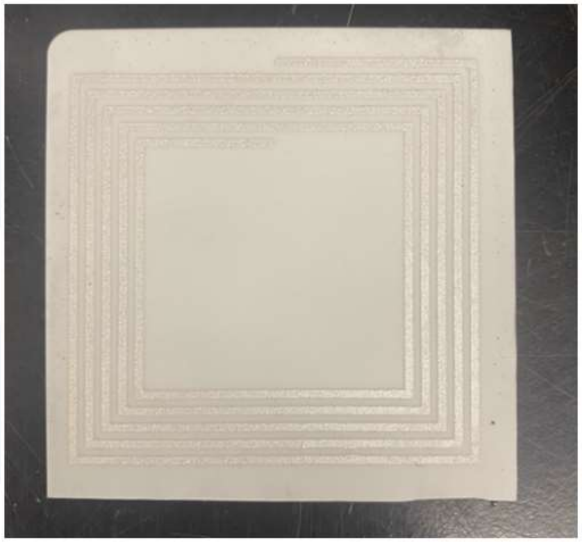
Properties of materials used in the ANSYS simulations

	Relative Permittivity	Relative Permeability	Conductivity (S/m)
Silver	1.000	0.999	6.100e7
Platinum	1.000	1.000	9.300e6
Copper	1.000	0.999	5.800e7
Air	1.001	1.000	0.000
Copper Oxide	12.00	1.0	1.000
Alumina (25 °C)	9.800	1.000	1.000e-4
Alumina (800 °C)	11.00	1.000	1.000e-4

Methodology-*Sensor Fabrication*

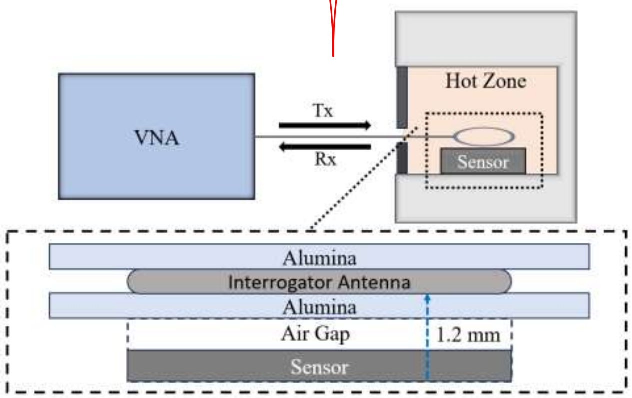
Al_2O_3 substrates (96%) → **Ag ink (fine(0.7-1.3 µm) and coarse (3-7µm))** → **Screen-printing (5 silver turn)**

Sintering (825 °C-4h) →



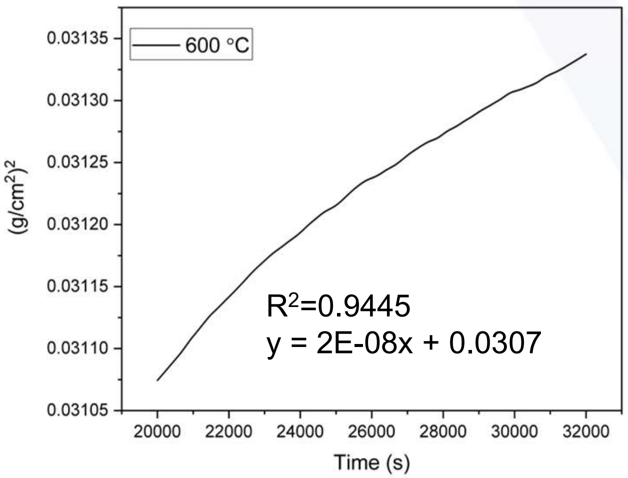
Methodology-Passive Wireless Sensor Experimental Layout and Orientation

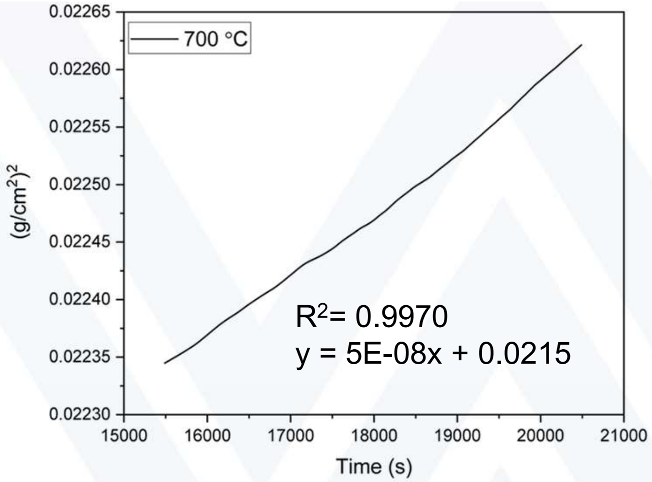
Ag 5-turn inductor sensor and copper plate → **Thermal stages (heating, isothermal and cooling)** → **Sensor S11 response**

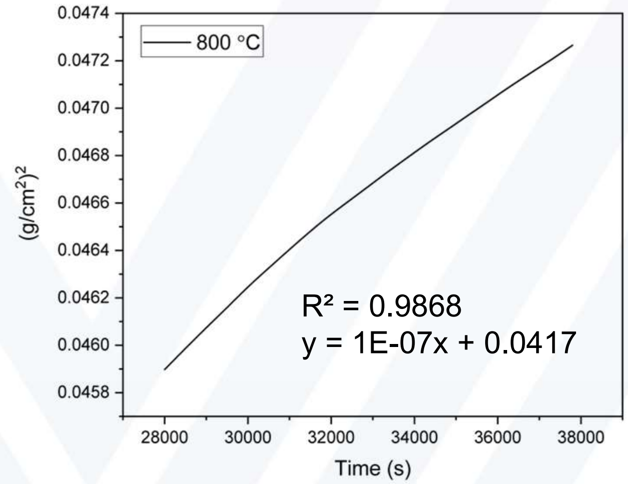


WestVirginiaUniversity

Corrosion Kinetics of Copper Results







Calculated oxidation parabolic constants (k'') for Cu samples in $g^2\,cm^{-4}\,s^{-1}$.

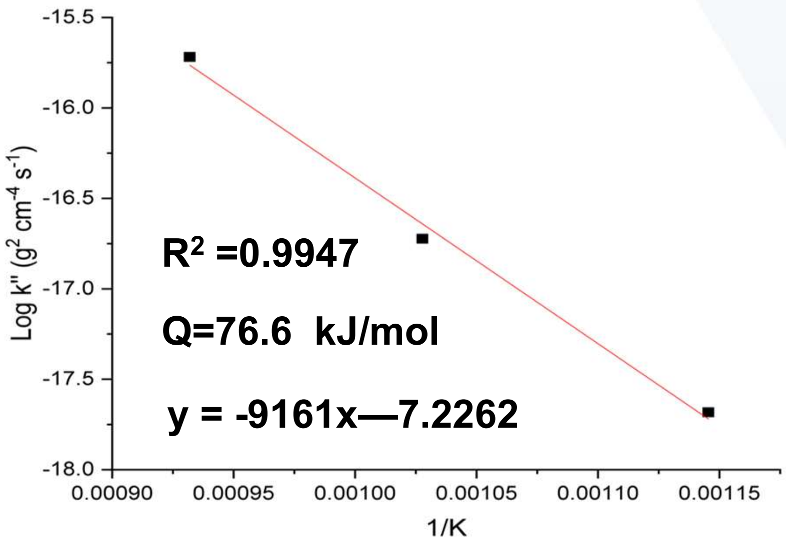
Temperature	k'' ($g^2\,cm^{-4}\,s^{-1}$)
600 °C	2×10^{-8}
700 °C	5×10^{-8}
800 °C	1×10^{-7}

The oxidation rate increases with increasing temperature.

Based on temperature dependence:

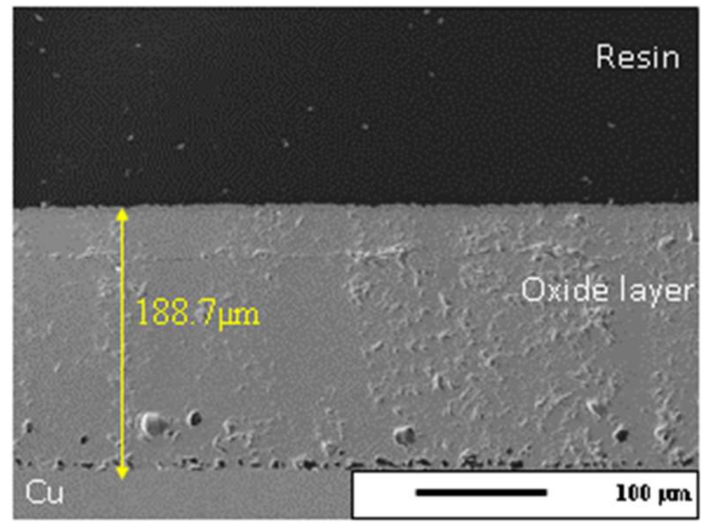
- **High temperature (900 - 1050 °C)**
- **Intermediate temperature (600 - 850 °C)**
- **Low temperature (350 - 550 °C)**

Arrhenius plot for the oxidation of copper in different temperatures



In the literature, the activation energy of copper in an air atmosphere between 600 and 800 °C was found to be 27-123 kJ/mol in various studies.

Thickness from the SEM: 188.7 µm.

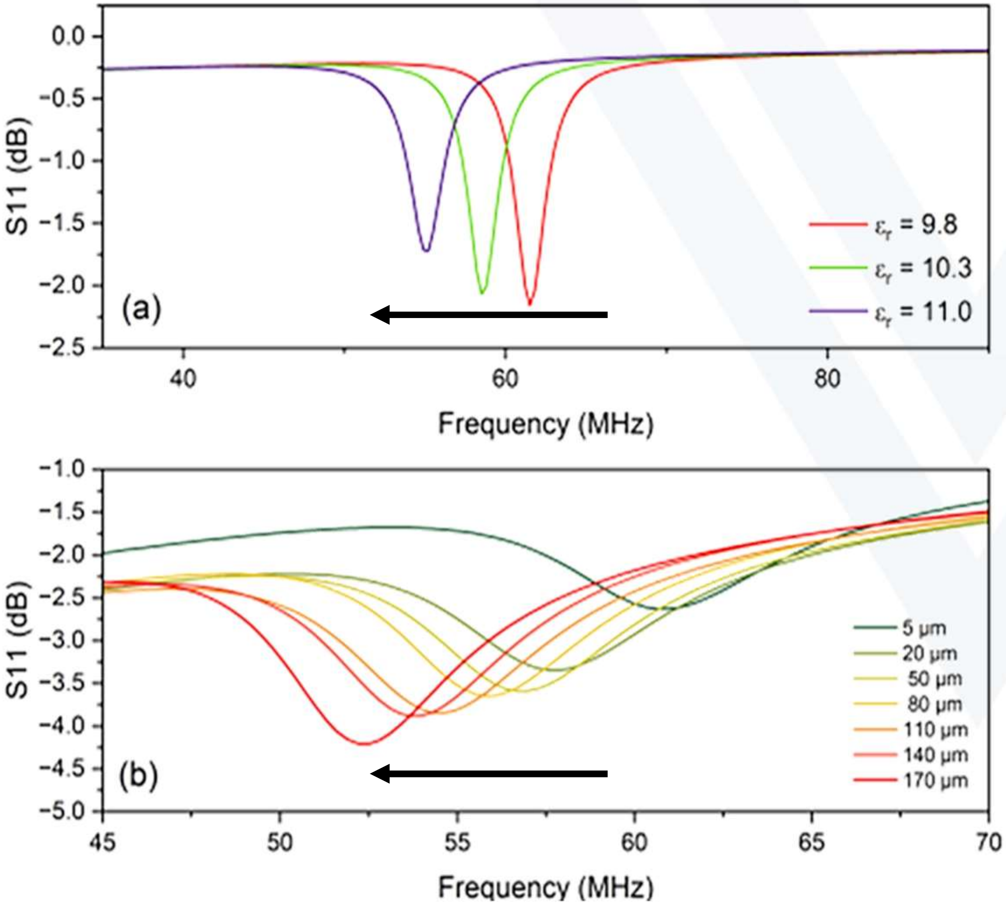


SEM cross-sectional image of oxide layers on copper oxidized under air atmosphere at 800 ºC- 4h

Belousov, V. V., & Klimashin, A. A. (2013). High-temperature oxidation of copper. Russian Chemical Reviews, 82(3), 273

ANSYS HFSS Sensor

Modelling Results



The relative permittivity of the dielectric material: 9.8 - 11.

Resonant frequency of sensor : 62 – 55 MHz.

The copper oxide thickness layer: 5-170 µm.

The signal magnitude: -2.5 to -4.25 dB.

The resonant frequency of sensor: 61 - 52 MHz.

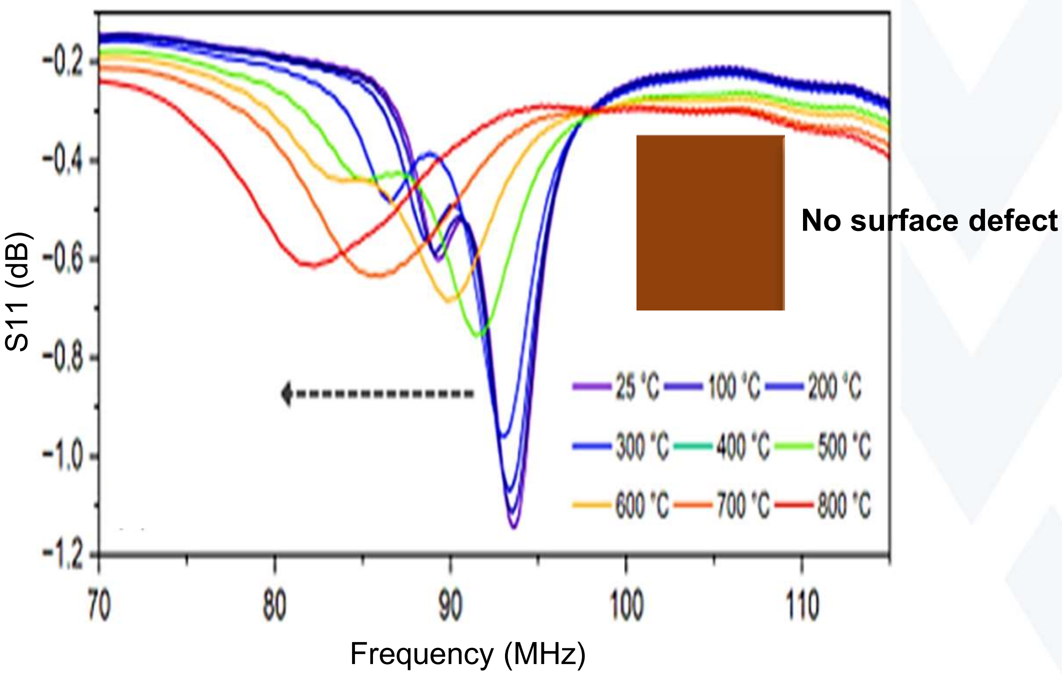
(a) ANSYS HFSS simulation results of LC sensor design by varying the relative permittivity of the Al_2O_3 dielectric layer from 9.8 to 11. (b) ANSYS HFSS simulation results of LC sensor with increasing the copper oxide layer between the ground plane and the dielectric layer of the simulation from 5-170 µm.

Passive Wireless Temperature and Corrosion Sensing at High Temperature Results

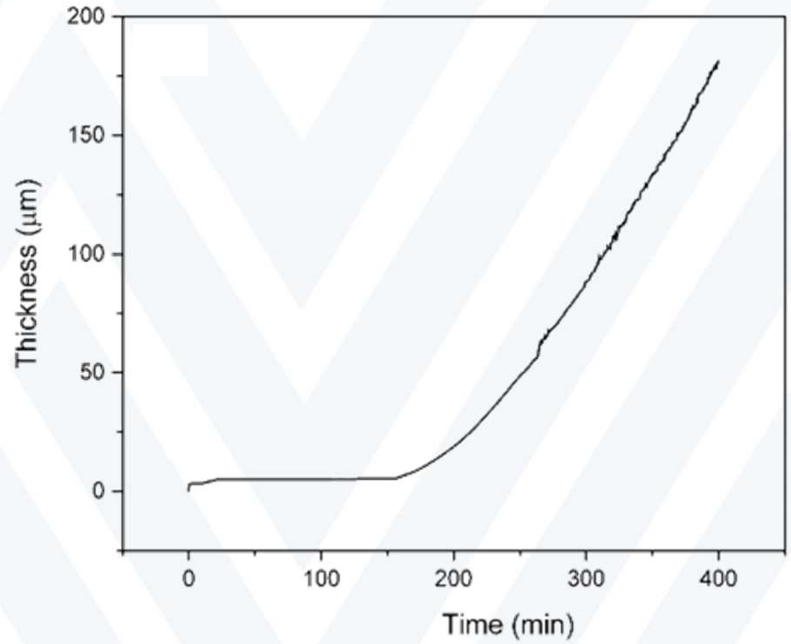
In the heating stage :

- **Resonant frequency of sensor shifted from 93 – 82 MHz.**
- **Signal magnitude decreased from -1.1 to -0.6 dB.**

Thickness from the TGA: 180 µm.



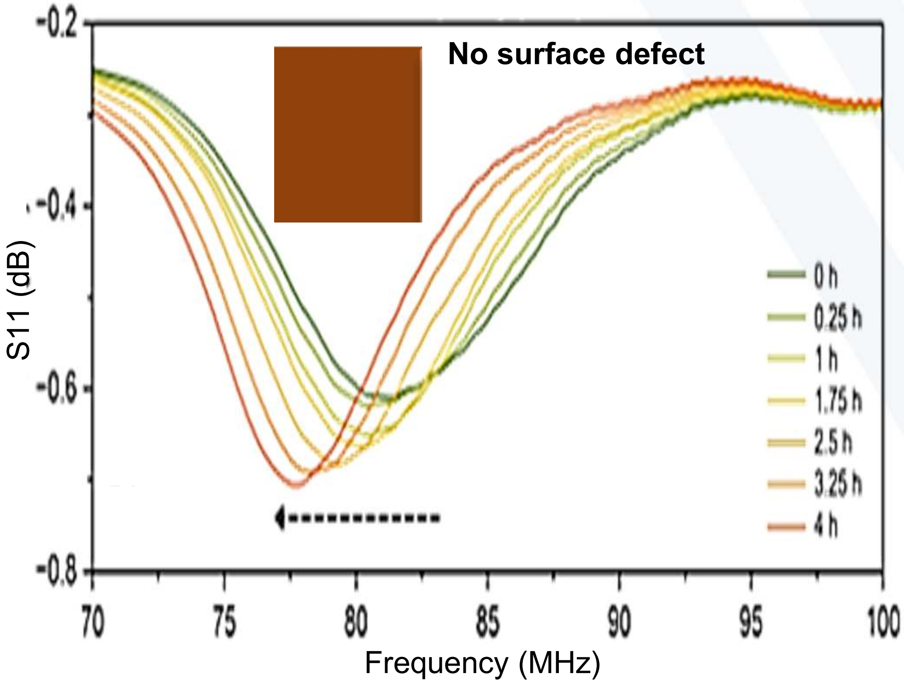
Passive wireless sensor heating furnace results on the copper ground plane with no surface defects



Copper oxide thickness growth obtained in TGA curves during the heating stage from room temperature to 800 ° C

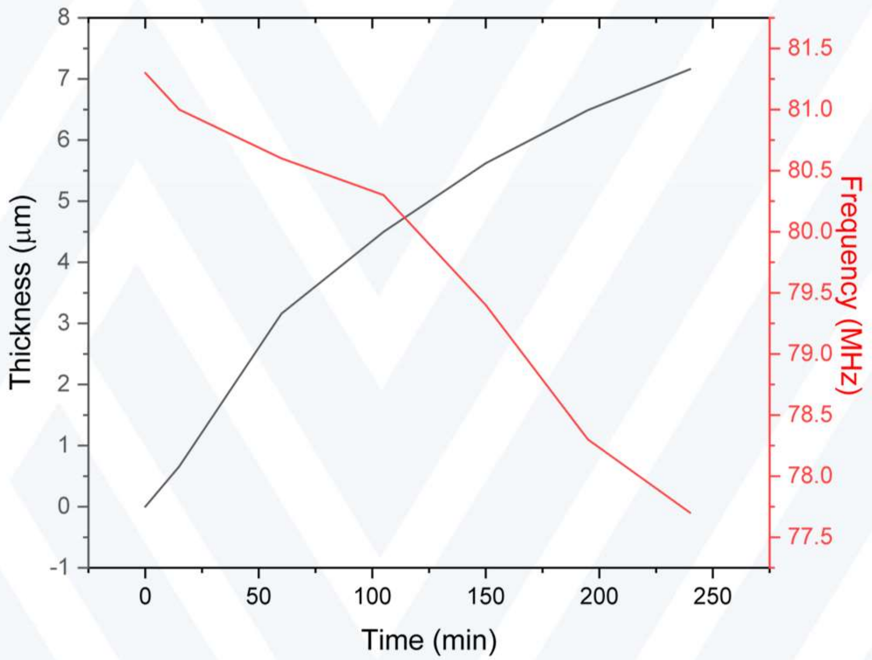
In the holding stage:

- **Sensor's peak increased in magnitude by approximately 0.12 dB.**

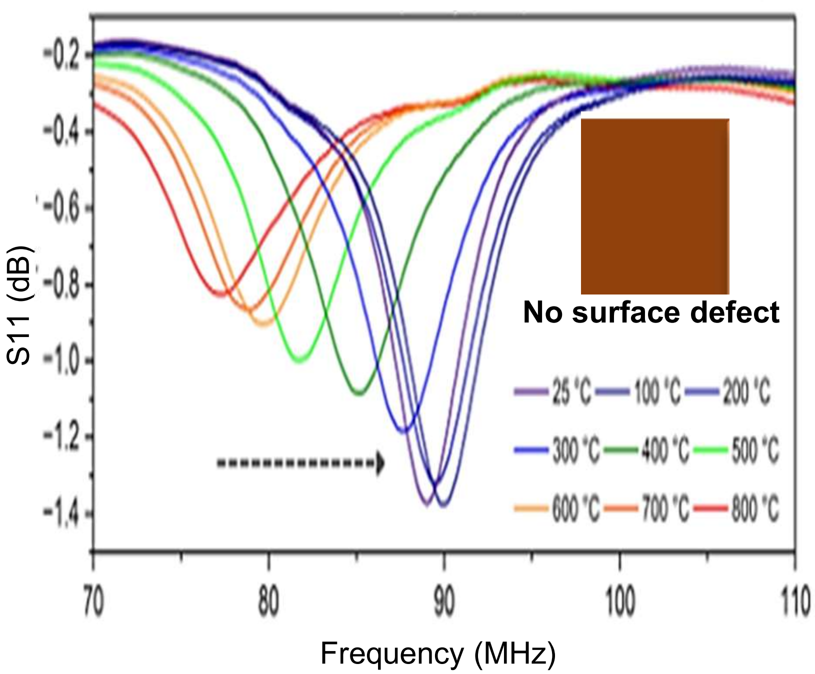


Passive wireless sensor holding furnace results on the copper ground plane with no surface defects

- **Resonant frequency of sensor shifted from 82 to 76 MHz.**



Graph of both the copper oxide thickness growth (extracted from the TGA data) and the measured sensor shift data, both graphed as a function of isothermal hold time at 800 ° C.

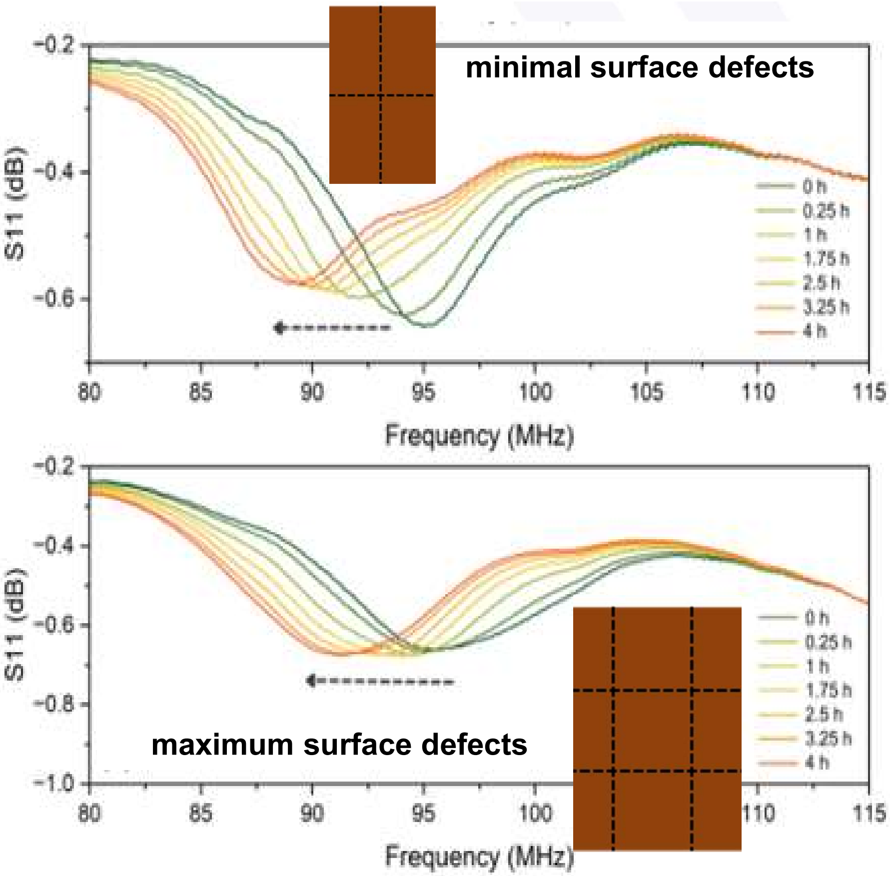


Passive wireless sensor cooling furnace results on the copper ground plane with no surface defects

In the cooling stage:

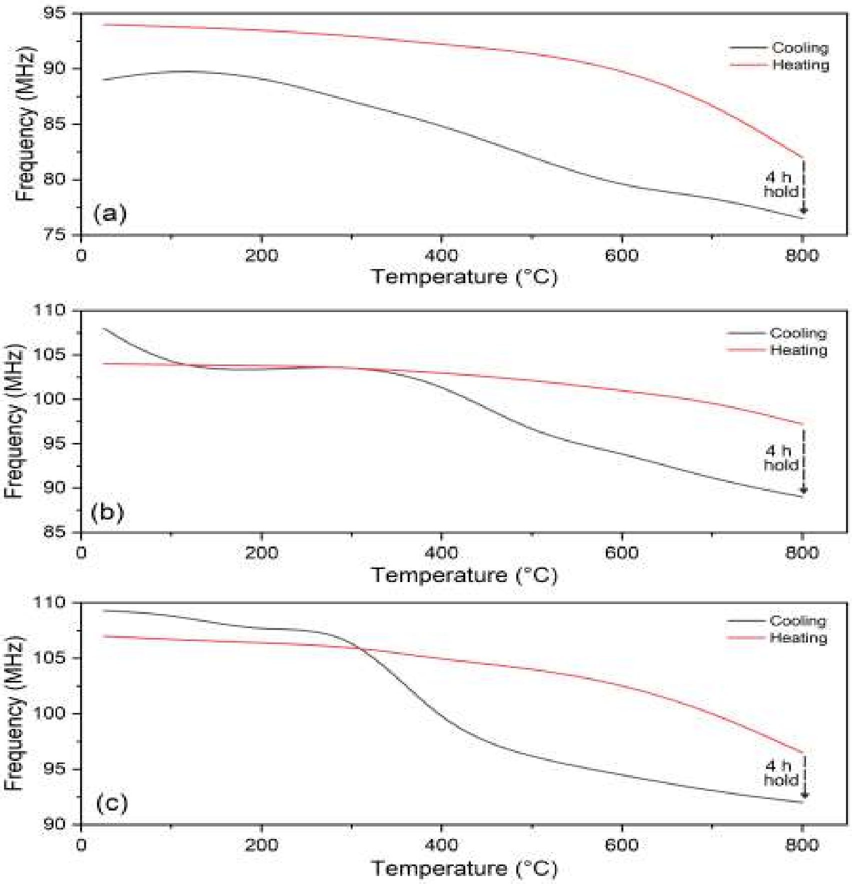
- **It increased in magnitude by approximately 0.5 dB.**
- **Resonant frequency of sensor shifted from 76 to 89 MHz.**.

Passive Wireless Sensing of Cracking and Spallation of Corrosion Layer Results



The maximum temperature hold segments of each ground plane with different quantities of defects

- **The sensor response has the same downward frequency shift observed from the defect-free sensor but displays a decrease in magnitude as opposed to an increase.**
- **This does not agree with the simulation results because this sensor experienced spallation.**
- **However, it does agree with which was a simulation that compared the effect of adding cracking to the oxide layer as it grows.**
- **This simulation provided evidence that this causes a decrease in the S11 magnitude.**



Passive wireless sensor hysteresis plots for each ground plane

- **It can be seen that the magnitude of the heating and cooling frequency shift is very consistent**
- **A frequency shift occurs during the maximum temperature hold at 800 °C that causes a gap between the heating and cooling plots.**
- **This gap proves to be a mechanism for distinguishing spallation as both of the other ground planes observed in Fig. (b) and Fig. (c) have a larger frequency change in their cooling rate.**

Conclusions

Conclusion

- The simulation showed that a square 5-turn planar Ag inductor supported on an Al_2O_3 substrate was the optimal design for corrosion characterization at 800 °C.

- The microstructure analysis of the oxidized samples showed, on average, 188.7 µm for the full harsh environment run.

- The work showed a similar correlated frequency shift and signal amplitude change with oxide growth.

- The work also proved the effect of oxide cracking and spallation events on the sensor response

Acknowledgment

- The U.S. Department of Energy has funded this research under the contract DE-FE0031912. We want to thank DOE for their support.

- Thank WVU Shared Research Facilities.

- We also would like to thank the faculty and staff of West Virginia University for their continued support

U.S. DEPARTMENT OF ENERGY

West Virginia University

Thank you for your attention!

Questions?

Dr. Oguzhan Bilac: oguzhan.bilac@mail.wvu.edu

Dr. Edward Sabolsky: ed.sabolsky@mail.wvu.edu