U.S. DEPARTMENT OF ENERGY | Office of NUCLEAR ENERGY

Advanced Sensors and Instrumentation

Understanding irradiation behaviors of ultrawide bandgap Ga_2O_3 high temperature sensor materials for advanced nuclear reactor systems

Advanced Sensors and Instrumentation (ASI) Annual Program Webinar

October 24 – 27, 2022

Associate Professor: Ge Yang, Ph.D.

North Carolina State University/Department of Nuclear Engineering

Project Overview

Project Team/Participants

- **PI and Associated Institution:** Dr. Ge Yang (Department of Nuclear Engineering, North Carolina State University)
- **Co-PI(s)/Collaborators and Associated Institutions:** Dr. Cheng Sun (Idaho National Laboratory), Dr. Ayman Hawari (North Carolina State University), Dr. Yaqiao Wu (CAES/Boise State University)
- **Identification of NSUF Facilities:** (1) North Carolina State University, PULSTAR Nuclear Reactor; (2) Center for Advanced Energy Studies (CAES)
- **NSUF Facility Technical Lead:** Dr. Ayman Hawari (North Carolina State University, PULSTAR Reactor Program); Dr. Yaqiao Wu (Center for Advanced Energy Studies, CAES)
- **Post-Doc/Students and Facility Staff Members:** Robert McRobie, Lucia Rebeca Gomez, Da Cao, Colby Fleming, Ming Liu, Ching-Heng Shiau

Motivation – A strong need for (U)WBG sensor materials

- Radiation-hard sensor materials and devices are key components for developing advanced nuclear energy systems

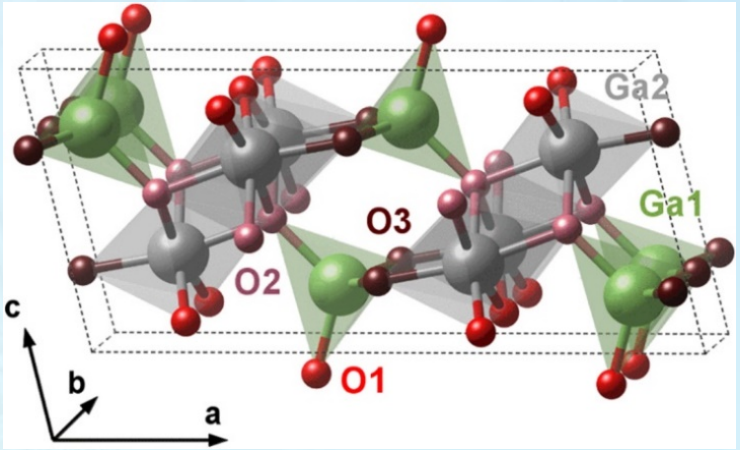
- Many traditional sensors have certain limitations for harsh environment nuclear applications due to their intrinsic material properties.
  - Survivability in radiation field
  - High temperature tolerance

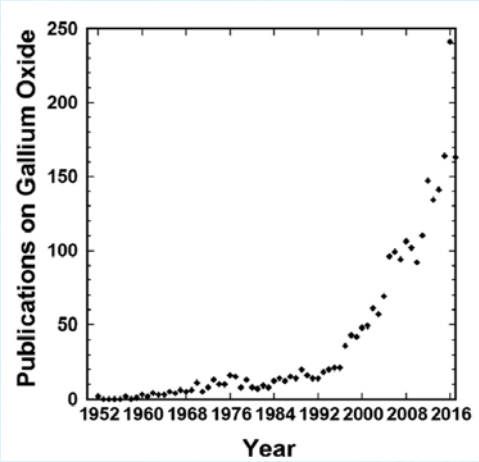
- Wide and ultrawide bandgap (U)WBG semiconductors are much less susceptible to displacement damage by irradiation than elemental and narrow bandgap compound semiconductors

Motivation – Ga_2O_3 for nuclear sensors and instrumentation

- **β-Ga_2O_3 is an emerging ultrawide bandgap compound that has many desired material advantages for nuclear sensor applications**
  - Thermal stability (M. P. > 1800 ^oC)
  - The most recent ultrawide bandgap material (4.5 – 5.1 eV)
  - Very high breakdown electric field (8 MV/m)
  - High quality bulk single crystals from melt
  - Reasonable availability of Ga_2O_3 materials

- **β-Ga_2O_3 holds high promise for fitting into many radiation-related application scenarios with the performance that are not met by currently used materials**
  - Harsh environment applicability
  - High sensing performance
  - Versatile and cost-effective synthesis and fabrication





S. J. Pearton et al., "A review of Ga_2O_3 materials, processing, and devices," Appl. Phys. Rev., vol. 5, no. 1, p. 011301, 2018.

Systematic irradiation research is urgently needed to study and deploy the emerging Ga_2O_3 nuclear sensor material!

Objective of this Project

Understand fundamental irradiation behaviors of emerging ultrawide bandgap Ga_2O_3 high temperature sensor materials through a series of well-designed irradiation experiments and post-irradiation examination (PIE) tests

Meeting the urgent need of the nuclear community!

Use of Two NSUF Partner Facilities with Complementary Capabilities

(1) North Carolina State University (NCSU) Nuclear Reactor Program PULSTAR User Facility (for neutron irradiation and positron measurements)

(2) Microscopy and Characterization Suite (MaCS) at Center for Advanced Energy Studies (CAES) (for PIE microstructural, compositional and cathodoluminescence examination)

Objective: Establish fundamental understanding of irradiation behaviors of ultrawide bandgap Ga_2O_3 sensor materials through targeted irradiation and PIE experiments

Task 1:
Conduct room temperature irradiation experiments of Ga_2O_3 samples at NCSU's PULSTAR Nuclear Reactor

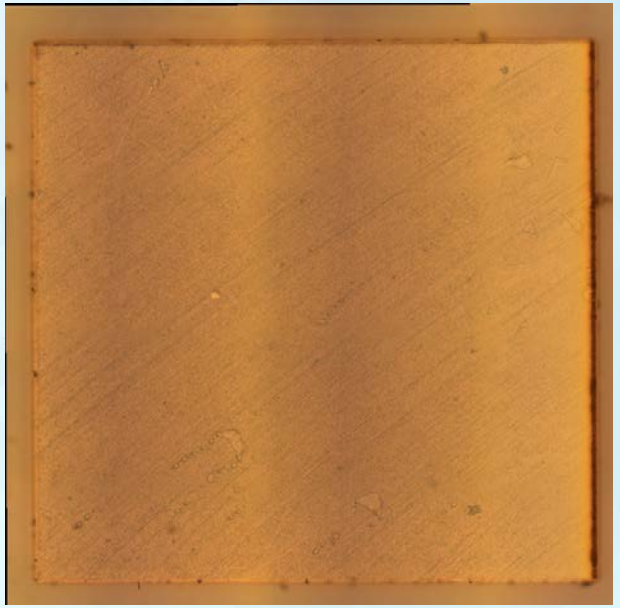
Task 2:
Perform systematic post-irradiation examination at NCSU and CAES to analyze Ga_2O_3 samples that have been irradiated at room temperature and compare with unirradiated Ga_2O_3 reference samples

Task 3:
Conduct high temperature irradiation experiments of Ga_2O_3 samples using a newly built in-pool high temperature furnace facility at NCSU's PULSTAR Nuclear Reactor

Task 4:
Perform systematic post-irradiation examination at NCSU and CAES to analyze Ga_2O_3 samples that have been irradiated at high temperature and compare with unirradiated Ga_2O_3 reference samples

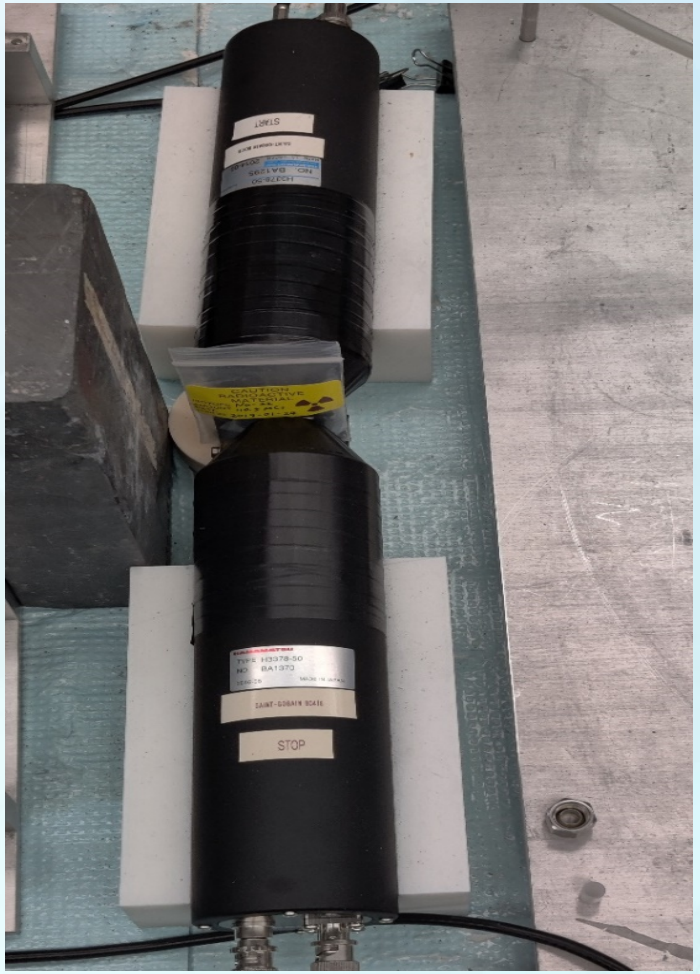
A series of Ga_2O_3 samples have been carefully prepared

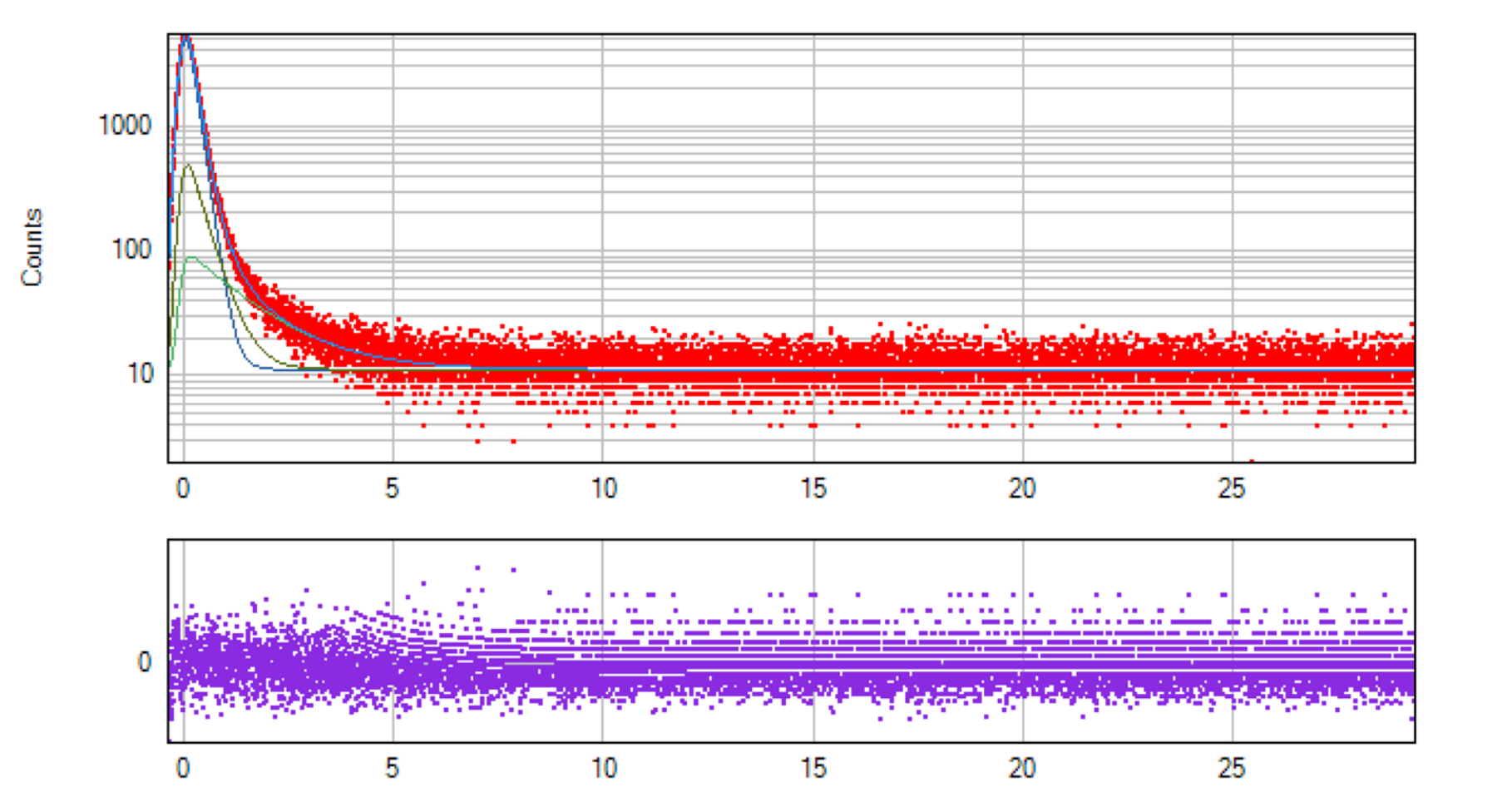
Comprehensive chemical cleaning work have been conducted



Polarized light microscopy image of Ga_2O_3

We started the positron measurements



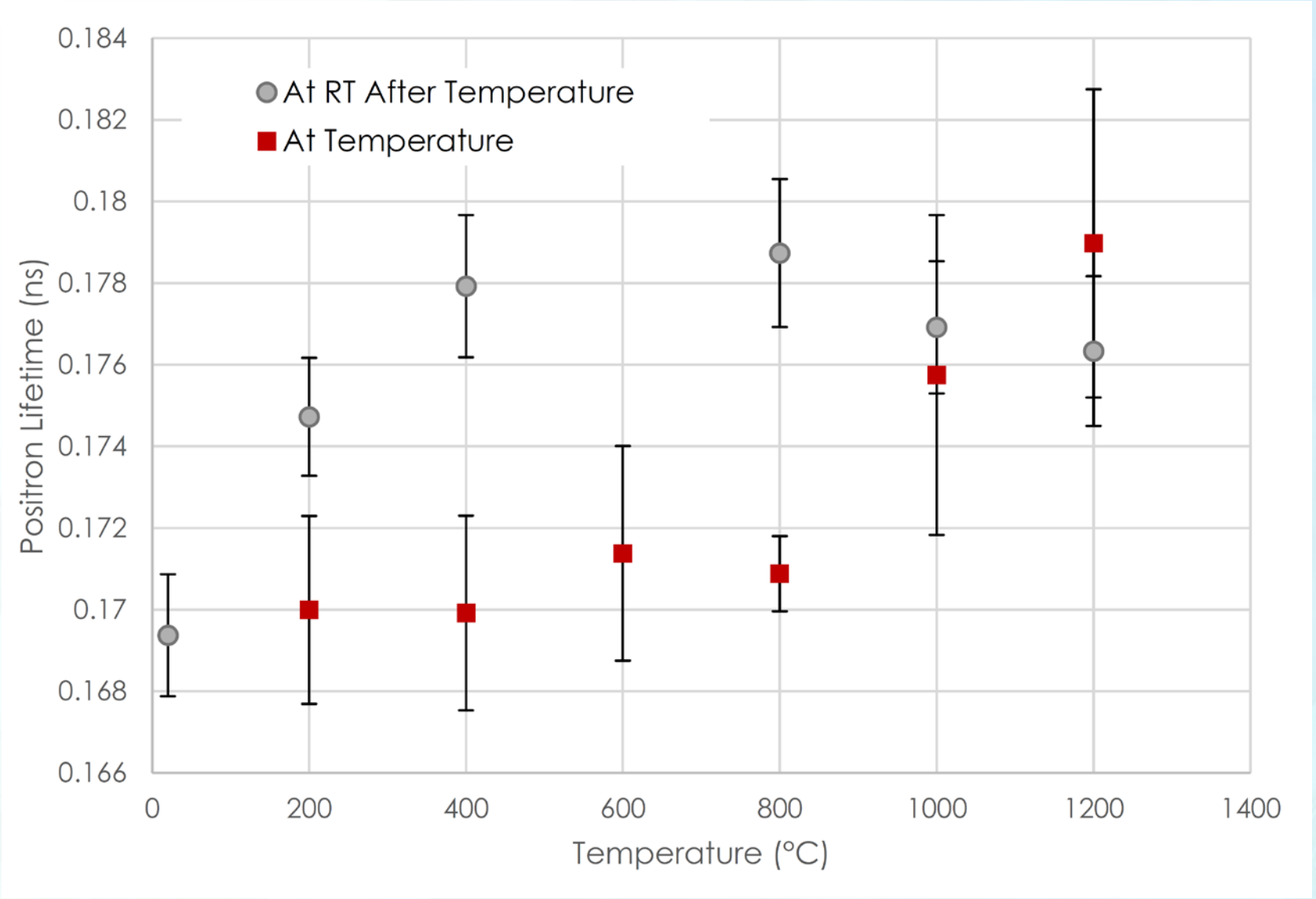


A typical Ga_2O_3 PALS spectrum and its fits (top plot). The variance of the fit is plotted below in purple

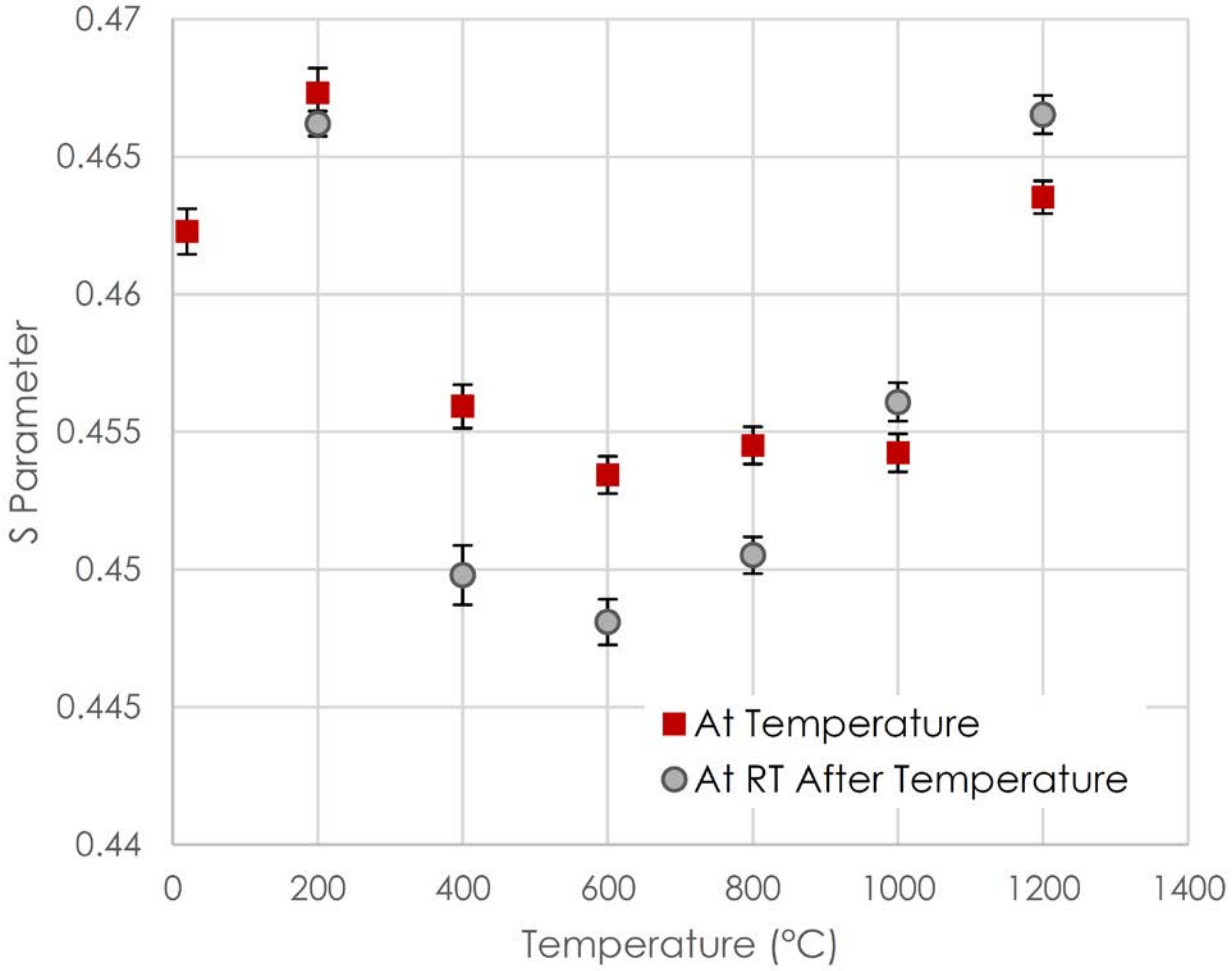
PALS Results at RT

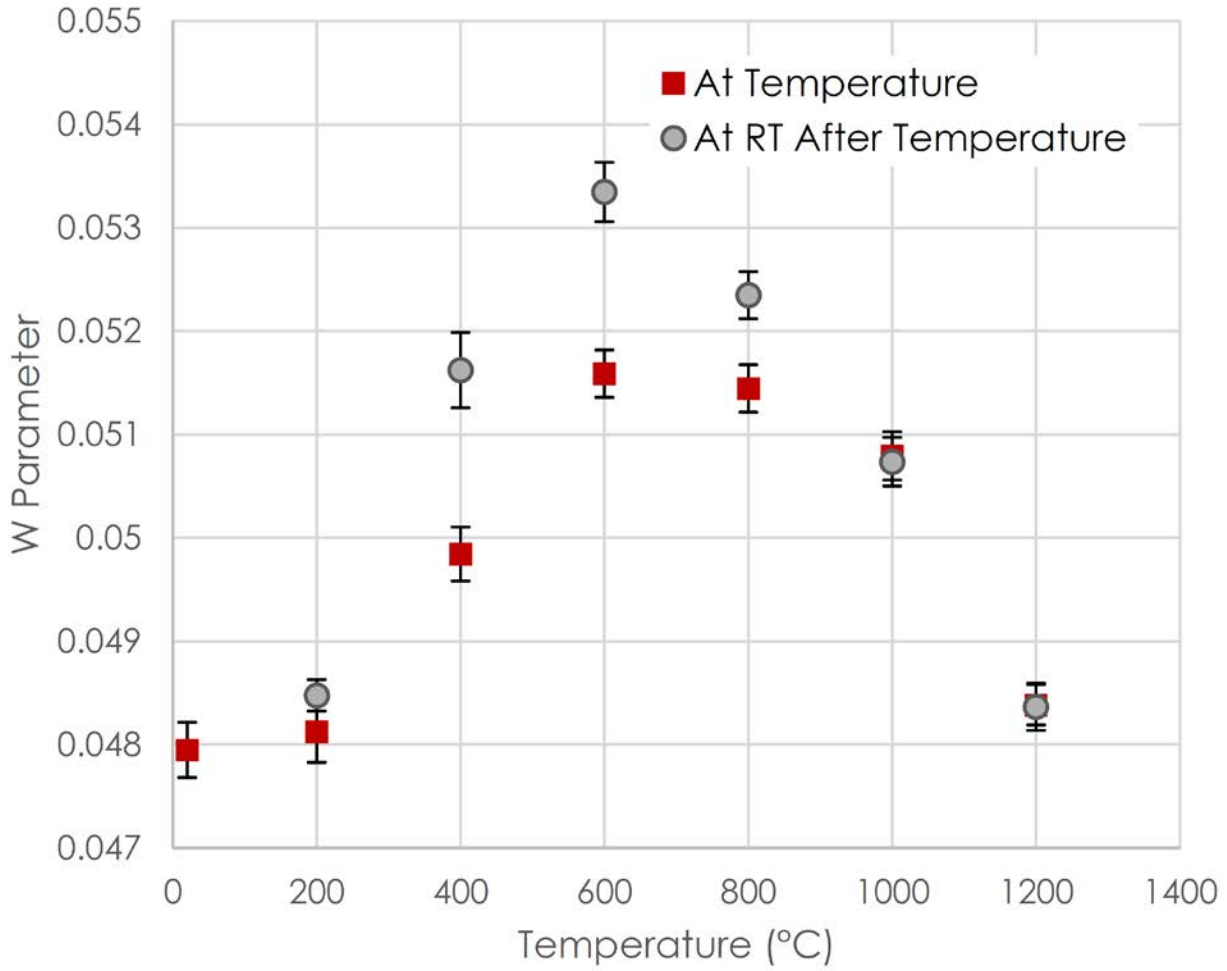
Sample	Run	τ1 (ps)	I1 (%)	τ2 (ps)	I2 (%)	τ3 (ns)	I3 (%)
Ga_2O_3 #1-#2	1	173±1	74.4±0.8	384±5	22.8±0.8	2.84±0.04	2.76±0.03
	2	171±2	73.0±0.9	374±5	24.2±0.9	2.85±0.04	2.82±0.03
	3	169±2	73.3±1.0	353±9	23.5±1.9	1.68±0.02	3.13±0.79

Positron lifetime of the Ga2O3 sample at each temperature and after cool-down from high temperature

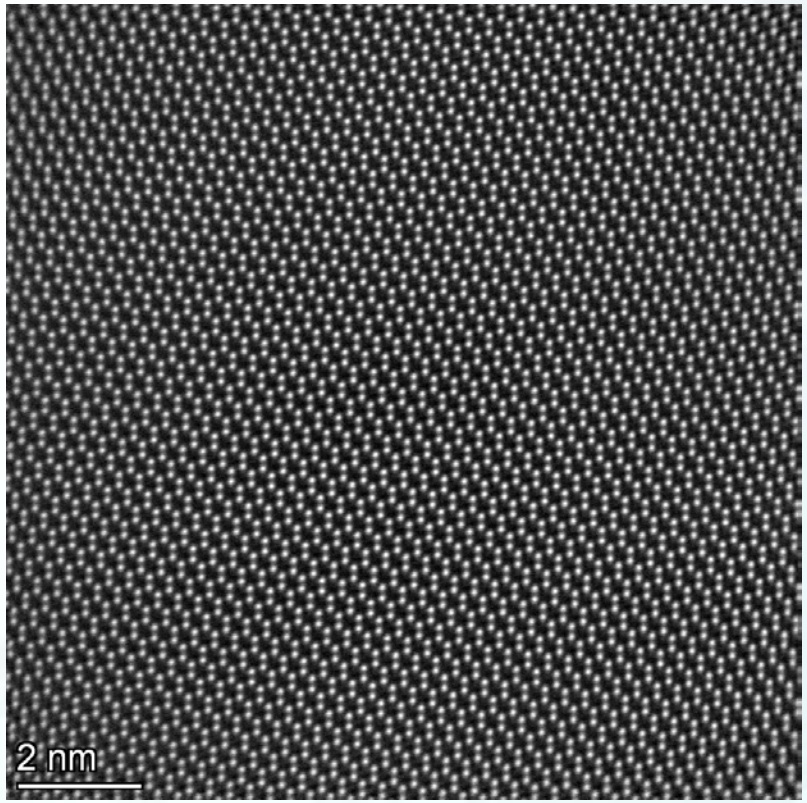


The S and W parameters of the Ga_2O_3 sample as a function of temperature

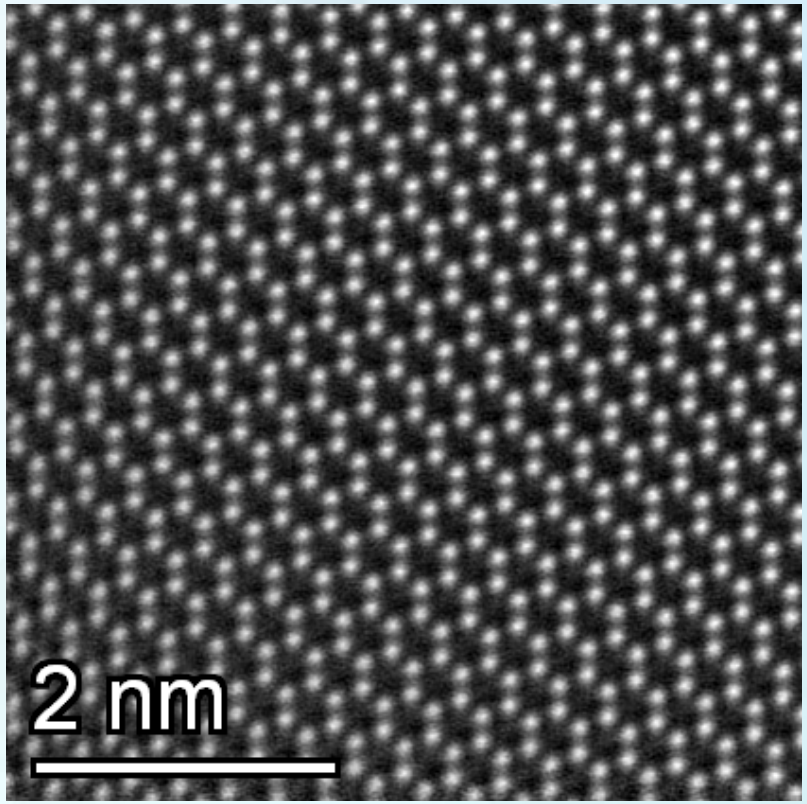




TEM Results



NSUF CINR: Ga2O3 Sensor; Spectra 300, HRSTEM image taken on 8/23/2022, unpublished.



Zoomed in of the left image at bottom-left corner.

Concluding Remarks

- All the measurements are going well and as planned.
- Experimental design for room temperature irradiation of Ga_2O_3 samples have been done.
- Positron measurements are continuing and room temperature irradiation of Ga_2O_3 crystals will start soon at PULSTAR reactor
- Systematic microstructural characterization of Ga_2O_3 crystals at CAES are continuing.
- We plan to present our results at the ANS Annual Meeting and Tech Expo.
- We are working to prepare a manuscript to summarize recent scientific discoveries for publication

Contact: Ge Yang, Tel: 919-515-5267; email: gyang9@ncsu.edu

Thank You