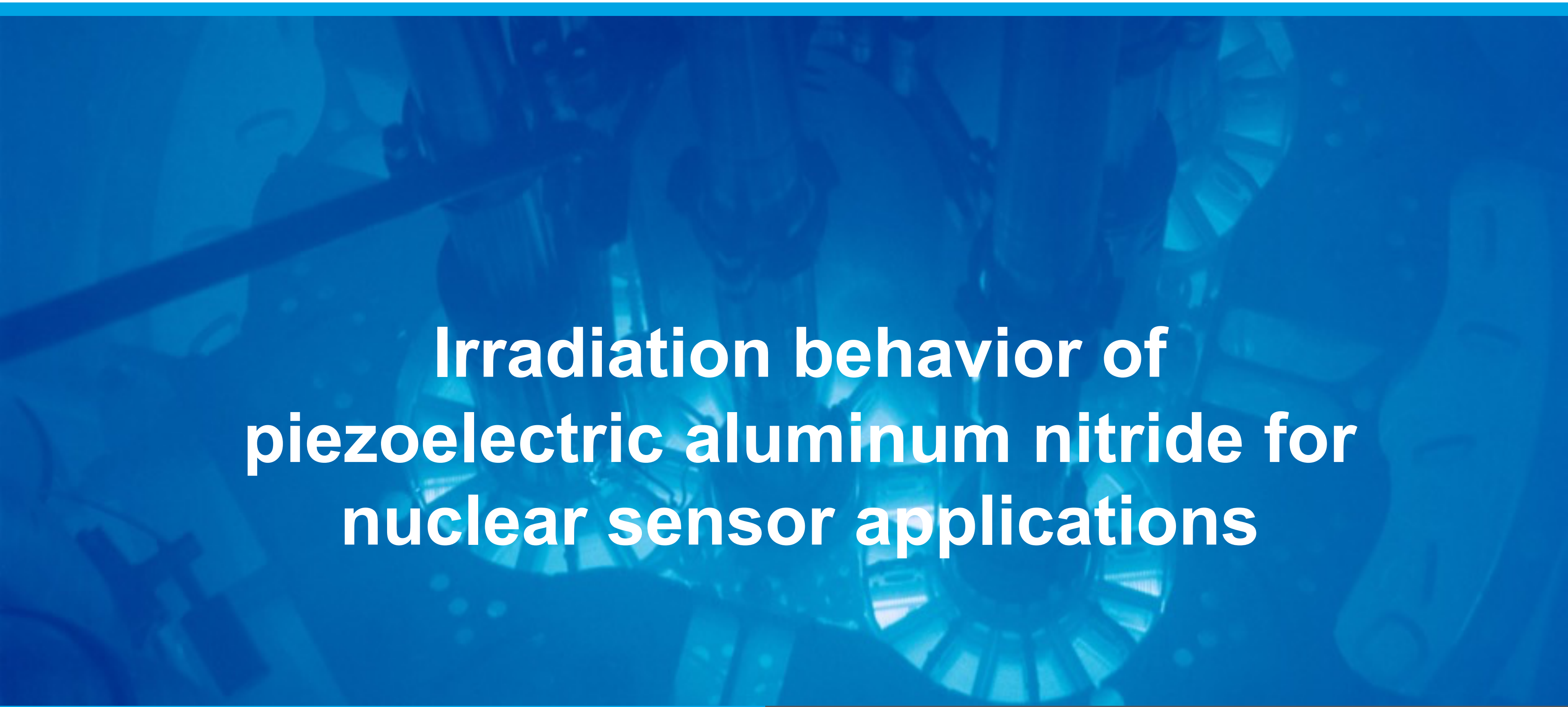


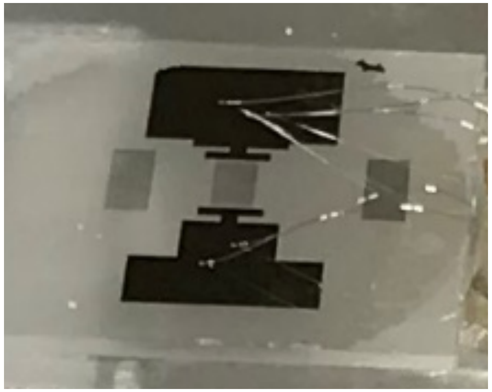
Irradiation behavior of piezoelectric aluminum nitride for nuclear sensor applications

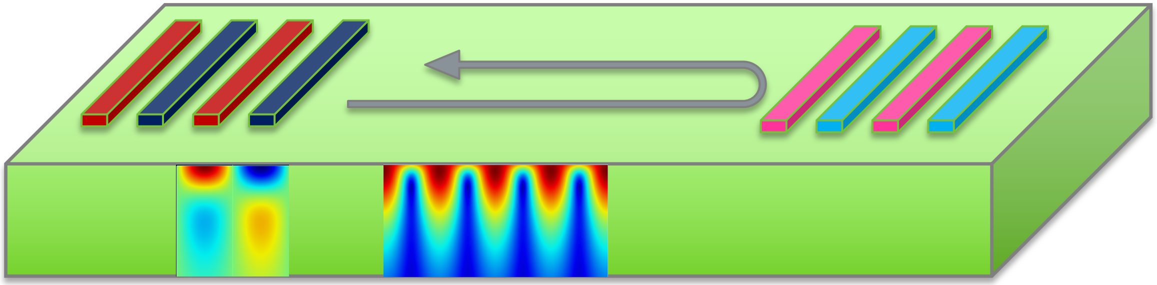
Advanced Sensors and Instrumentation
Annual Webinar

October 29, November 5,
November 12 , 2020

Marat Khafizov
The Ohio State University

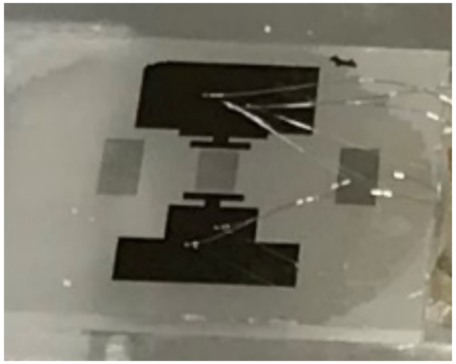
Project Overview

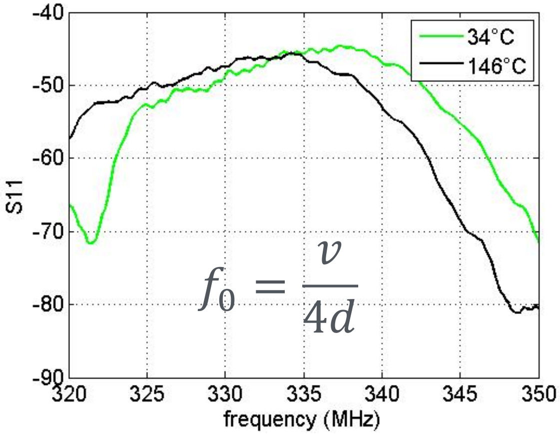




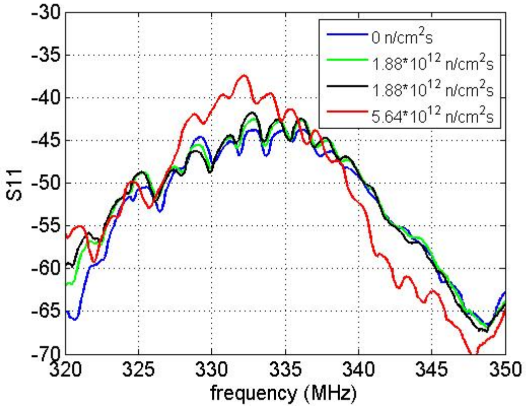
- NSUF Project Goal and Objective:
  - Understand the impact of radiation environment on behavior of piezoelectric materials
- Participants (2020):
  - Marat Khafizov (Ohio SU), Alex Chernatynskiy (Missouri S&T), Joshua Daw (Idaho NL)
- Performance period: October 2018-September 2021

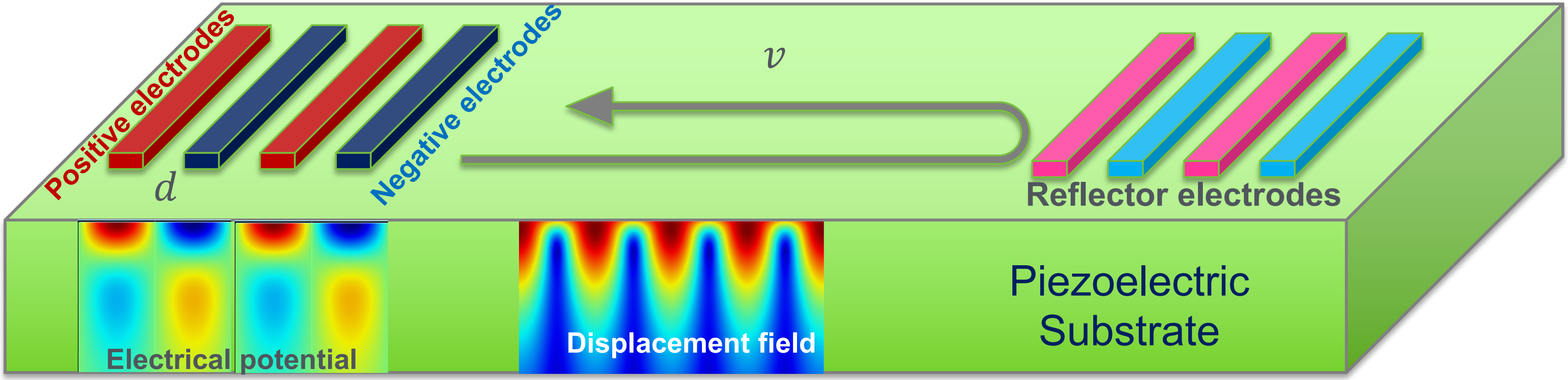
Interdigitated transducer (IDT) SAW





$$f_0 = \frac{v}{4d}$$

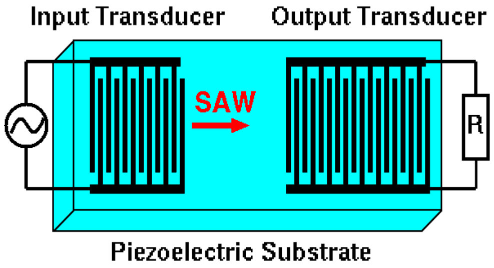




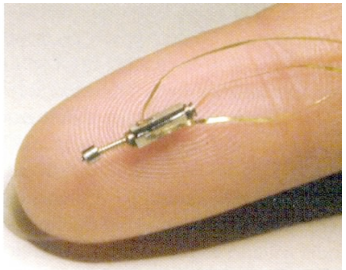
- Surface acoustic wave (SAW) are generated and detected through piezoelectric effect that couples electric field between adjacent electrodes and elastic strain
- SAW devices are sensitive to environmental conditions and used as sensors

Piezoelectric devices

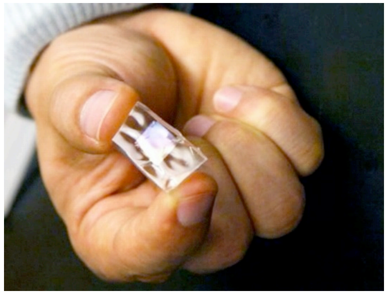
Google Image: Piezoelectric transducer



Google image for IDTs SAW



Google Image: micromotor



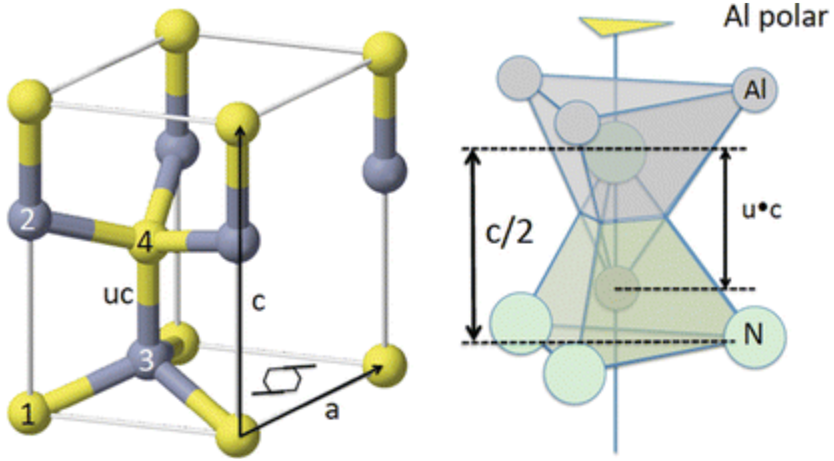
Google Image: Energy Harvester

- Engineering performance parameters of piezo-electric devices:
  - electromechanical coupling coefficient $K^2 = \frac{C_{33} d_{33}^2}{e_{33}}$
  - Resonant frequency $f_0 = \frac{v}{d}$,
    - *d* is device thickness and sound velocity is $\rho v^2 = C_{33}$
- Goal: measure impact of radiation damage on these parameters

Piezoelectric materials

$$\rho \frac{\partial^2 u_i}{\partial t^2} = C_{ijkl} \frac{\partial^2 u_k}{\partial x_l \partial x_j} + e_{kij} \frac{\partial^2 \varphi}{\partial x_k \partial x_j}$$

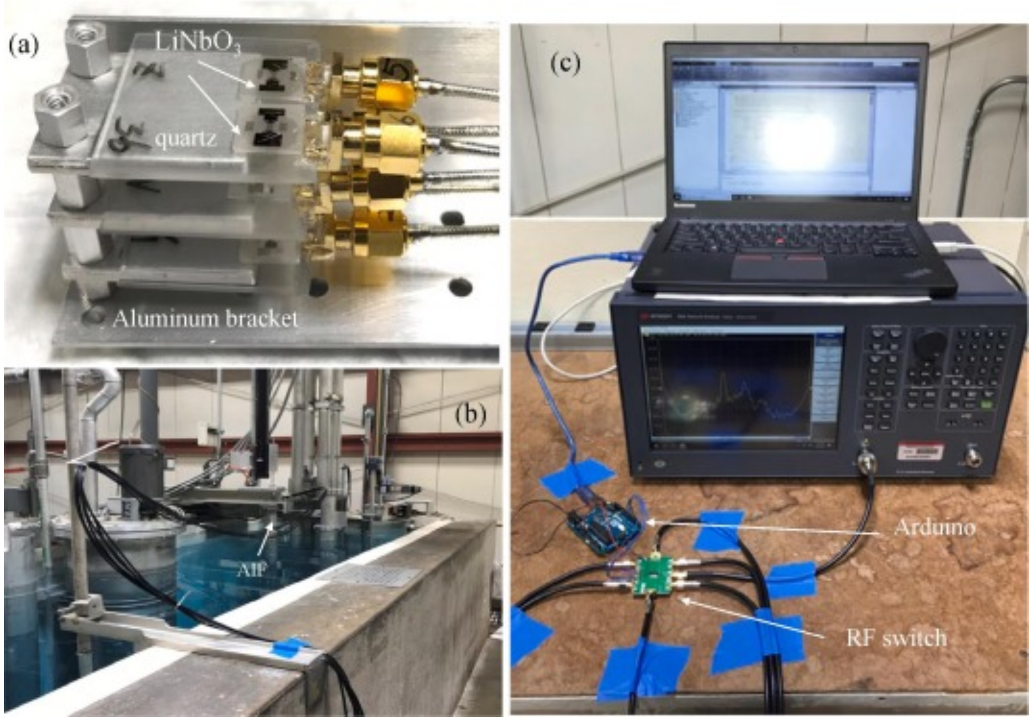
$$e_{ijk} \frac{\partial^2 u_j}{\partial x_k \partial x_i} = \varepsilon_{ij} \frac{\partial^2 \varphi}{\partial x_i \partial x_j}$$



- Response of piezoelectric devices is determined by physical properties:
  - Dielectric constants, ε_{ij} – electric field
  - Elastic constants, C_{ij} – stress and sound velocity
  - Piezoelectric constants, d_{ijk} or e_{ijk} – relates displacement and electric field
  - Density, ρ –sound velocity
- Goal: measure impact of radiation damage on these properties

Google Image: accelerometer

Neutron irradiations at OSU Research Reactor



Device characterization:

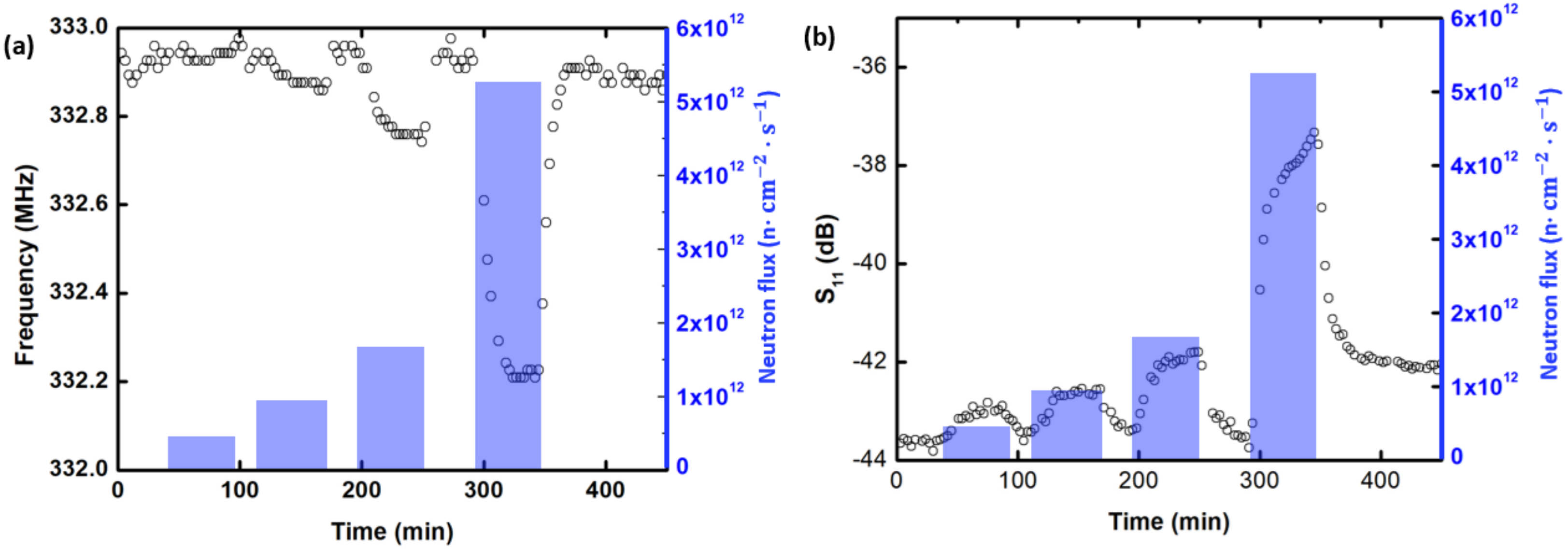
- S_{11} parameter are measured using RF network analyzer employing gating

Irradiation conditions:

- Ohio State University Research Reactor
- AIF dry tube facility
- Max total flux 4.5×10^{12} n/cm^2·s at full power (500 kW)
- Total fluence upto
  - 5.0×10^{17} n/cm^2

Sha et al., Nucl. Instrum. Meth. B **472**, 46 (2020)
Wang et al., Nucl. Instrum. Meth. B **481**, 35 (2020)

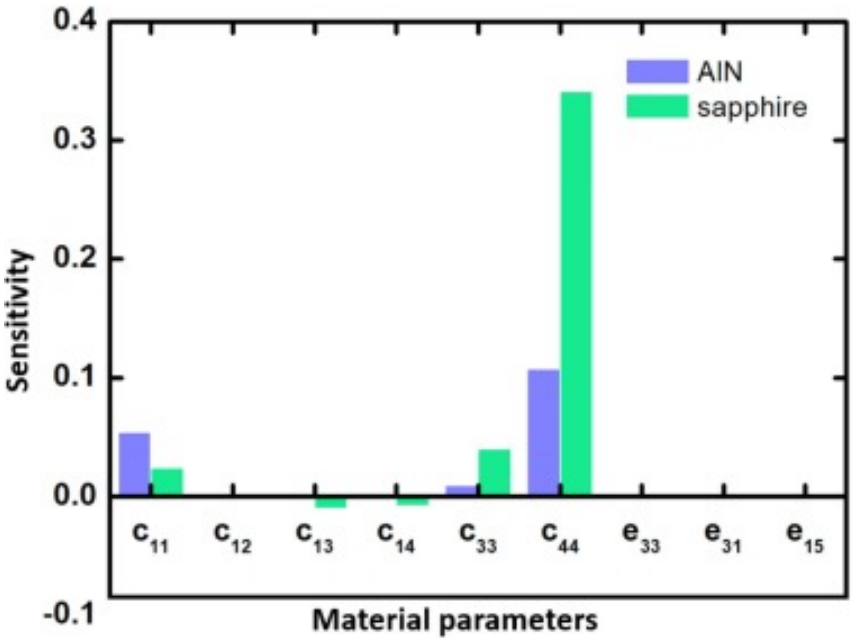
Reactor power dependent response of AlN



- Under neutron irradiation both resonant frequency and amplitude undergo gradually increasing change that saturates with time
- Changes are reversible
- Hypothesis that observed change are either a result of damage from neutrons and gamma rays or gamma heating

Wang et al., Nucl. Intrum. Meth. B **481**, 35 (2020)

Sensitivity of device to physical properties



$$\rho \frac{\partial^2 u_i}{\partial t^2} = C_{ijkl} \frac{\partial^2 u_k}{\partial x_l \partial x_j} + e_{kij} \frac{\partial^2 \varphi}{\partial x_k \partial x_j}$$

$$e_{ijk} \frac{\partial^2 u_j}{\partial x_k \partial x_i} = \varepsilon_{ij} \frac{\partial^2 \varphi}{\partial x_i \partial x_j}$$

SAW coupling coefficient: $K^2 = 2\frac{V_f - V_m}{V_f}$

SAW resonance frequency: $f_0 = 4\frac{V_f}{d}$

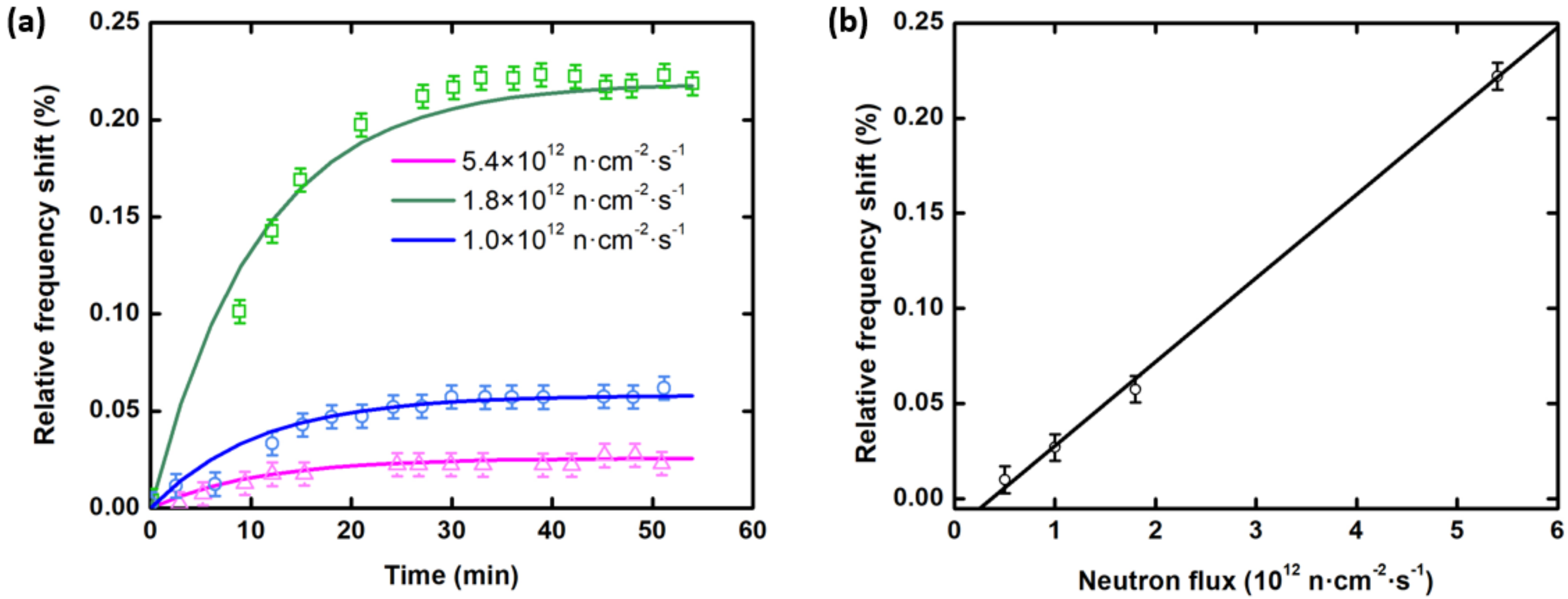
Wang et al., Nucl. Intrum. Meth. B. **481**, 35 (2020)

Deliverable and Accomplishments

- Two journal publications
  - “Impact of nuclear reactor radiation on the performance of AlN/sapphire surface acoustic wave devices”, Y. Wang, G. Sha, C. Harlow, M. Yazbeck, M. Khafizov, Nucl. Instrum. Meth. B **481**, 35 (2020)
  - “In-situ measurement of irradiation behavior in $LiNbO_3$”, G. Sha, C. Harlow, A. Chernatynskiy, J. Daw, M. Khafizov, *Nucl. Instrum. Meth. B* **472**, 46 (2020)
- 4 conference presentations
  - TMS 2020, MS&T 2020, REI 2019, OSU IMR 2019
- Enable development of piezoelectric based sensing for radiation environments
- *Marat Khafizov, Khafizov.1@osu.edu.*

Supplementary slides

AlN device transient response



- Frequency shift is attributed to changes in elastic constants
- Elastic constants decrease when lattice expands due to either thermal expansion and/or irradiation swelling
- Microstructure evolution parameters can be extracted from kinetics

Wang et al., Nucl. Intrum. Meth. B. **481**, 35 (2020)

Point defects effect on elastic constants (DFT)

1. Density Functional calculations of the elastic constants via Density Functional Perturbation Theory (VASP)

2. GGA density functional for solids (PBESol)

3. 3x3x3 supercell: defect concentration of ~2%, only neutral defects are considered here.

4. Good agreement with experiment for ideal structure (in GPa): C_{11}=411, C_{33}=389, C_{44}=125, C_{13}=99.

Presence of any defects softens C_{33}, the elastic constant to which the experiment is most sensitive.