Contract No:

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Ga_2O_3: A new class of radiation detector material

Ge Yang, Jacob Blevins
Department of Nuclear Engineering, North Carolina State University

Ralph B. James
Savannah River National Laboratory

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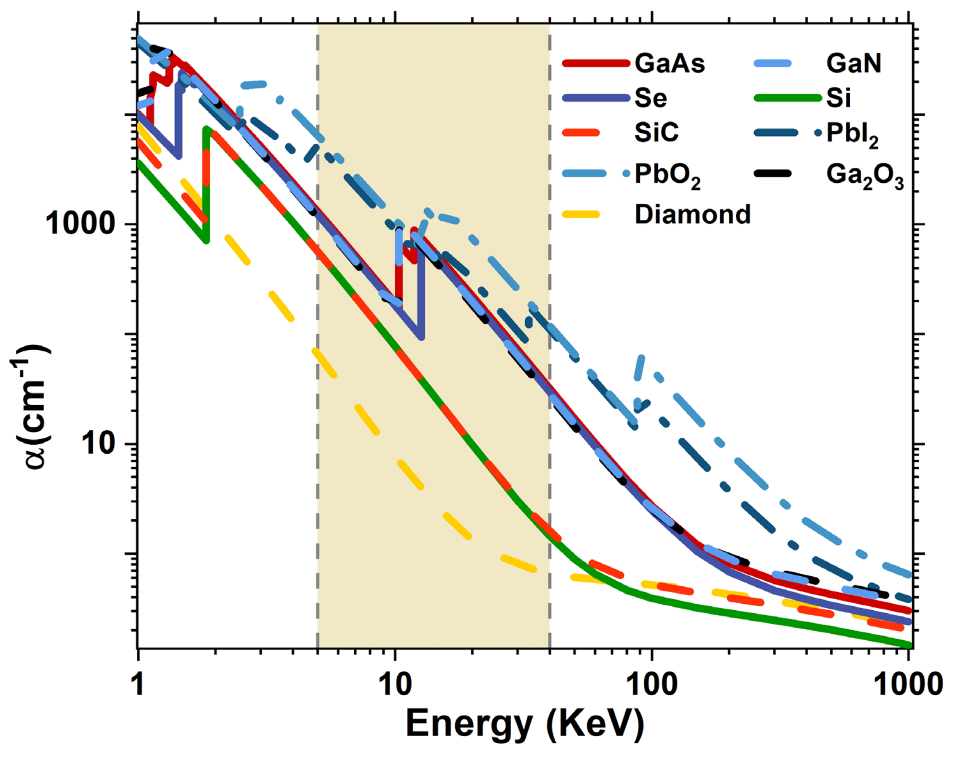
Outline

- Motivation
- Introduction
- Optical and electrical characteristics
- Detector tests
- Summary

Motivation – A strong need for (U)WBG detectors

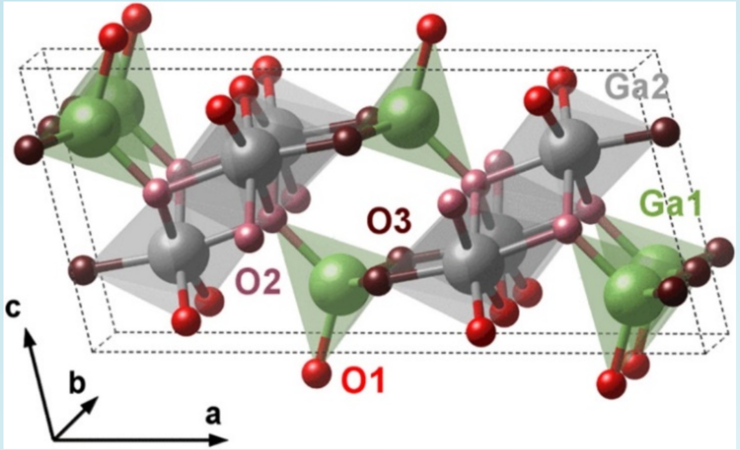
- Radiation detectors are key components for numerous products and applications.
- Elementary detectors have many limitations related to their intrinsic material properties.
  - Harsh environment.
  - Cooling and compromised density.
  - High Voltage operation.
- Wide and ultrawide bandgap semiconductors are much less susceptible to displacement damage by particle irradiation than elemental and narrow bandgap compound semiconductors.

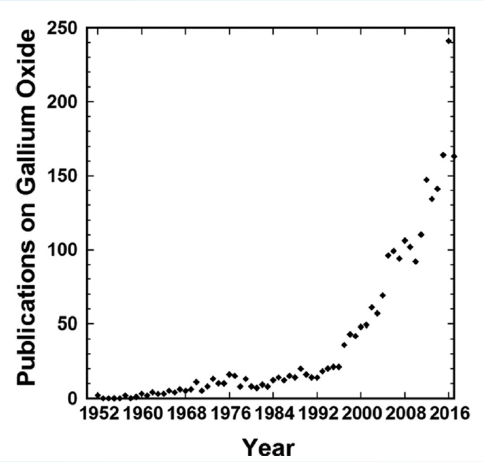


Linear attenuation coefficient of Ga_2O_3 (6.44 g/cm^3) compared to several current and candidate X-ray sensing material.

Motivation – Ga_2O_3 for radiation detection

- **β-Ga_2O_3 has many material advantages**
  - Thermal stability (M. P. > 1800 ^{o}C)
  - The least mature and 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
  - Cost-effective large-scale manufacturability
- **β-Ga_2O_3 holds high promise for fitting many radiation detection application needs not met by currently used materials**
  - Harsh environment applicability
  - Versatile and cost-effective synthesis and fabrication
  - High detector performance

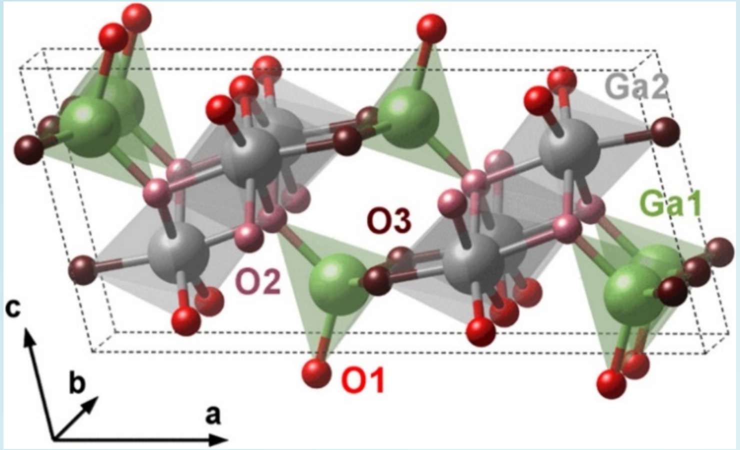


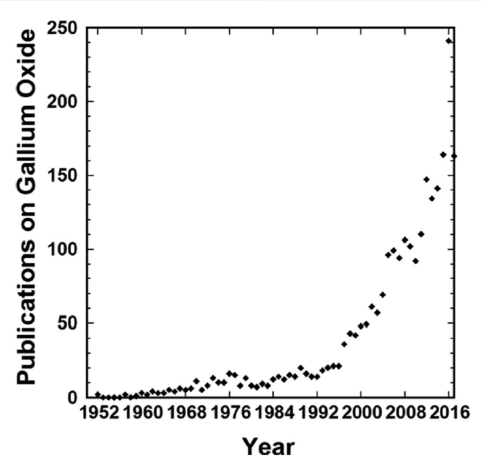


S. J. Pearton et al., "A review of Ga_2O_3 materials, processing, and devices," Appl. Phys. Rev., vol. 5, no. 1, p. 011301, Jan. 2018.

Ga_2O_3 properties

- Control of conductivity through doping and mitigation of trap states is key to realizing device applications.
- Mg, N, and Fe compensate n-type conductivity.
- Si, Sn, Ge, F and Cl are n-type dopants.
- Atmosphere dependent post-growth annealing can be used to control conductivity as well (annealing in oxygen reduces the free electron density, while annealing in nitrogen or hydrogen leads to an increase in n-type conductivity).





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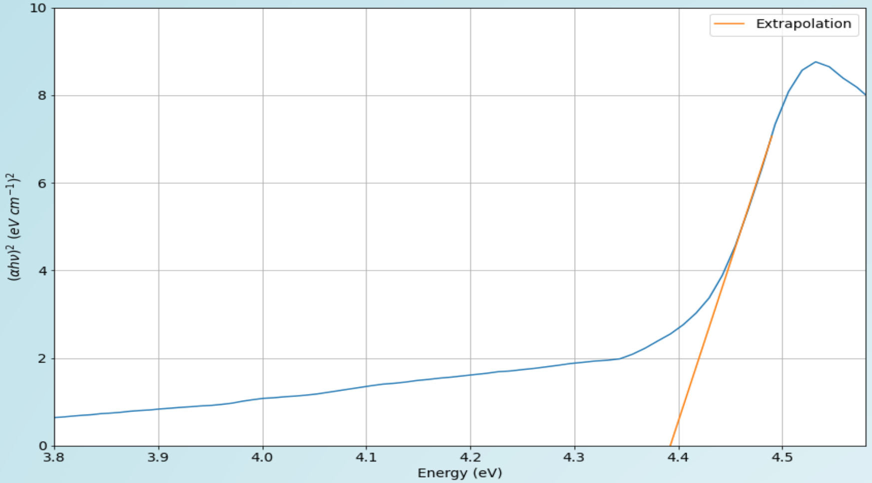
Different Ga_2O_3 samples were used in our study

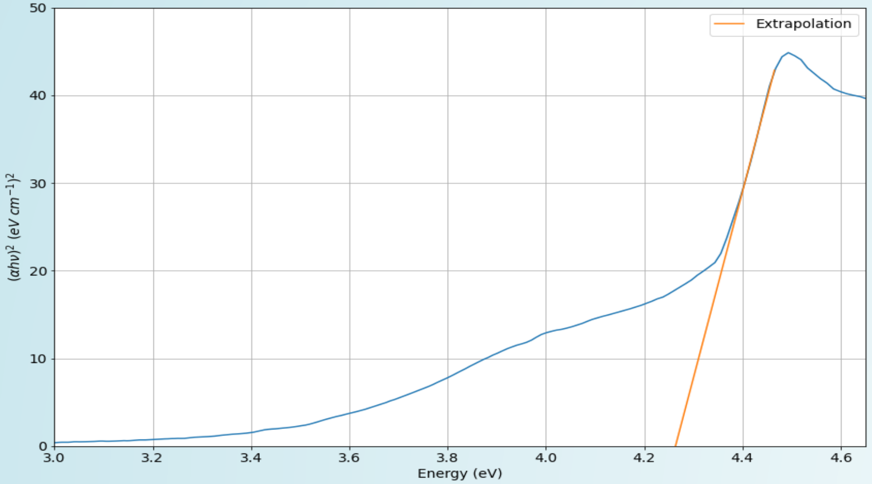
- Ga_2O_3 grown by the floating zone (FZ) method and the edge-defined film-fed growth (EFG) method
- Undoped Ga_2O_3, Fe-doped Ga_2O_3 and Mg-doped Ga_2O_3

Bandgap Analysis: Mg and Fe doping in FZ samples

- **Tauc plots were created from transmission data using a Deuterium-Halogen light source**
- **The Mg-doped sample has an estimated indirect bandgap of 4.39 eV**
- **The Fe-doped sample has an estimated indirect bandgap of 4.26 eV**
- **These band gaps are on the lower end of reported values**
- **Traditional bandgap values of undoped Ga_2O_3 range near 4.8-4.9 eV**
- **One possible explanation is high levels of dopants/impurities**



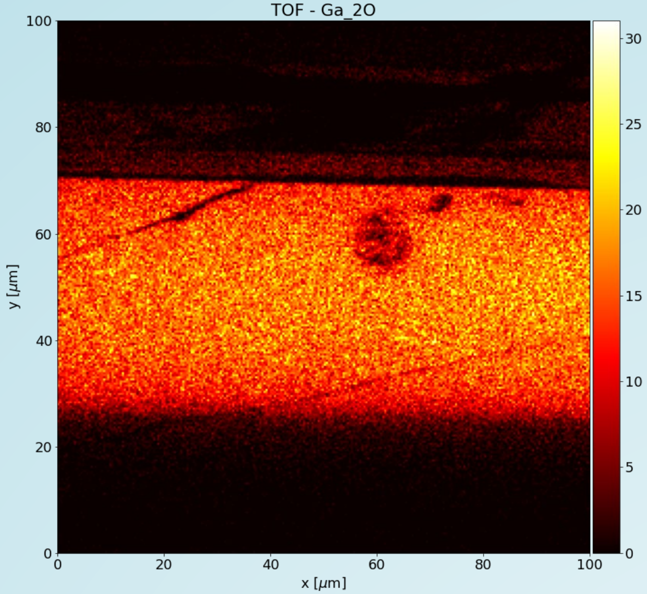
Mg-Doped

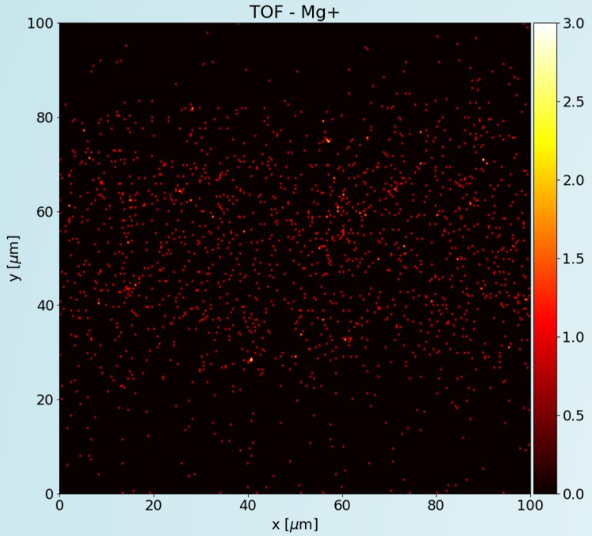


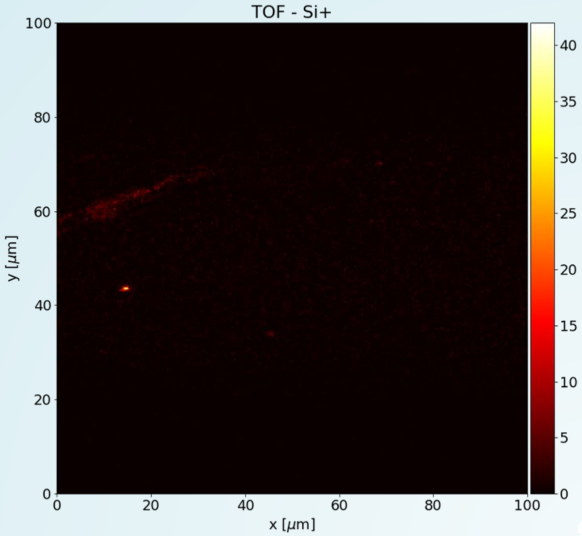
Fe-Doped

TOF-SIMS: Mg-Doping

- Time of flight - secondary ion mass spectrometry (TOF-SIMS) can be used to observe dopant/impurity distributions within the sample
- The distribution of Mg was uniform across the sampling area
- Direct comparison of dopant/impurity counts from the spectrometer are not appropriate due to different secondary ion potentials
- The presence of Si was also observed, which could be due to the unintensional doping from the raw materials and processing steps





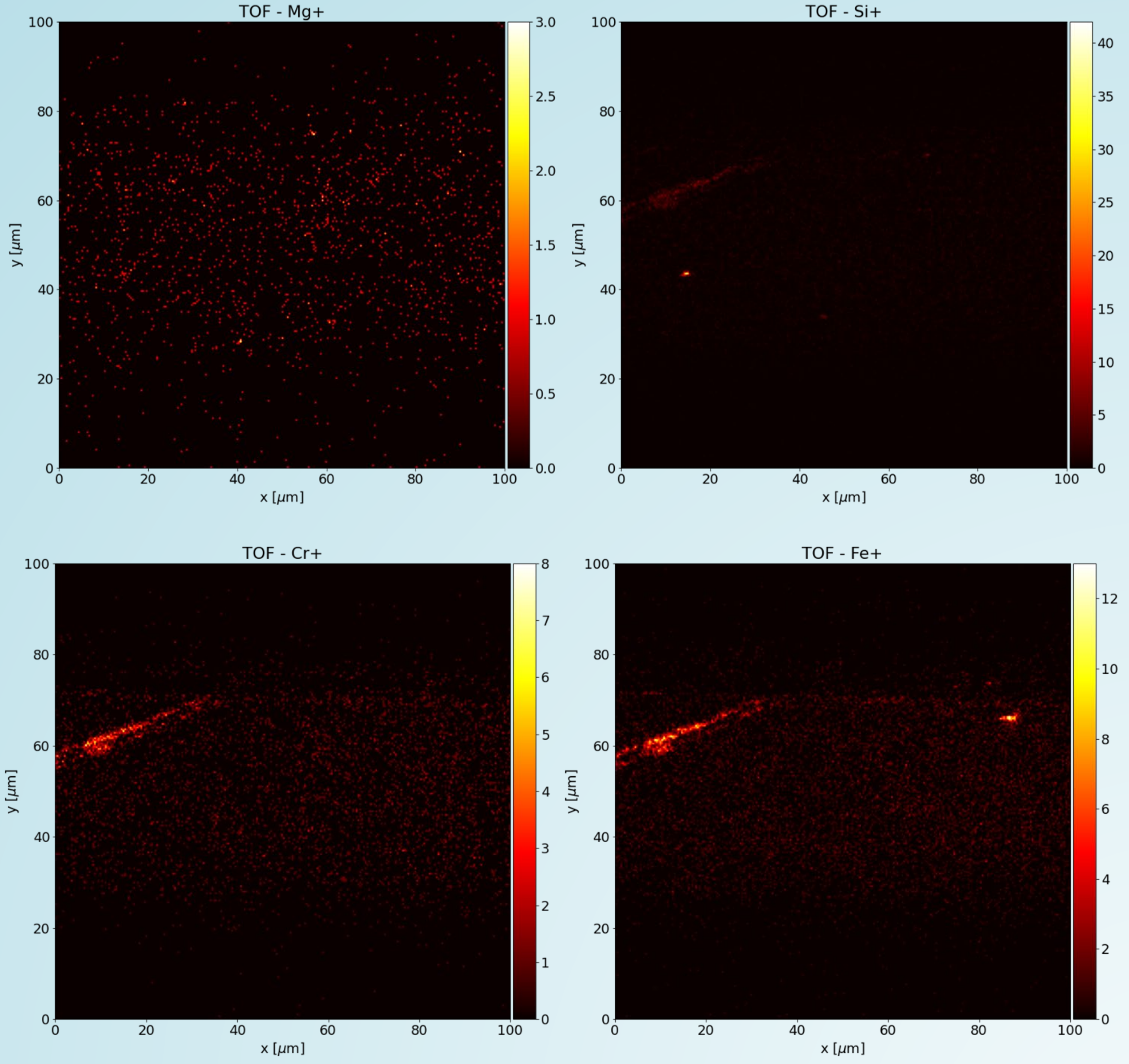


TOF-SIMS: Mg-Doping

- Interestingly there appeared to be higher levels of Cr and Fe at some localized areas

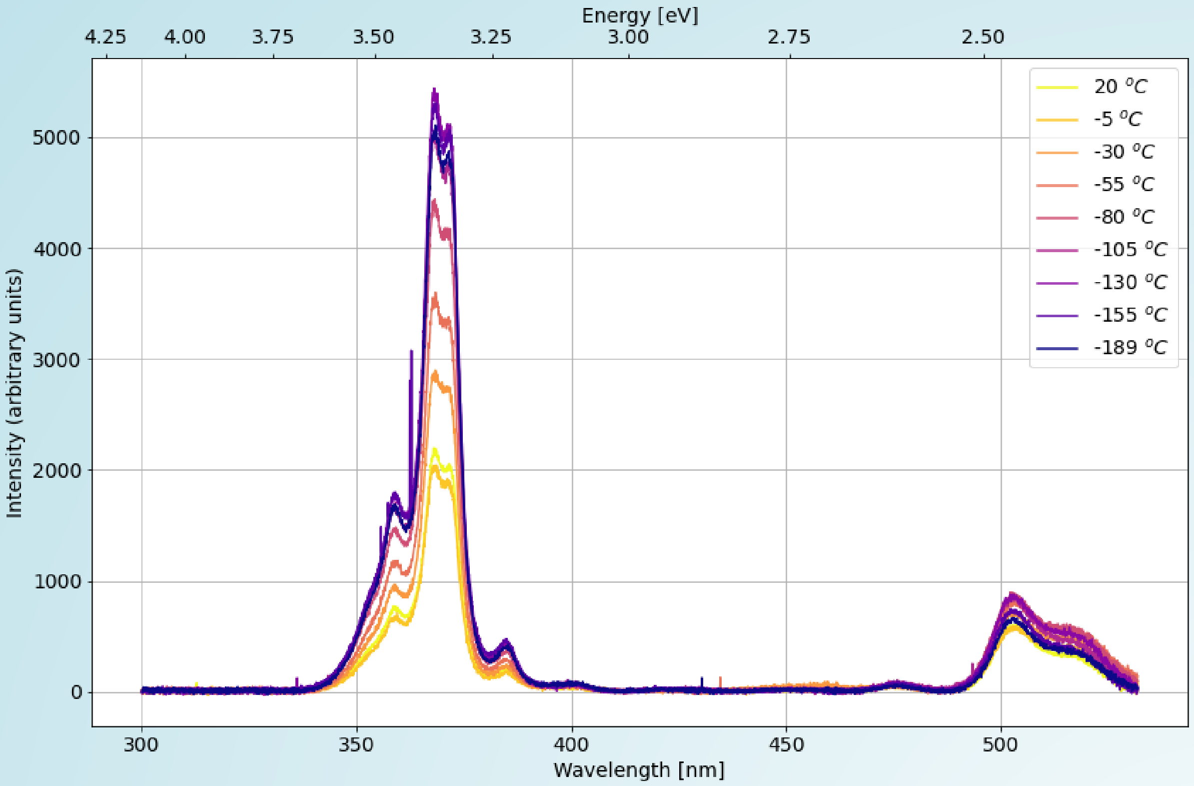
- Note the spatial distributions are different at different locations - especially Si has a hot concentration spot

- These impurity/dopants are important to understand as they could pertain to the cathodoluminescence (CL) results and possible emission mechanisms



Cathodoluminescence (CL): Mg-Doping

- Beam: 944 pA at 15 keV
- Ga_2O_3 traditionally has a UV blue-green luminescence.
- The origin of the green luminescence ~ 550 nm is not completely clear as many studies report it in undoped samples and others report it only arises through intentional doping with Sn for example.
- Our sample did not emit the traditional broad blue luminescence but did yield green luminescence
- This blue luminescence is believed to result from the recombination from a donor level oxygen vacancy to an acceptor level Schottky defect or gallium vacancy
- Two possible explanations:
  - Another emission mechanism has quenched the blue luminescence.
  - FZ yielded extremely low levels of oxygen vacancies

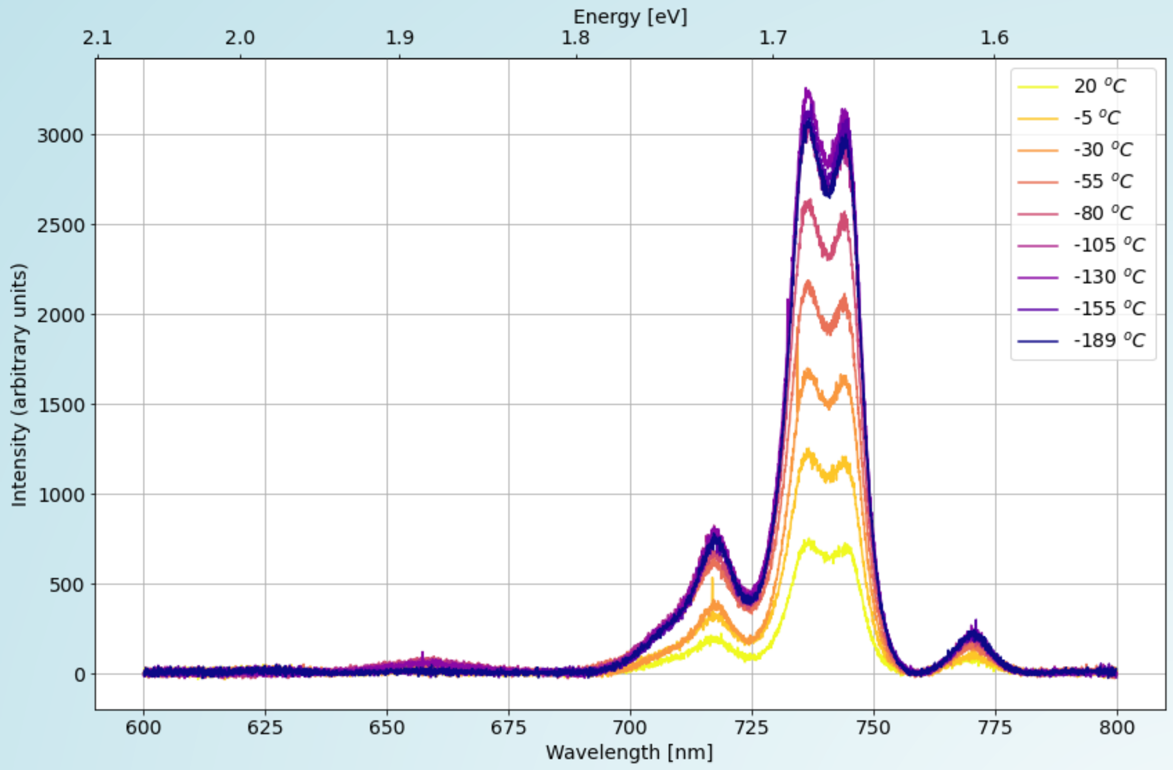


Cathodoluminescence (CL): Mg-Doping

- **Undoped Ga_2O_3 does not emit luminescence in the 600-800 nm range. Thus, this should be dopant/impurity driven.**

- **Similar to the higher energy emissions, all emission peaks increase in intensity down to near -130 ^{o}C then drop only slightly in intensity with further decreases in temperature.**

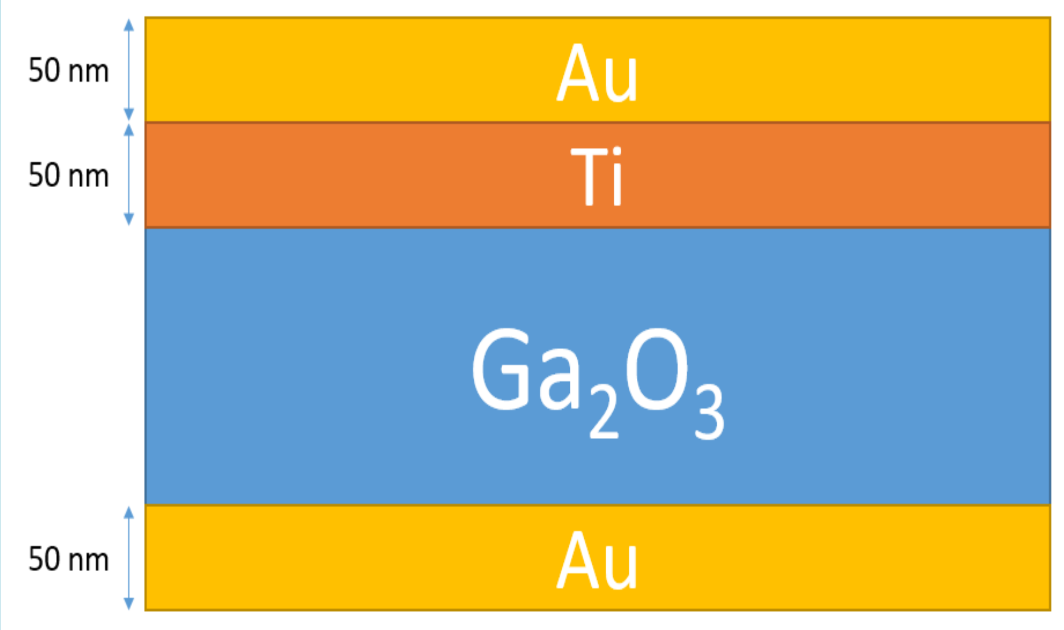
- **As in the previous figure, every peak increases in intensity to near -130 ^{o}C.**



Electrode Deposition

- A vertical sandwich electrode configuration was used for both samples.
- 50 nm for each layer: Au/Ti - Ga_2O_3 - Au
- Based on previous works and the work function of Au, it can produce a Schottky contact with Ga_2O_3.
- To enhance the electrode contacts, a rapid anneal at 400 ^oC for 1 minute was performed.
- Short annealing times are required as the Ti electrode tends to create a TiO_2 layer for longer anneals, which increases the series resistance.

Vertical Electrode Structure



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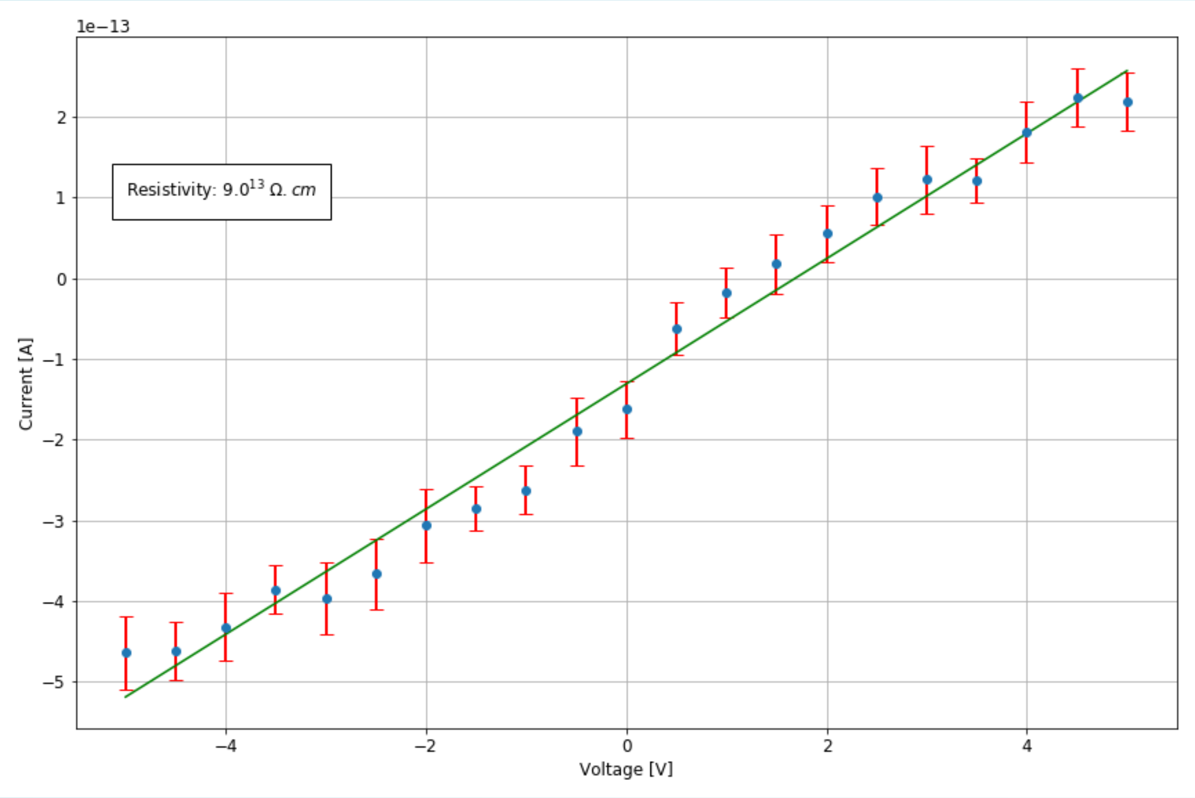
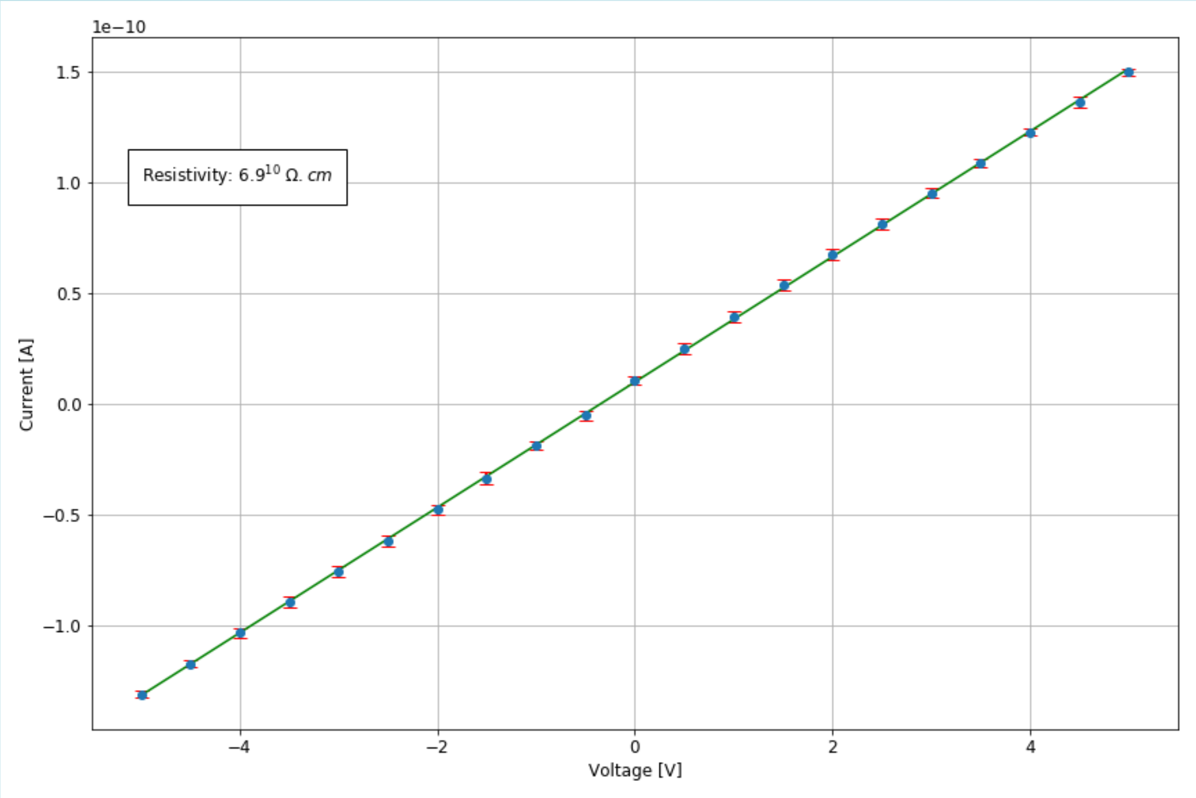
I-V Characteristics: Mg Doping

- **Although the Au electrode was expected to create a Schottky diode, the I-V curve still showed some ohmic behavior.**
- **The Mg doping successfully increased the resistivity far above that of typical undoped samples.**
- **The resistivity at near 10^{14} Ω.cm allows for the potential of highly sensitive and low-noise radiation detection.**
- **The I-V curve linearity extended up to 1000 V (system limits).**



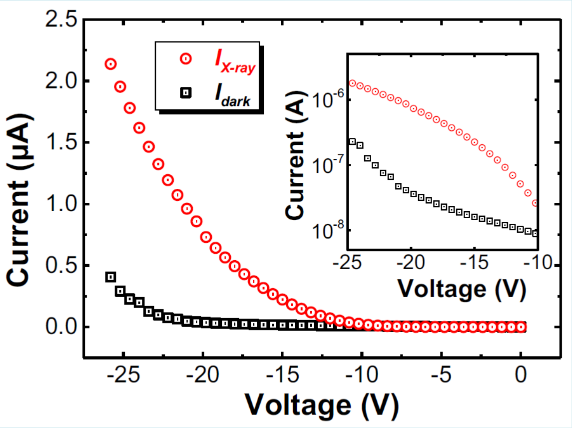
I-V Characteristics: Fe Doping

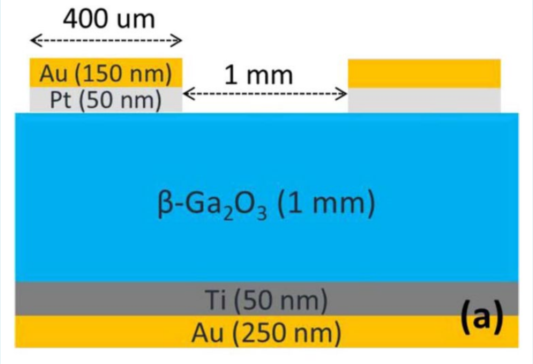
- Again, the Au electrode did not create a Schottky diode, but the I-V curve showed ohmic behavior.
- Resistivity: 7×10^{10} Ω.cm
- The resistivity is far lower than that of the Mg-doped sample.
- This could be a result of the large amount of unintentional Fe in the Mg-doped sample.
- The I-V curve linearity extended up to 1000 V (system limits).

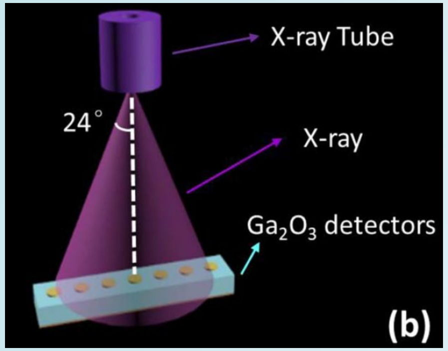


X-ray sensors based on β-Ga_2O_3

- One previous study published in 2018-2019
  - Annealed at 1500 ^{o}C in an air atmosphere for 48 hours.
  - Double-side chemical mechanical polishing (CMP).
- Response linearity was demonstrated with no saturation effect.
- High photo-to-dark current ratio exceeding 800 at –15 V.
- When biased at 0V, the detector showed perfect photovoltaic characteristics, demonstrating the great potential of using β-Ga_2O_3 SBDs as passive X-ray detectors or X-ray photocells.







(100) undoped β-Ga2O3 EFG based x-ray sensors.

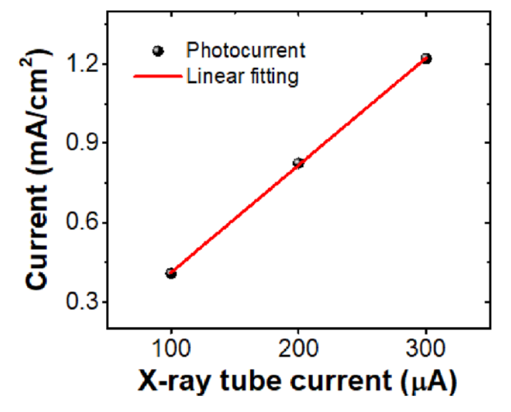
X. Lu et al., "X-ray Detection Performance of Vertical Schottky Photodiodes Based on a Bulk β-Ga_2O_3 Substrate Grown by an EFG Method," ECS J. Solid State Sci. Technol., vol. 8, no. 7, pp. Q3046–Q3049, 2019.

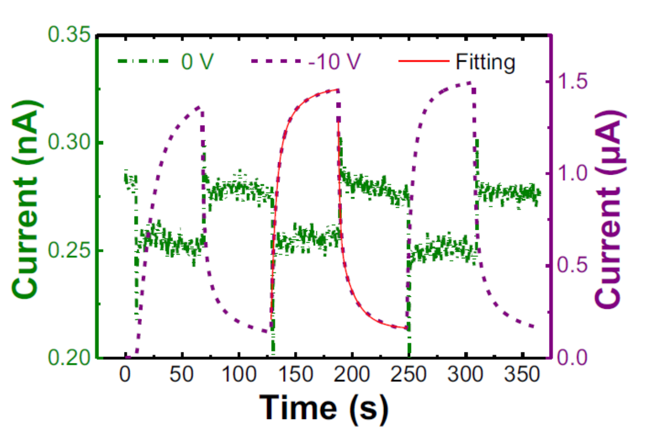
X-ray sensors based on β-Ga_2O_3

- Two different time constants are obtained for the photocurrent rising process (τ_{r1} = 13.8 *s* and τ_{r2} = 1.4 *s*), while during the photocurrent decaying process the two time-constants are τ_{d1} = 17.1 *s* and τ_{d2} = 4.0 *s*.

- The fast response of an unbiased SBD detector corresponds to a photovoltaic mechanism, where the photo-generated carriers in the space-charge region are swept out rapidly by the build-in electric filed.

(100) undoped β-Ga_2O_3 EFG based X-ray sensors. (Lu, 2018)





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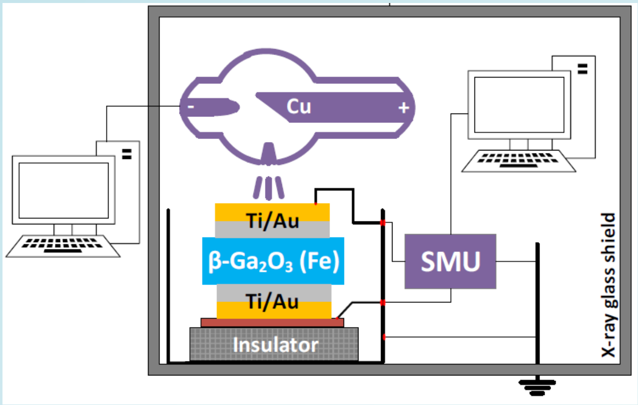
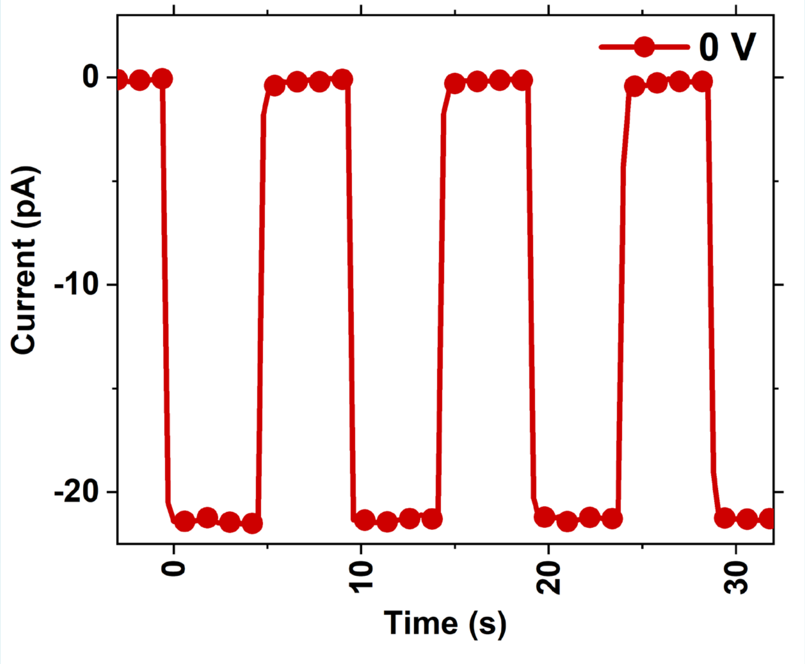
XRIC Characterization of EFG β-Ga_2O_3

- Zero Voltage mode (Passive operation) (45 KV, 40 mA)
  - X-ray induced current reaching -21 pA
  - Dark transient current of -0.15 (+/-0.05) pA
  - SNR = 139
  - No experimental lag

$$SNR = \frac{I_{x-ray\ induced} - I_{dark}}{I_{dark}}$$



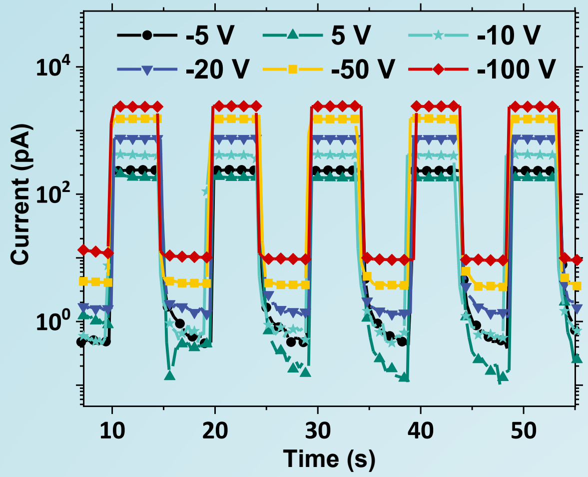


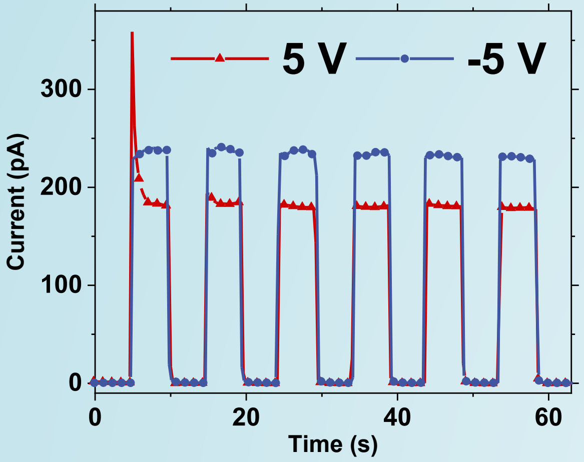
XRIC Characterization

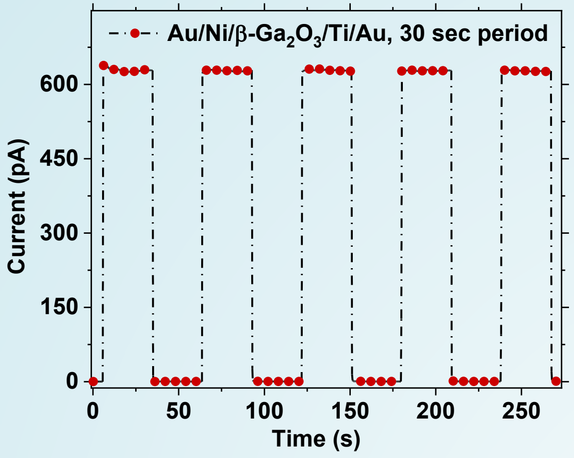
- SNR for operating voltages between -5 V and -50 V stays above 800 and decreases for the higher applied voltages.

- SNR stays above 1000 for applied voltages between -5 V and -20 V, and it is further optimized at -5 V exceeding 1200.

- μτ factor calculated from single carrier Hecht model treatment was 2.28x10^{-5} cm^2/V
    - 45.6 μm carrier drift length for 10 V.
    - 456 μm carrier drift length for 100 V.







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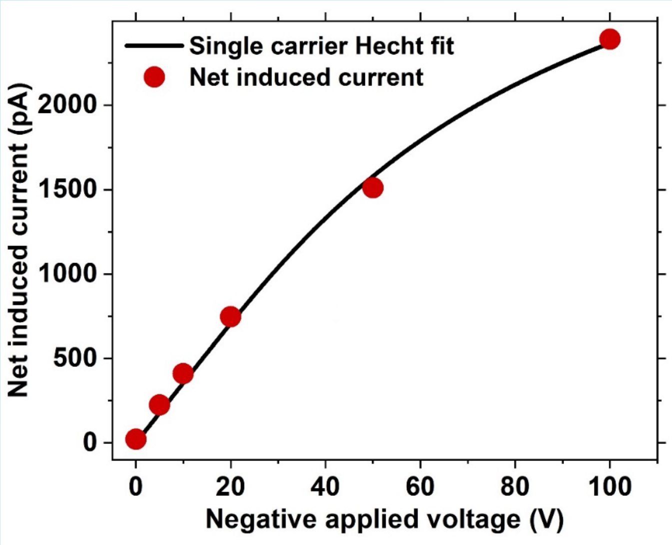
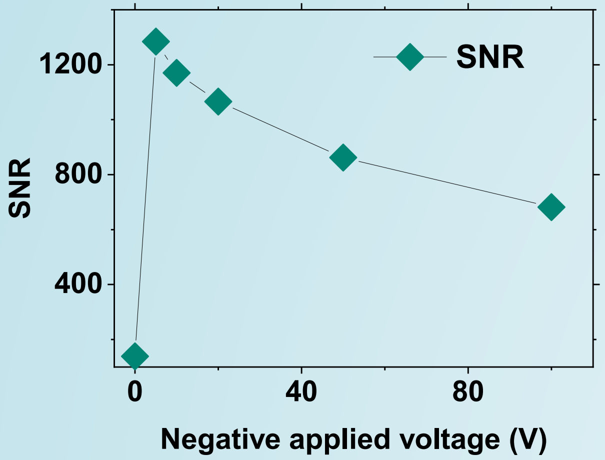
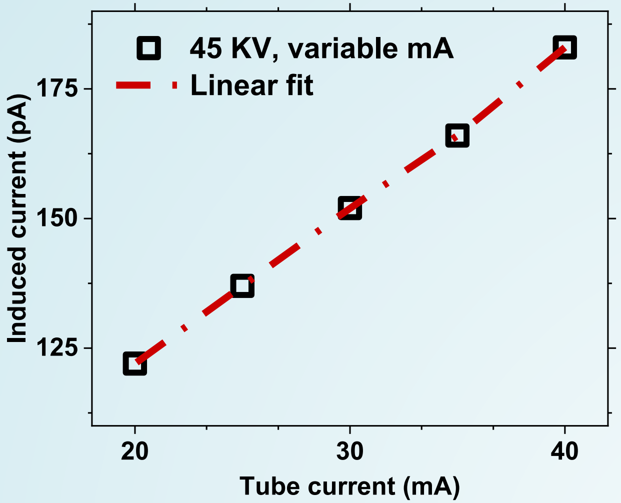
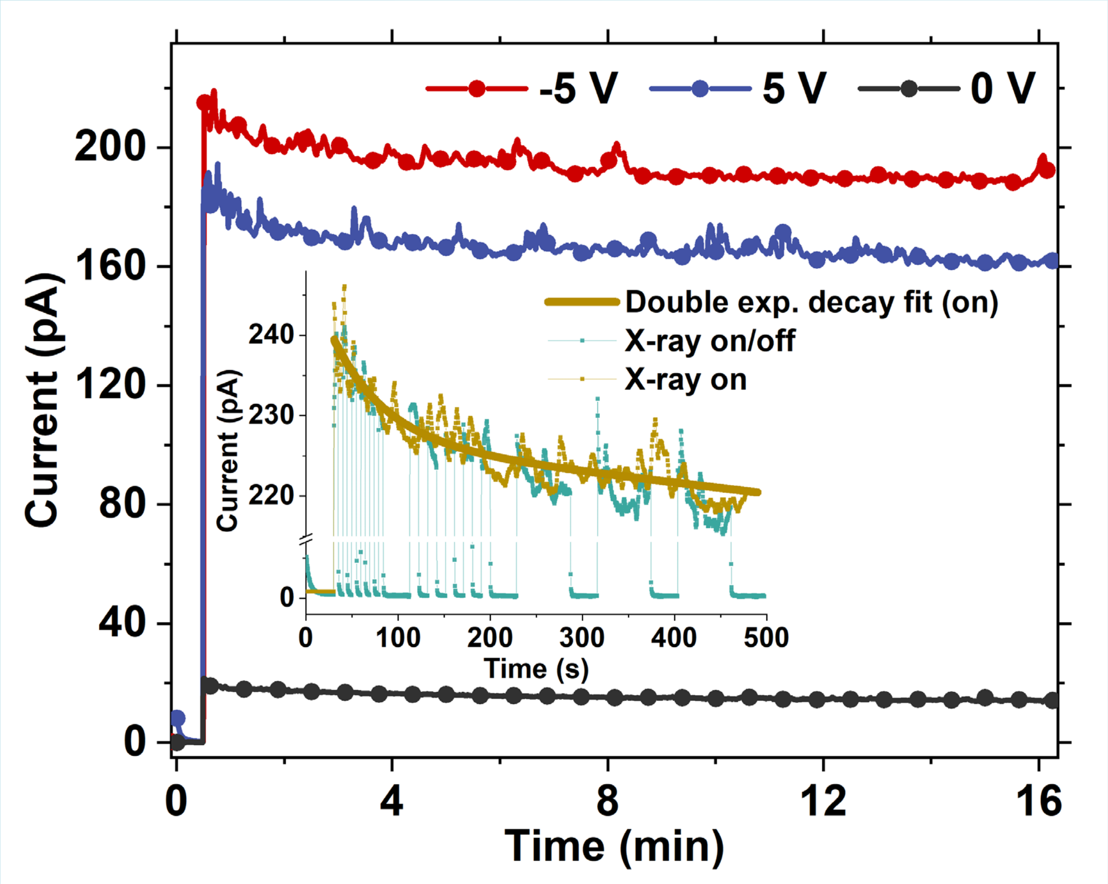






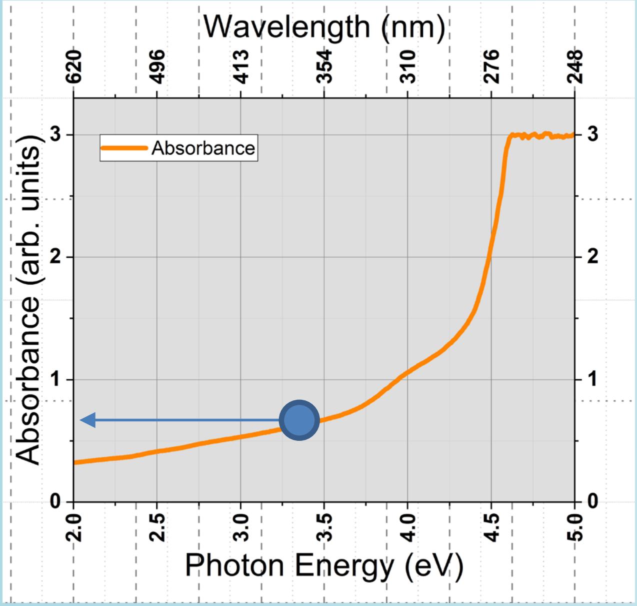
XRIC Characterization

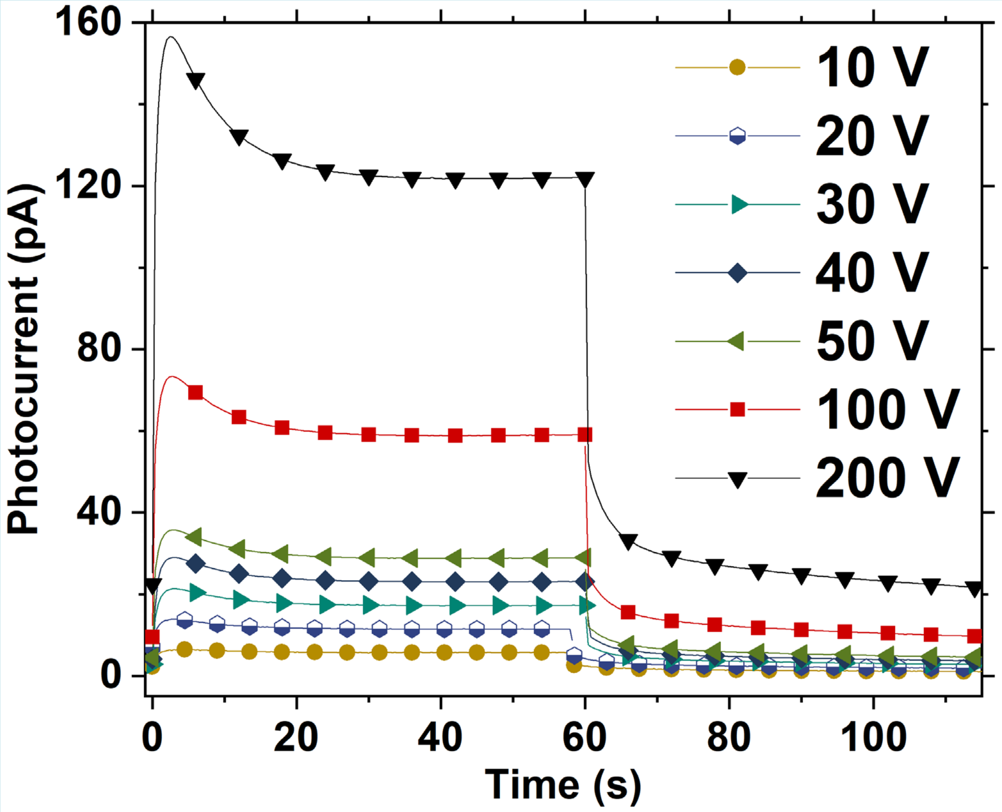
- Highly stable XRIC even at very low operating voltages (5,-5,0 V)
- Small exponential decay within the first minute that stabilizes after that
  - $\tau_1 = 57.7\ sec$ and $\tau_2 > 10^6\ sec$, stability
  - Less than 10% decrease in the first minute.
- Operation status independent (for the ON/OFF frequency used)
  - Indicating ion migration and charge accumulation.
  - Slight polarization effect.



UVIC Characterization

- Sub-band gap excitement with 365 nm LED (3.4 eV) was used (band gap of β-Ga_2O_3(Fe) is 4.45 eV)
- 10%-90% rise/fall time improved from 2 sec/16 sec at 5 V to 1 sec/10 sec at 200 V





Summary

- Ga_2O_3 has been explored as a new radiation detector material.
- CL spectra illustrated the well-known UV emissions but the absence of a broad blue emission. The green and red emissions are believed to be related to dopants/impurities.
- TOF-SIMS showed that Mg and Fe, which could act as acceptors, were both evident in the Mg-doped sample.
- The behaviors of high SNR were investigated under three operation modes for X-ray detection.
- We observed high linearity between X-ray induced photocurrent and X-ray tube current.
- The exciting timing performance of β-Ga_2O_3(Fe) detectors was demonstrated.
- Our results show that Ga_2O_3 has great potential as a new radiation detector material with excellent temporal response for a wide range of applications.

Acknowledgement

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Thanks for your attention!