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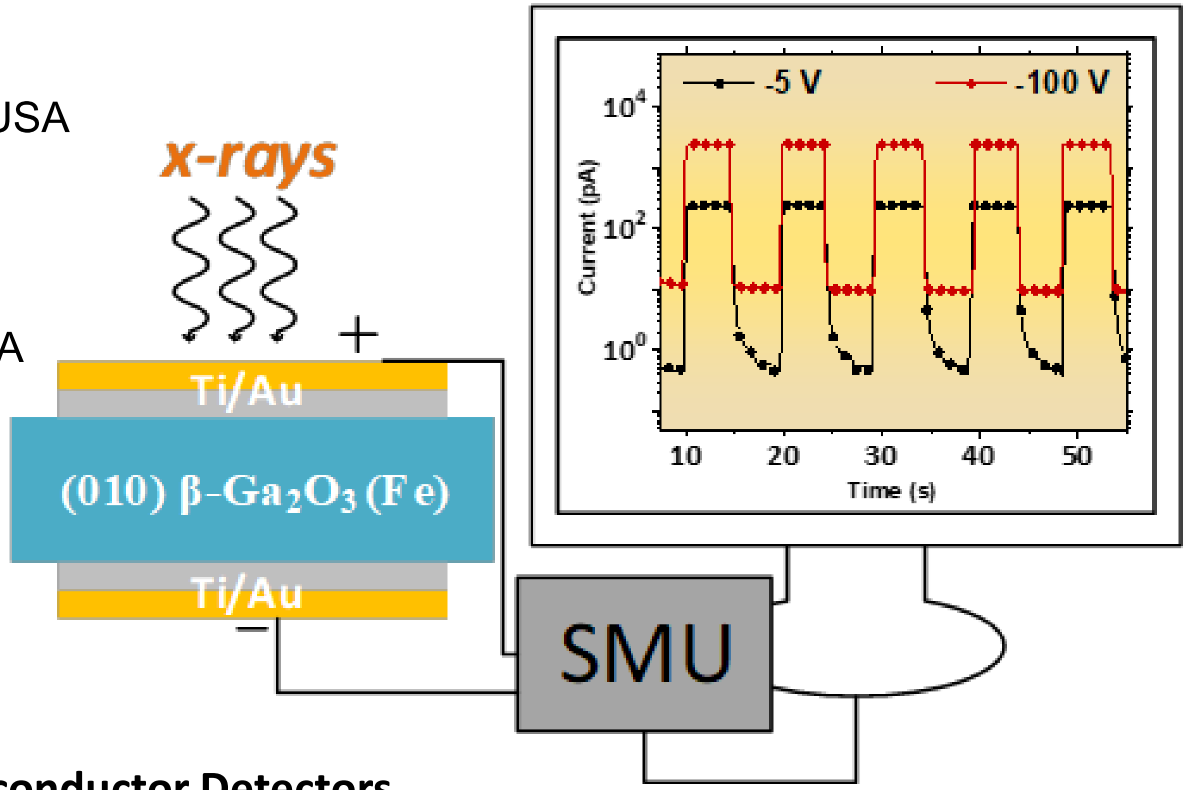
β-Ga_2O_3 for Next Generation X-ray Detectors

Ibrahim Hany, Ge Yang*

North Carolina State University, Raleigh, NC, 27695-7909, USA
(*Email: gyang9@ncsu.edu)

Ralph B. James

Savannah River National Laboratory, Aiken, SC, 29808, USA



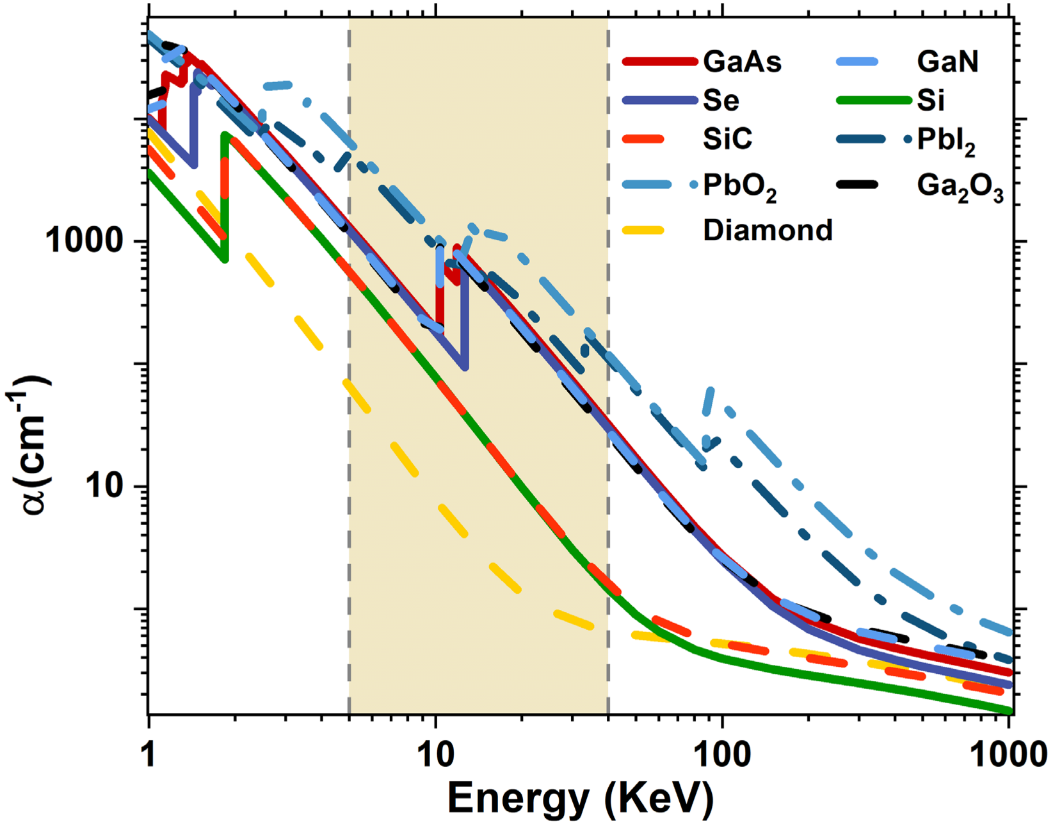
2020 IEEE NSS & MIC
27th International Symposium on Room-Temperature Semiconductor Detectors

Outline

I. Motivation
II. Introduction
III. Optical and electrical characteristics of β-Ga_2O_3 (Fe)
IV. X-ray Induced Current (XRIC) Characterization
V. Temperature-dependent Cathodoluminescence (CL) for β-Ga_2O_3 (Fe)
VI. Summary

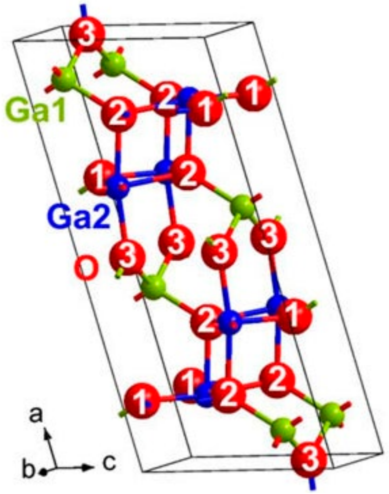
I. Motivation – the need for (U)WBG detectors

- 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.



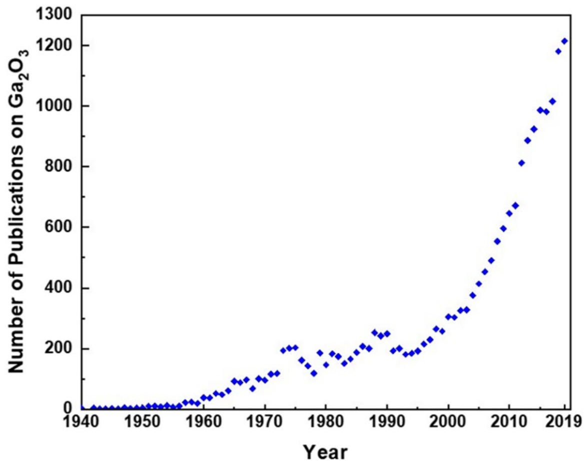
I. Hany et al., "Fast X-ray detectors based on bulk β-Ga_2O_3 (Fe)," J. Mater. Sci. 55, 9461-9469, 2020.

I. 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)
  - Control of n-type conductivity via doping and post-growth processes
  - High-quality bulk single crystals from melt
  - Cost-effective large-scale manufacturability

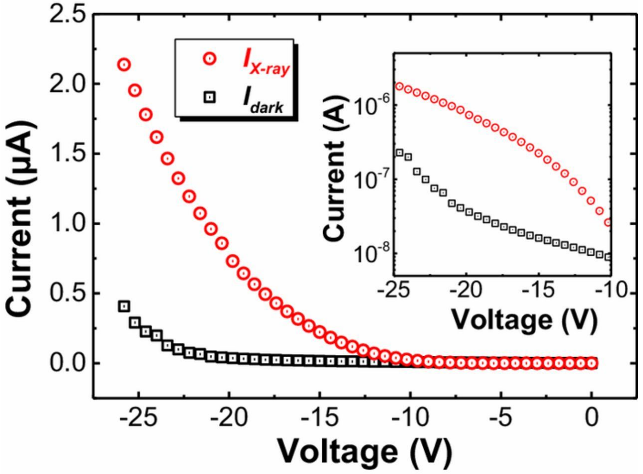
- **β-Ga_2O_3 holds high promise for addressing many radiation detection application needs not met by currently used materials**
  - Harsh environment applicability
  - Versatile and cost-effective synthesis and fabrication
  - High detector performance

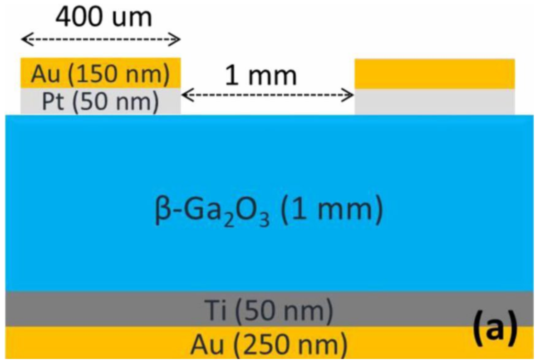


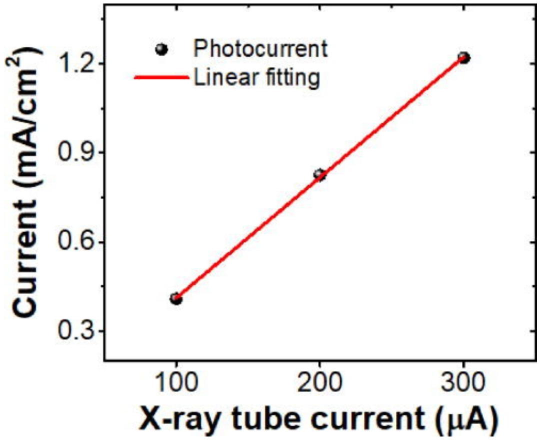
J. Zhang et al., "Recent progress on the electronic structure, defect, and doping properties of Ga_2O_3," APL Materials, 8, 2, 20906, 2020.

II. Introduction – X-ray sensors based on β-Ga_2O_3

- One previous study published in 2018-2019
  - Annealed at 1500 °C in 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.







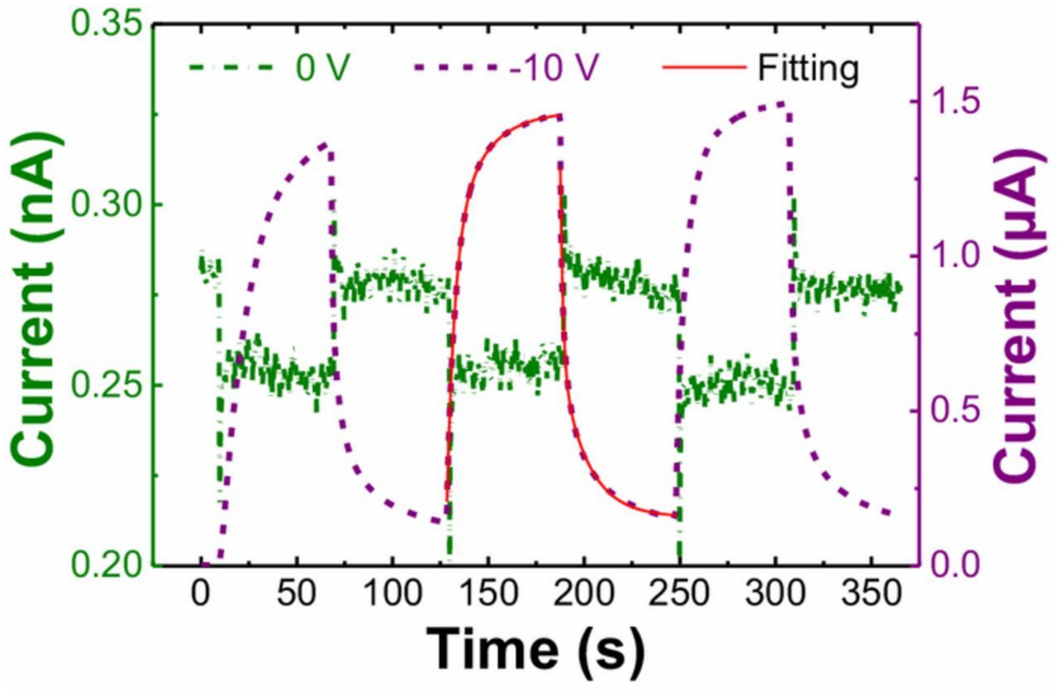
(100) undoped β-Ga_2O_3 EFG based x-ray sensors

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. 8, 7, Q3046–Q3049, 2019.

II. Introduction – 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.



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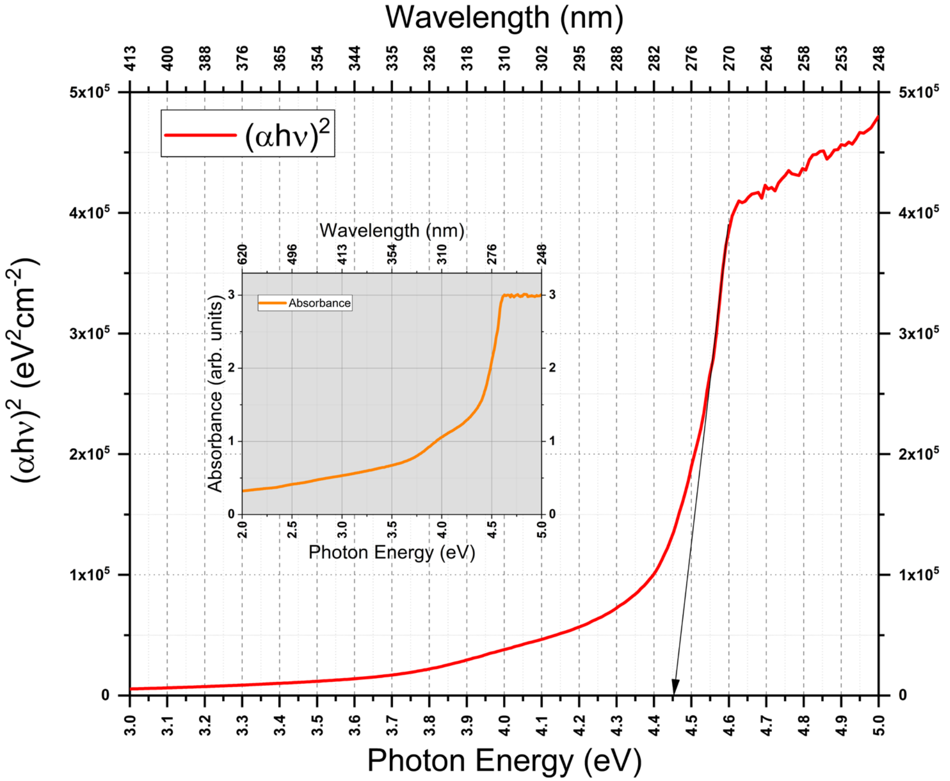
III. Optical and electrical characterization – bandgap

- Optical bandgap deducted from Tauc plot was 4.45 eV based on direct band gap treatment.
- No near band-gap shoulder was shown.
- The UWB opens the path for UV detection and the possibility for x-ray, γ-ray detection as well as charged particles.

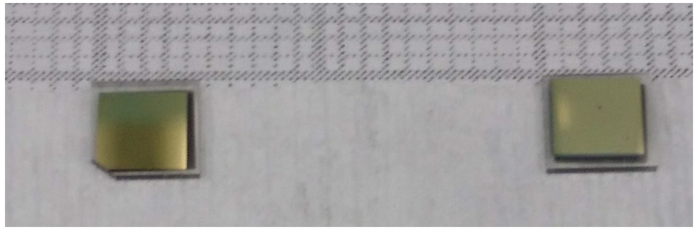
Tauc Plot showing optical bandgap of 4.45 eV. Inset shows optical absorption curve raw data which was used for Tauc plot construction.



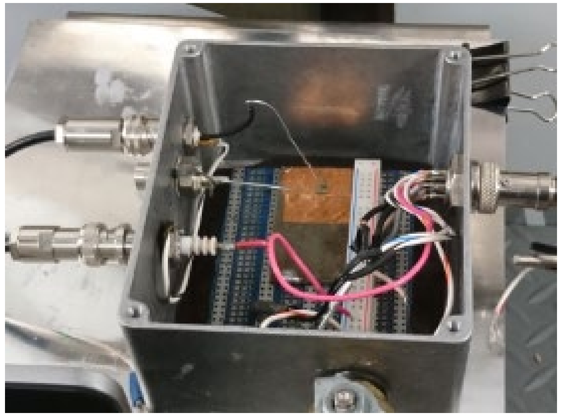
I. Hany et al., "Low temperature cathodoluminescence study of Fe-doped β-Ga_2O_3," Materials Letters 257, 126744, 2019.

III. Optical and electrical characterization – resistivity

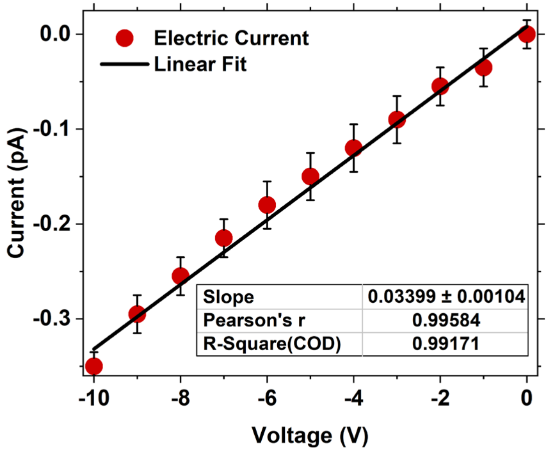
- 4x4 mm^2 Au/Ti (50/50 nm) electrodes were deposited on both sides of 5x5 mm^2 sample.
  - DC sputtering for Ti, e-beam for Au
- Very high resistivity in the order of 10^{14} Ω.cm was revealed from I-V measurement.
- 4x4 mm^2 Au/Ti (50/50 nm) and Au/Ni (40/50 nm) electrodes were deposited for testing Schottky behavior; however the I-V behavior was not different from the Au/Ti Ohmic sample.
  - DC sputtering for Ti, e-beam for Au and Ni
- Controlled 10-minute air annealing at 400 ^{o}C didn't change I-V behavior for both samples.



Au/Ni/β-Ga_2O_3/Ti/Au and Au/Ti/β-Ga_2O_3/Ti/Au



In-house built versatile testing box used for I-V, XRIC and UVIC measurements



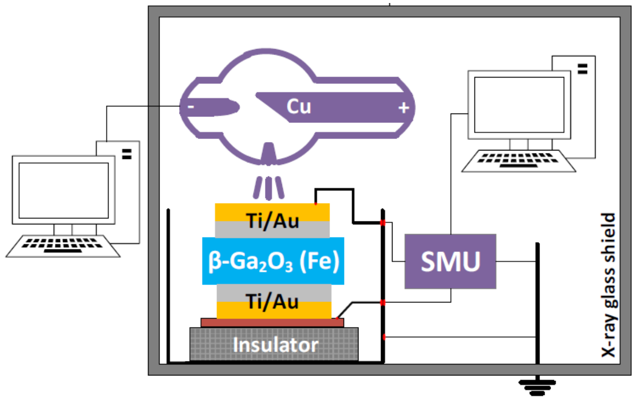
Au/Ti/β-Ga_2O_3/Ti/Au I-V characteristic curve

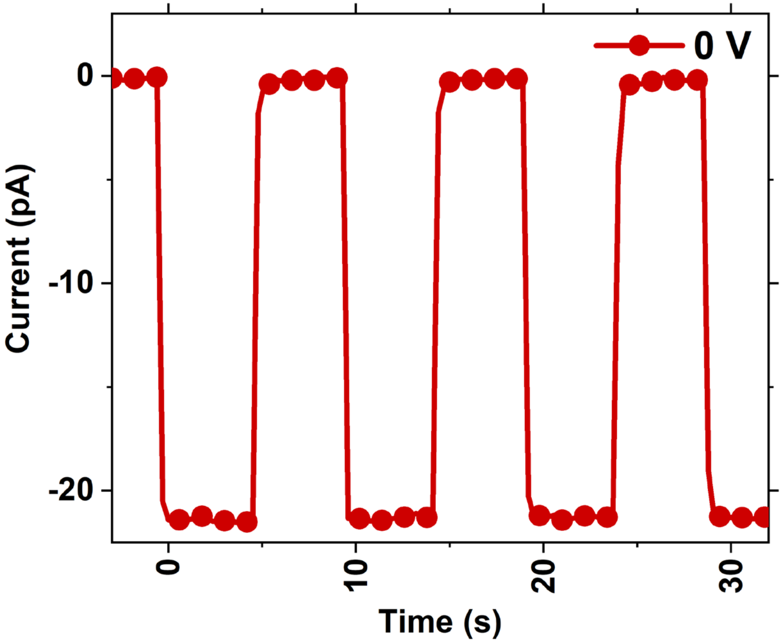
I. Hany et al., "Low temperature cathodoluminescence study of Fe-doped β-Ga_2O_3," Materials Letters 257, 126744, 2019

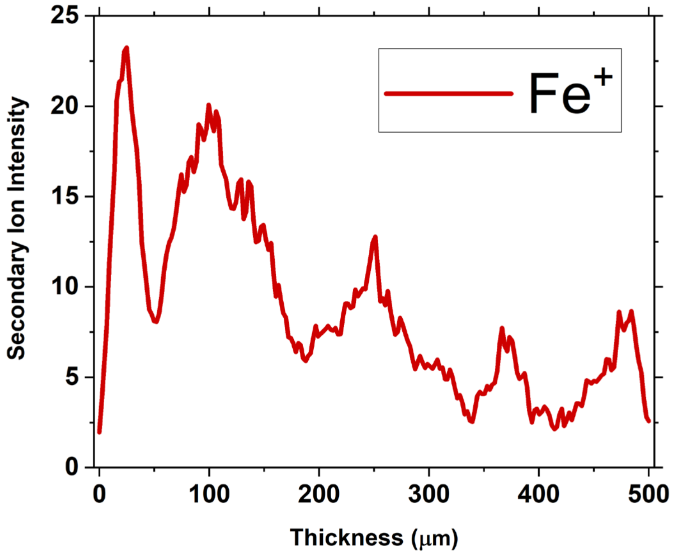
IV. XRIC Characterization

- 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

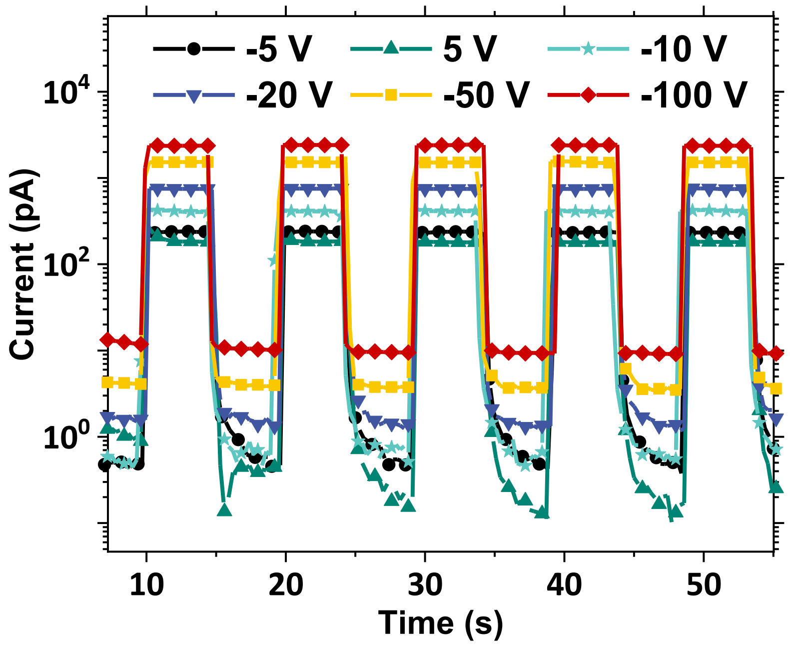
$$SNR = \frac{I_{x-ray\ induced} - I_{dark}}{I_{dark}}$$

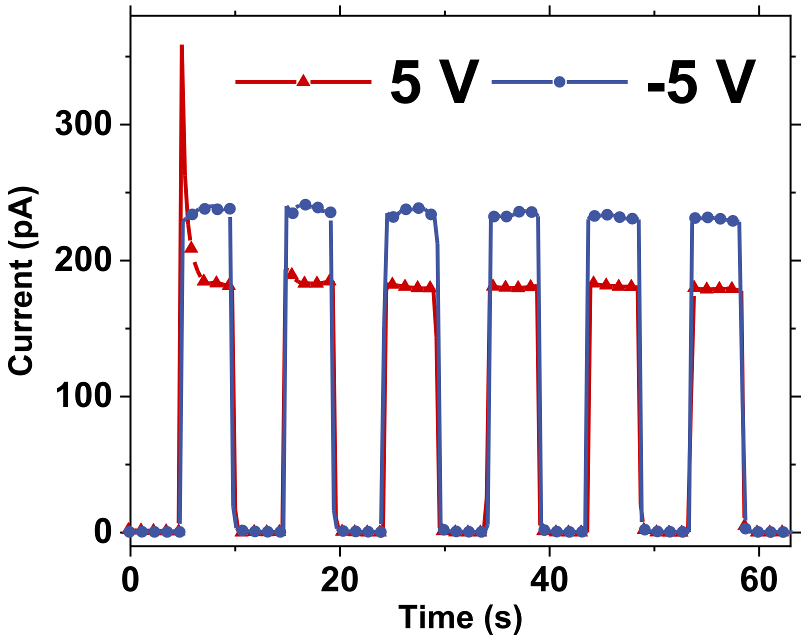






IV. XRIC Characterization





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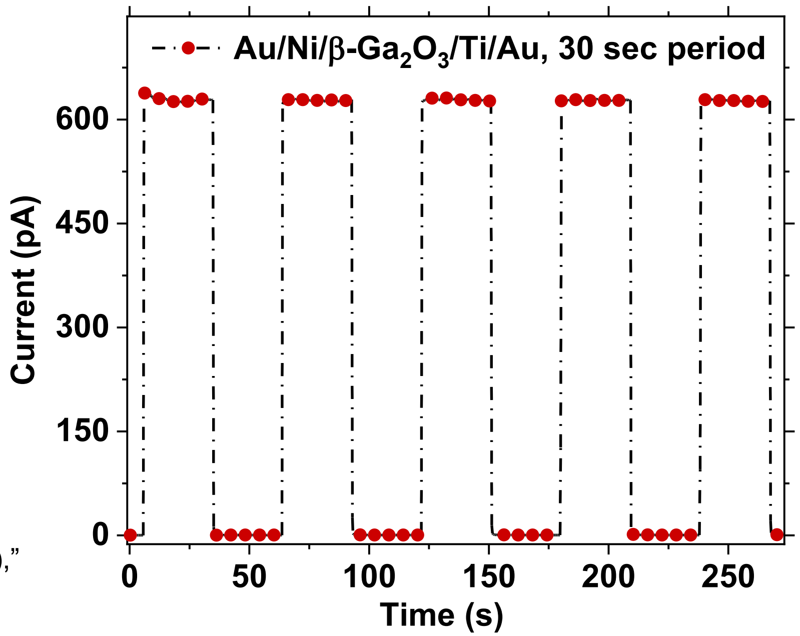
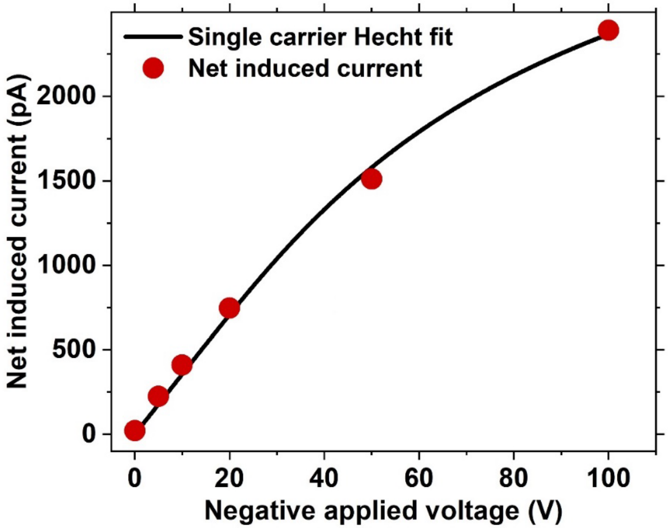
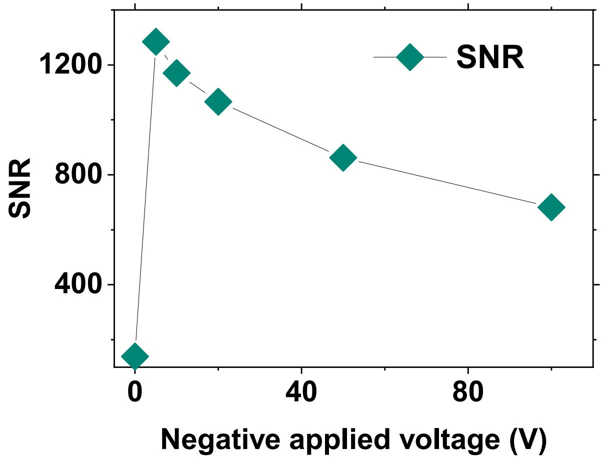
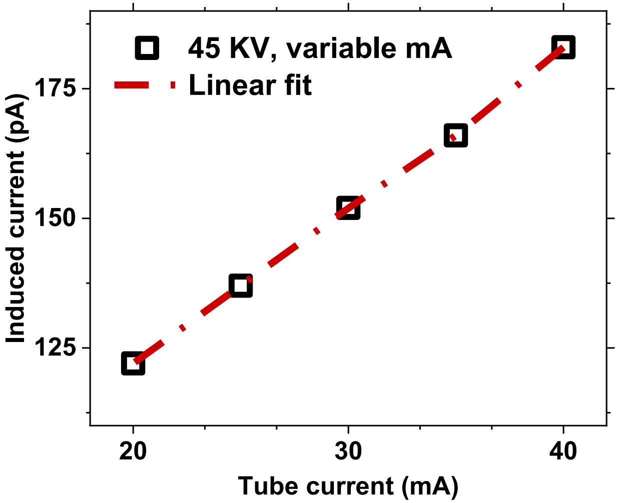


IV. XRIC Characterization

- 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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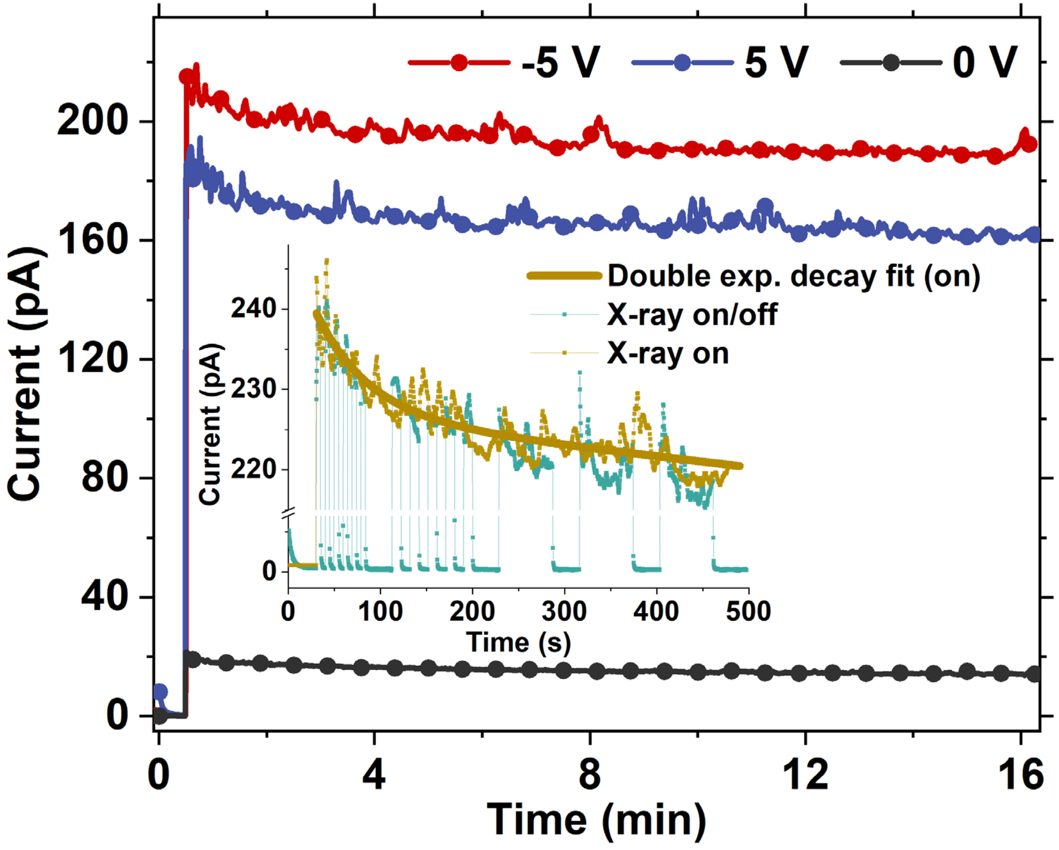
IV. XRIC Characterization

- 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



I. Hany et al., "Fast X-ray detectors based on bulk β-Ga_2O_3 (Fe)," J. Mater. Sci. 55, 9461-9469, 2020.

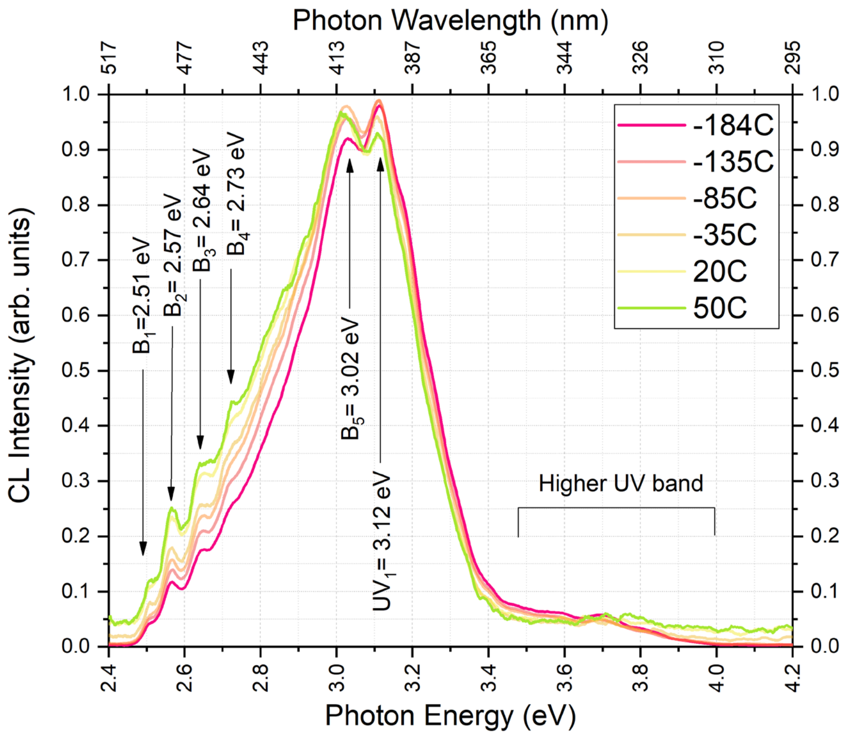
IV. XRIC Characterization

- **a-Ga_2O_3 :** (H. Liang et al., "Flexible X-ray Detectors Based on Amorphous Ga_2O_3 Thin Films," ACS Photonics, vol. 6, no. 2, pp. 351–359, 2019.)
- **Unintentionally doped β-Ga_2O_3:** (X. Lu et al., "Schottky x-ray detectors based on a bulk β-Ga_2O_3 substrate," Appl. Phys. Lett., vol. 112, no. 10, p. 103502, 2018.) and (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.)

Material	Preparation method	Rise time (s)	Decay time (s)	SNR
a-Ga_2O_3	RF sputtering (PO_2 1.4×10^{-3} Pa)	15.5	1.1	-
	RF Sputtering (PO_2 1.0×10^{-3} Pa)	50.1	3.3	$>10^4$
Unintentionally doped β-Ga_2O_3	EFG	18.3 (-15 V)	20.9 (-15 V)	>800 (-15 V)
		<0.02 (0 V)	<0.02 (0 V)	-
β-Ga_2O_3 (Fe)	EFG	<0.3	<0.3	$>10^3$ (low voltages)
				$>10^2$ (0 V and high voltage)

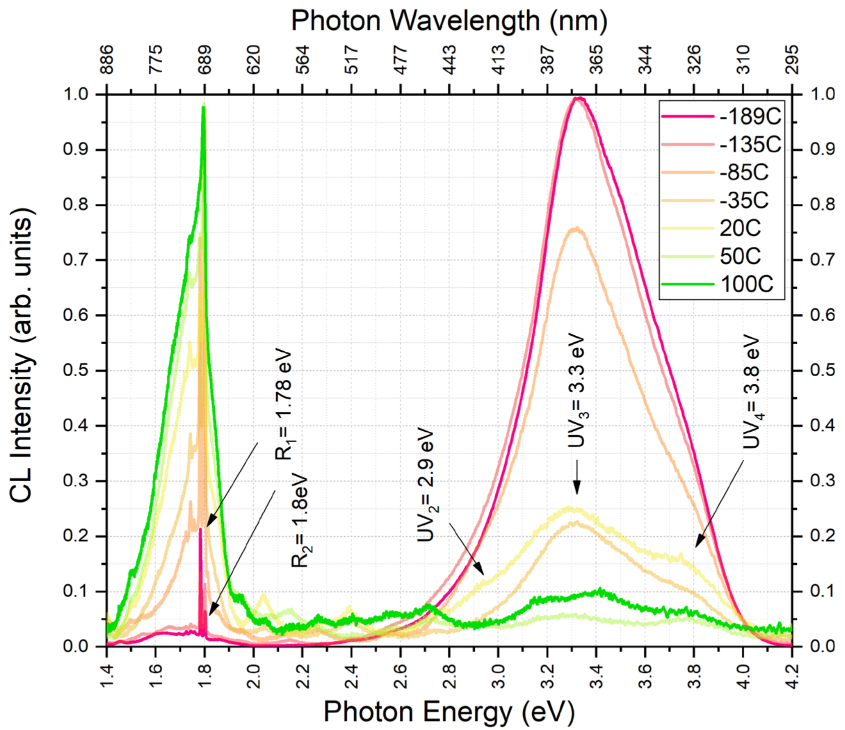
I. Hany et al., "Fast X-ray detectors based on bulk β-Ga_2O_3 (Fe)," J. Mater. Sci. 55, 9461-9469, 2020.

V. Temperature-dependent CL β-Ga_2O_3 (Fe)



- HT air annealing potentially decreases V_O concentration and eliminates V_{Ga}+V_O complexes.
- Potential change in V_{Ga} nature and/or concentration.
- Red luminescence possible origins are (1) Nitrogen diffusion and (2) Cr impurities. New evidence points to the latter.

Defect	Defect type	Signature
$V_{Ga}+V_O$	Vacancy	B_{1-4} (acceptor)
V_O	Vacancy	B_5 and UV_{1-3} (donor)
V_{Ga}	Vacancy	B_5 (acceptor)
Fe_{Ga}	Substitutional (dopant)	UV_1 (acceptor)
STH	Electronic defect	UV_{2-4}



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VI. Summary

- β-Ga_2O_3 (Fe) was investigated as a direct X-ray detection material motivated by its high resistivity and ultra-low leakage current.
  - High SNR under three operation modes
  - High linearity between X-ray induced photocurrent and X-ray tube current
  - Improved transport properties
    - Controlling Fe and Cr distribution may increase μτ-factor
  - High stability upon continuous illumination for 15 minutes.
    - V_O and V_{Ga} potentially assist in the initial polarization effect
- The results demonstrate the great potential of β-Ga_2O_3(Fe) as a radiation resistant X-ray detector with excellent temporal response for a wide range of applications.

Thank you for your attention!