



# Heavy-ion irradiation induced defects in GaN and Ga<sub>2</sub>O<sub>3</sub>

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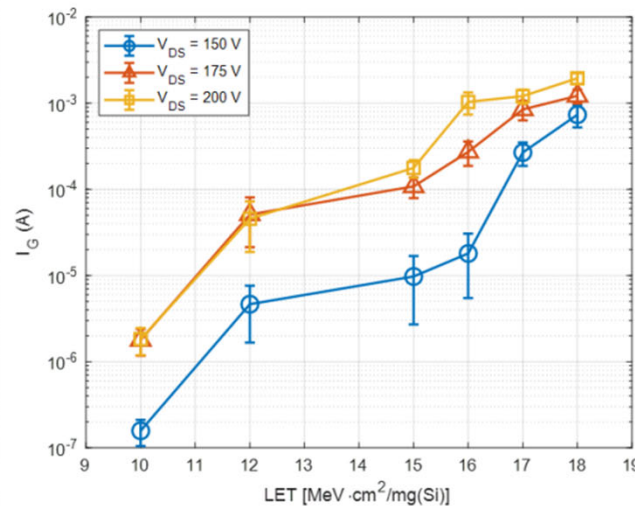
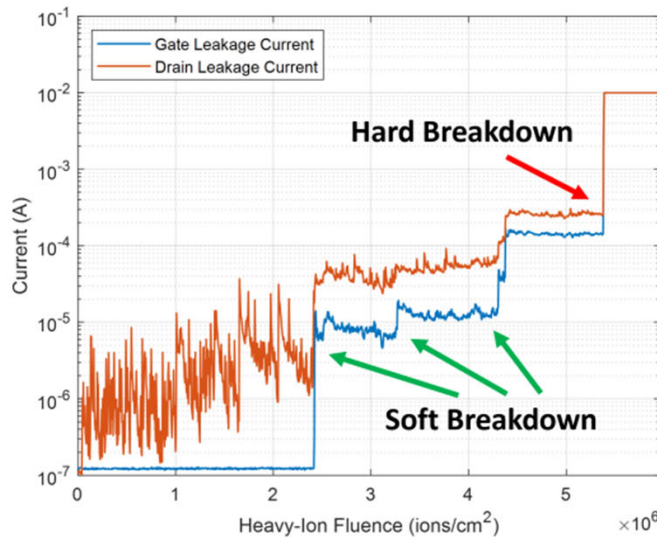
THE OHIO STATE UNIVERSITY  
COLLEGE OF ENGINEERING



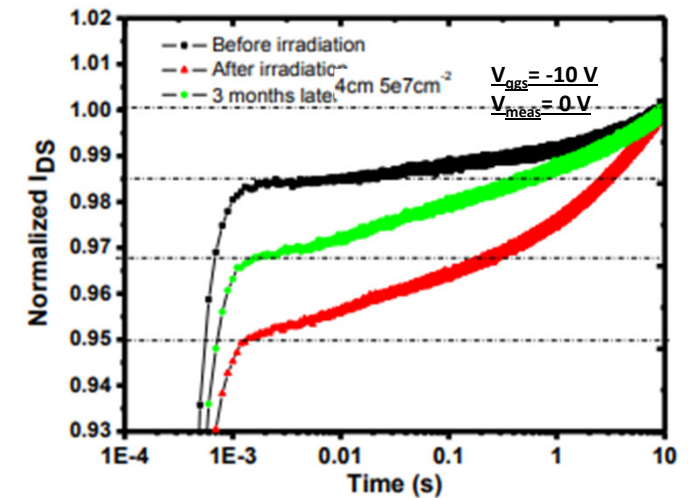
- Motivation for heavy ion irradiation and our initial experiments
- Swift heavy ion irradiation of GaN diodes
- Swift heavy ion irradiation of  $\beta$ -Ga<sub>2</sub>O<sub>3</sub> diodes
- Discussion of GaN and  $\beta$ -Ga<sub>2</sub>O<sub>3</sub> differences
- Any time left: discussion of how this is different than proton irradiation
- Next steps



## Example of heavy ion irradiation causing degradation and device failure



## Gate lag after heavy ion irradiation



- Swift heavy ions lead to single events such as SEB and SEGR, but also SELC and such
- This year's plan
  - Investigate traps created by heavy ions (zero bias)
    - Develop basic understanding of ion-induced traps in WBG/UWBG materials
  - Explore trap-related current transport (e.g. gate leakage) mechanisms and other trap impact in transistors and diodes (delayed due to beam problems at GSI)

# Au irradiation results of GaN



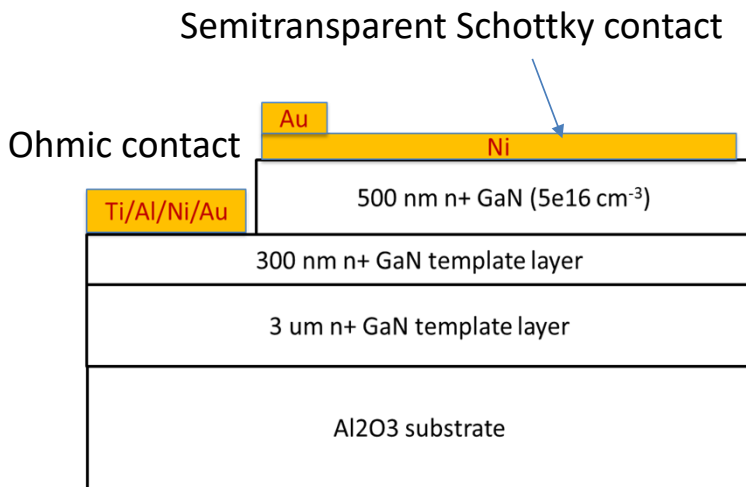


## Radiation experiment

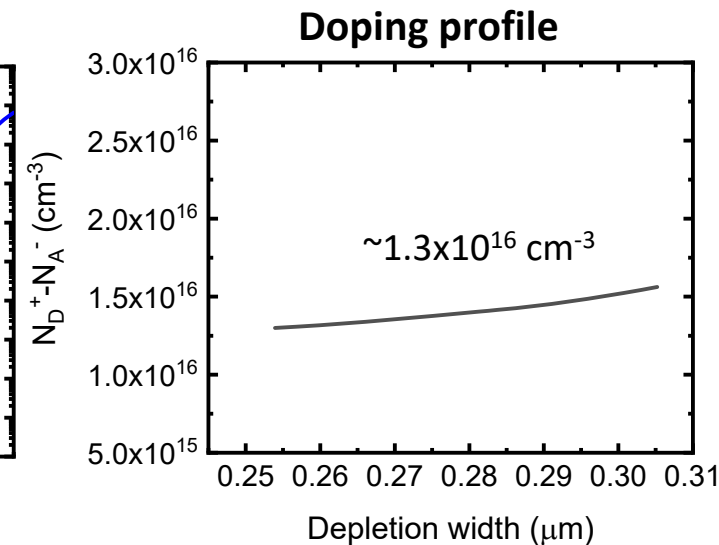
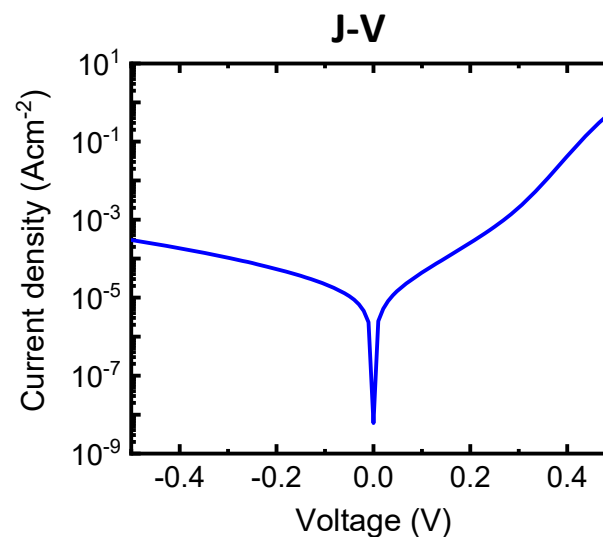
Study impact of heavy ion (Au) on traps in GaN SBD

- 946 MeV Au ions with fluence of  $2 \times 10^7$ ,  $7 \times 10^7$ ,  $1 \times 10^8$ , and  $4 \times 10^8 \text{ cm}^{-2}$ .
- Collaboration with **Maik Lang** (UT Knoxville) and GSI

## Structure of GaN Schottky barrier diodes



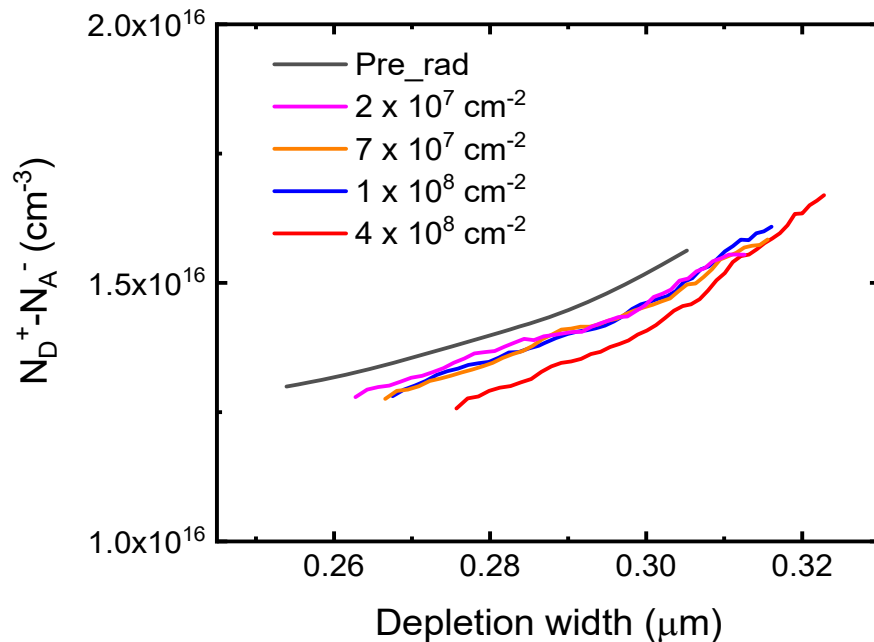
## Pre-rad characteristics



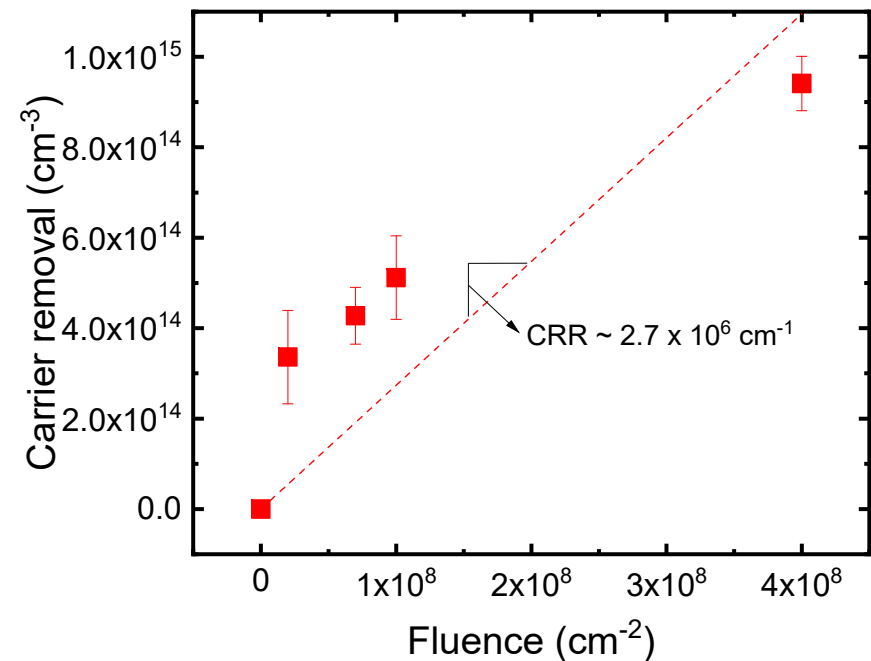
Grown by UCSB (Zach Biegler, Jim Speck) and fabricated at OSU



## Doping profiles as function of fluence



## Carrier removal as function of fluence

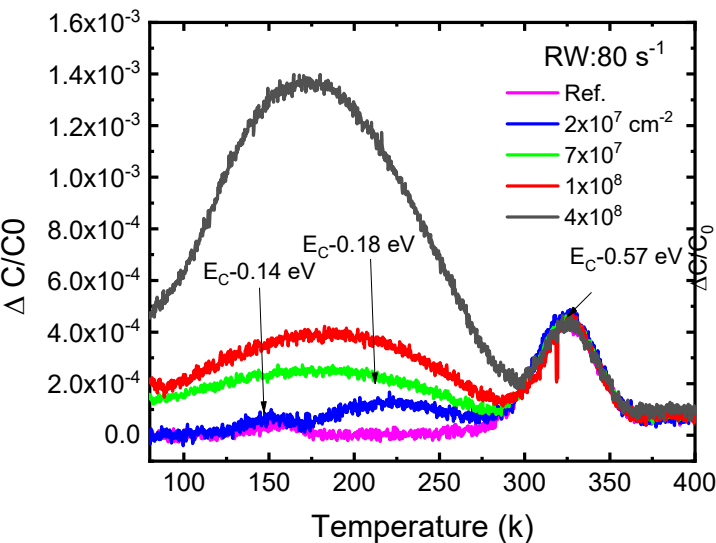


- Doping decreases with increasing fluence
  - “Average” carrier removal rate (CRR)  $\sim 2.7 \times 10^6 \text{ cm}^{-1}$  (assuming typical linear relation)
  - Non-linear CRR
    - Plan to repeat this at next beam time, but
    - Is this due to saturation due to damage radius? Probably not
    - Related to local heating/defect annihilation right? Other have ideas?

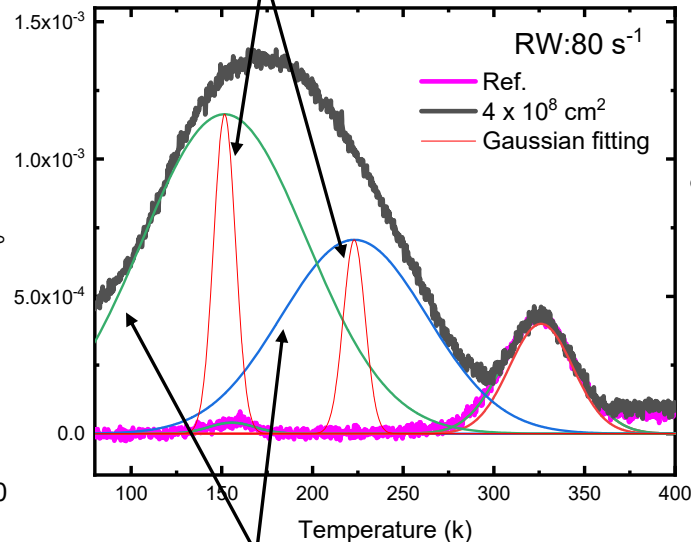




## DLTS



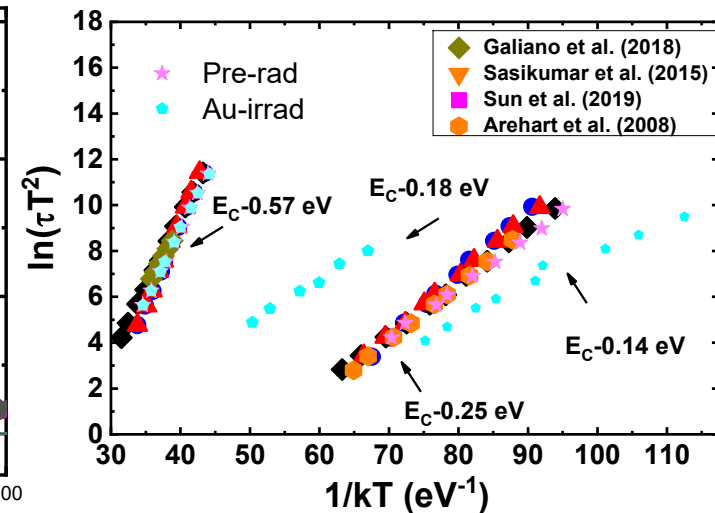
## Ideal DLTS peak width



## DLTS peak fitting

- 3 traps observed at  $E_C-0.14$ ,  $0.18$ , &  $0.57$  eV
  - $E_C-0.57$  Fe related[3] & is constant with radiation fluence
  - $E_C-0.14$  &  $0.18$  eV
    - Sensitive to radiation fluence
    - DLTS peaks broad and merge into one large, broad peak
      - Much wider than ideal point defect DLTS peak width

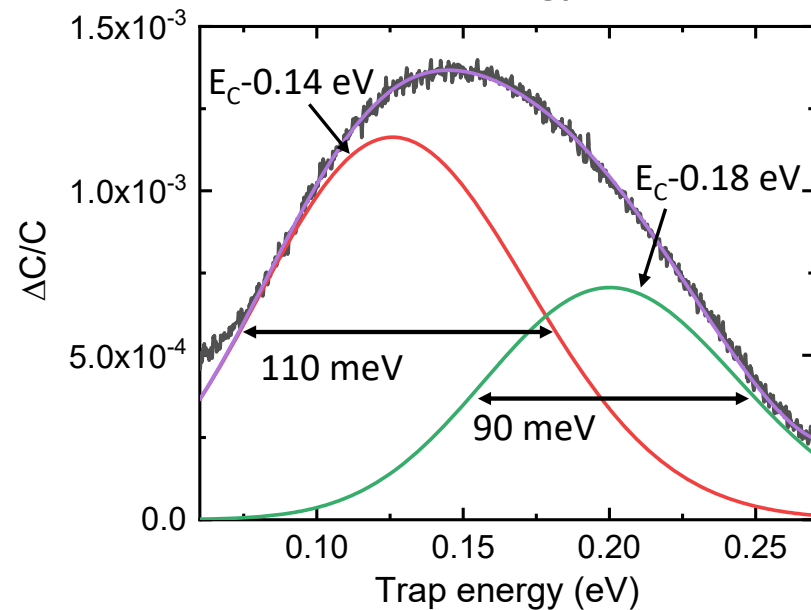
## Arrhenius plot





# Understanding the $E_C-0.14$ & $0.18$ eV traps

DLTS with energy x-axis\*



\* Assumes capture cross section to get this

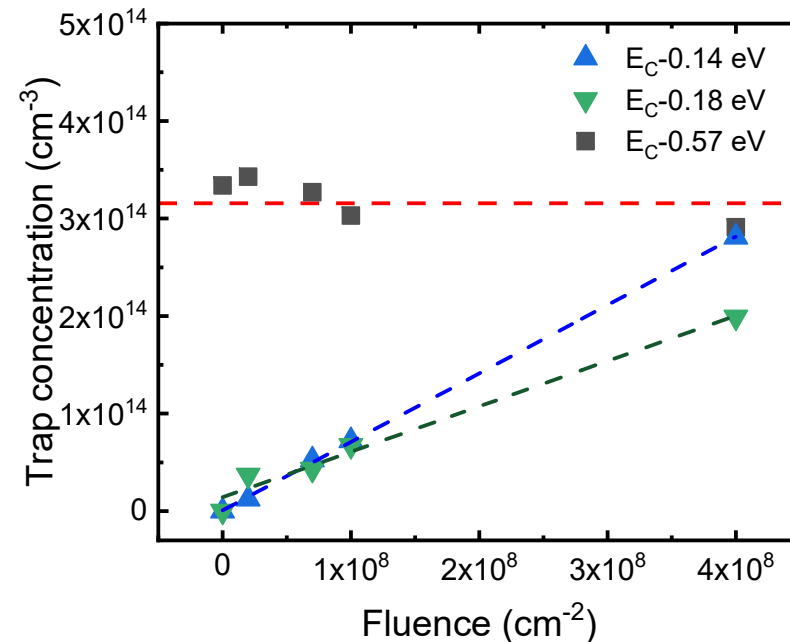
$$E_C - E_T \propto -kT \ln \left[ \frac{1}{\sigma_n v_{th} N_C} \right]$$

$\sigma_n$  electron capture cross section

$v_{th}$  thermal velocity

$N_C$  conduction band density of states

Trap concentrations vs. fluence



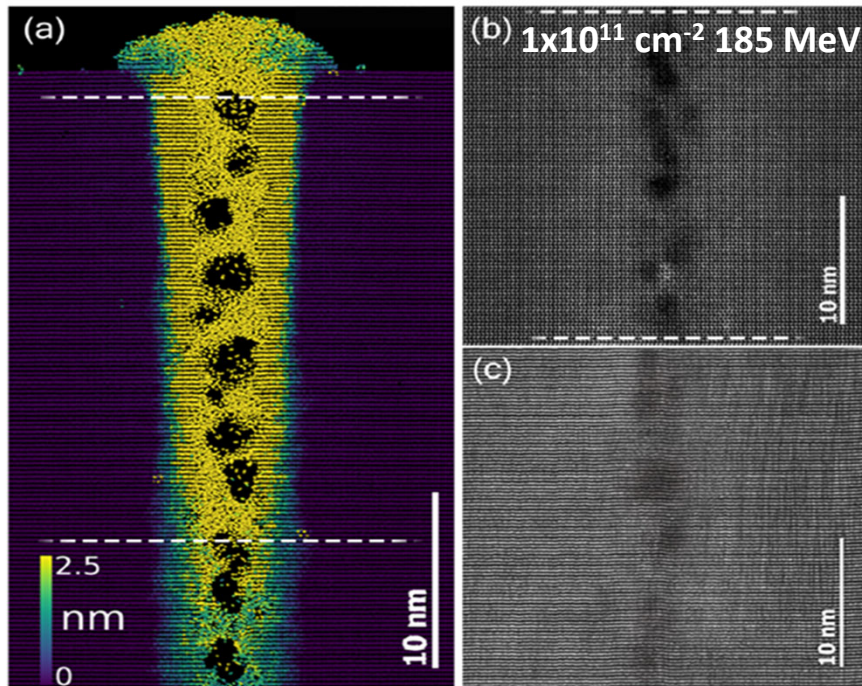
- Broad peak indicates wide energy range:  $E_C-0.14 \pm 55$  &  $E_C-0.18 \pm 45$  meV
  - Extremely broad with this model
- $E_C-0.14$  eV trap introduction rate  $7.0 \times 10^5 \text{ cm}^{-1}$
- $E_C-0.18$  eV trap introduction rate  $4.4 \times 10^5 \text{ cm}^{-1}$
- What causes this large trap energy range?





# Understanding the $E_c$ -0.14 & 0.18 eV traps

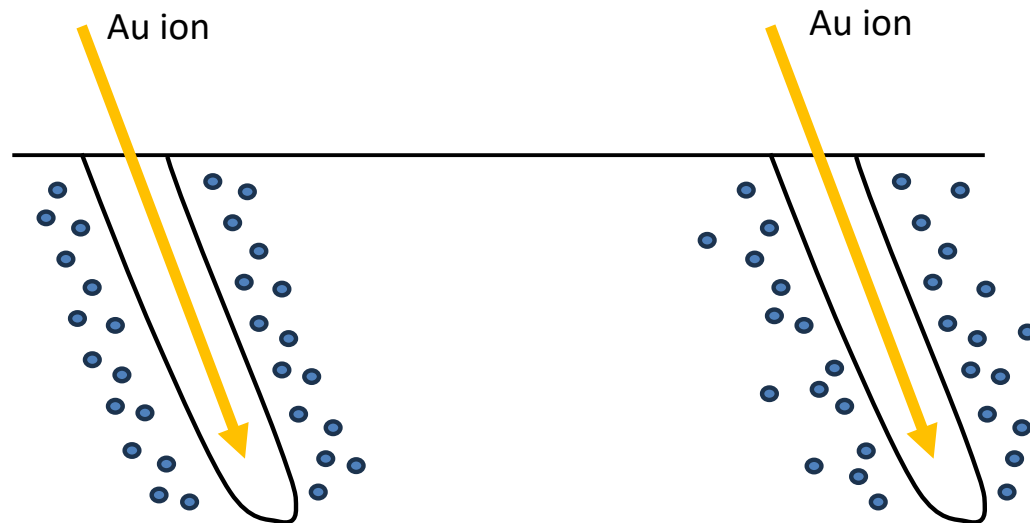
## Au radiation damage on GaN [1]



### Heavy ions

- Creates tracks
  - Creates cloud of defects much, much wider than track
- Amorphous at center, but point defects will extend well beyond this radius

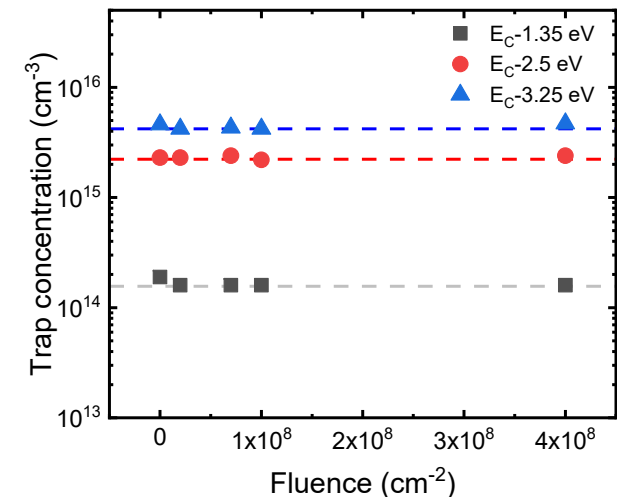
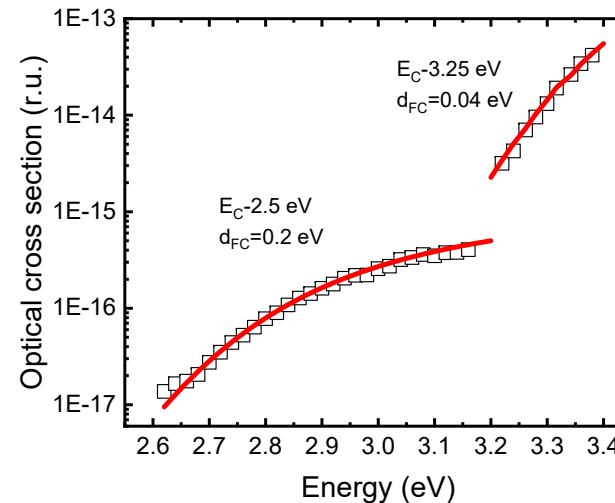
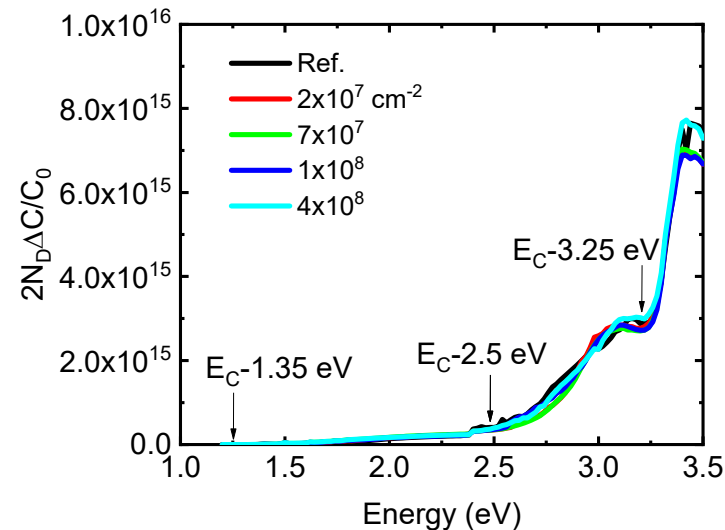
### Heavy ion damage



Spatially close defects  
Interacting wavefunctions  
Stress gradients  
Bond variation (length or angle)  
**Result is very likely defect energy bands**



## Steady-state photocapacitance (SSPC)    Deep Level Optical Spectroscopy (DLOS)    Trap concentration vs fluence

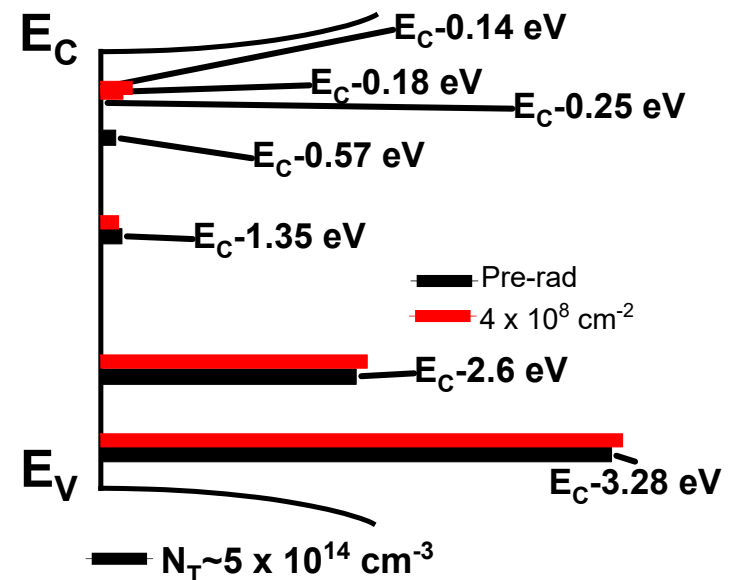


- Mid-gap and near valence band states remain essentially independent of Au fluence
- $E_C-1.35$  and  $E_C-3.25$  are both C related [1,2]
- $E_C-2.5$  eV can be C or  $V_{Ga}$  related
  - Likely C in this case due to larger  $d_{FC}$
  - Expect  $V_{Ga}$  traps at higher fluences
    - Just need higher fluences -or-
    - Recombining defects after ion impact?
      - $V_{Ga}-H_x$  defects are still in the bandgap, so not impurity related



- 946 MeV Au heavy ion irradiation results in:
  - Total carrier removal rate  $2.7 \times 10^6 \text{ cm}^{-1}$ 
    - Non-linear CRR not well understood
  - $\sim E_C - 0.14$  and  $E_C - 0.18$  eV trap introduction
    - Broad energy distributions (90-110 meV)
      - Likely due to highly localized damage
  - Other deep levels show no trends with Au irradiation
    - No increased Au-induced  $V_{Ga}$  observed so far

GaN trap spectra pre/post-Au irradiation



# Au irradiation results of $\beta$ -Ga<sub>2</sub>O<sub>3</sub>





## Radiation experiment:

946 MeV Au-ion irradiation (same as GaN experiments)

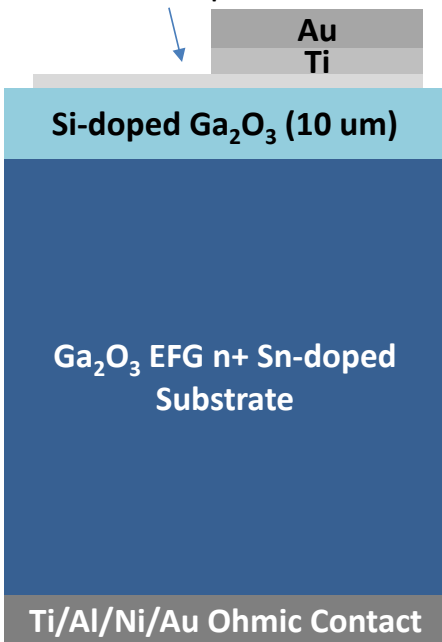
Fluences from  $4 \times 10^7$  to  $3.5 \times 10^8$  cm<sup>-2</sup>

Devices grounded during irradiation

The radiation time take few seconds

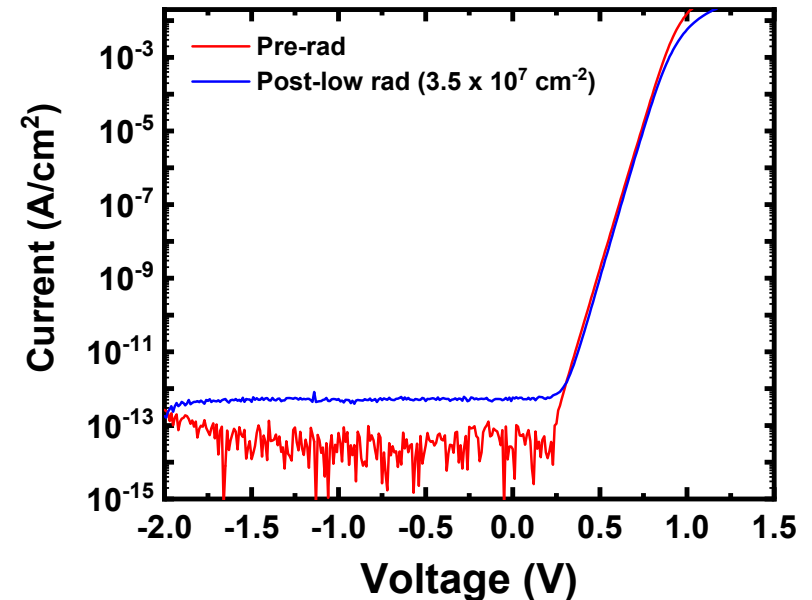
## HVPE-grown $\beta$ -Ga<sub>2</sub>O<sub>3</sub> diode structure

Semitransparent Ni Schottky contact



Sample provided by Rajan (OSU)

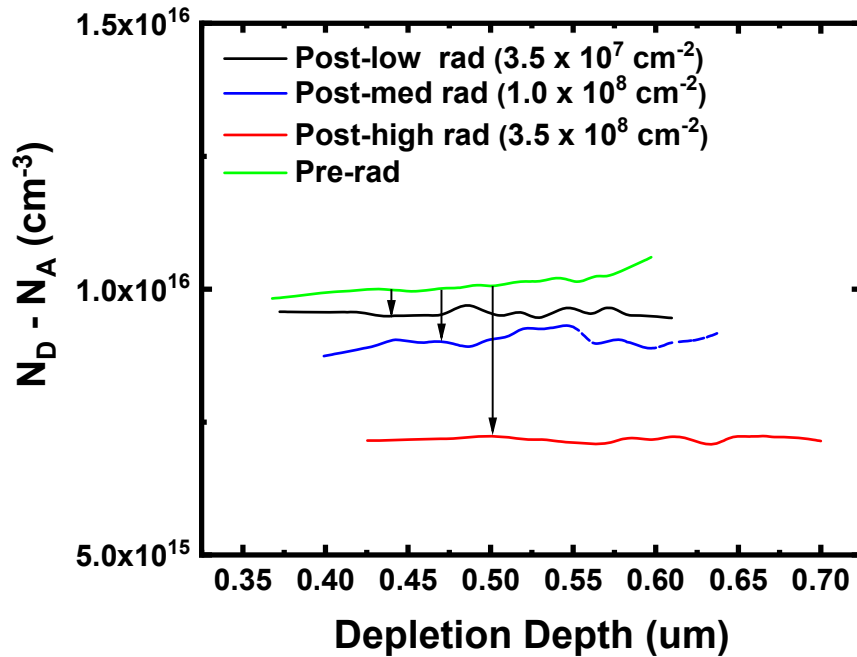
I-V before and after radiation



- Ideality factor  $\sim 1.02$ - $1.06$  after irradiation
- Barrier height  $\sim 1.3$  eV for all samples and pre/post-rad
- Leakage decreased, but looks like bad offset as current sign never changes
  - Don't draw conclusions from this yet

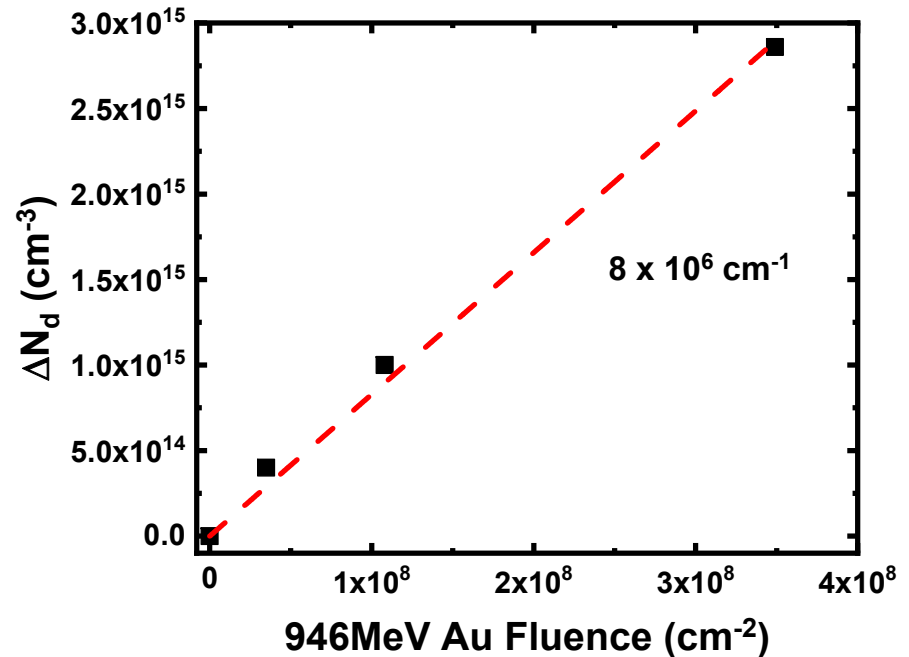


Doping profiles from C-V for each fluence



- Monotonic decrease in doping with radiation fluence
- 30% net doping reduction at  $3.5 \times 10^8$  cm<sup>-2</sup>

Carrier removal vs radiation fluence



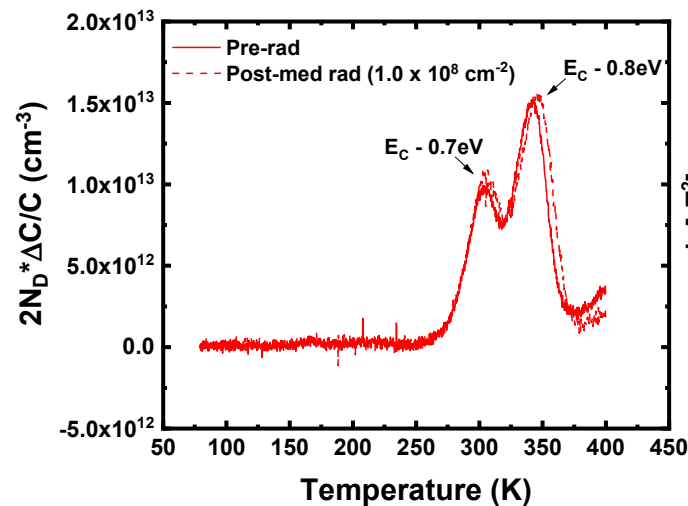
Much more linear carrier removal compared with GaN  
Carrier removal rate was  $8 \times 10^6$  cm<sup>-1</sup>

- More on this later

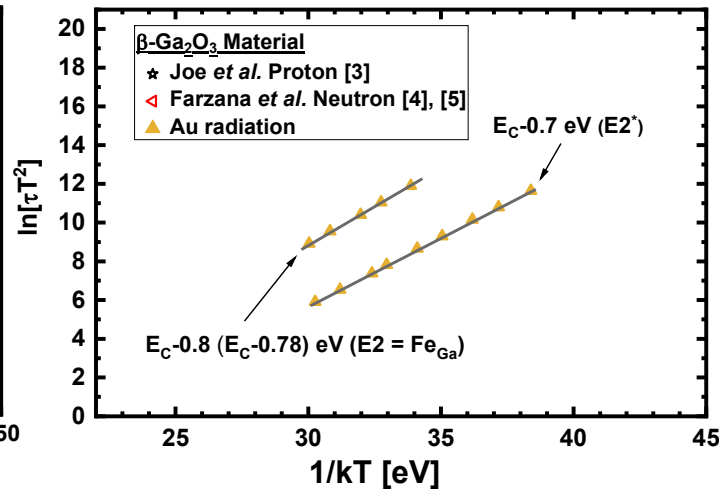


# Lack of Au irradiation impact on DLTS levels

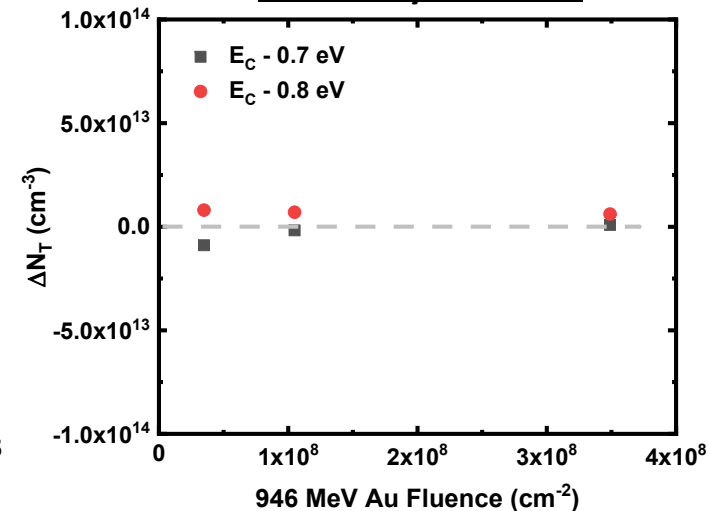
**DLTS Pre and Post Au Irradiation**



**Arrhenius for Au Radiation Trap**



**Trap Concentration Change  
Caused by radiation**



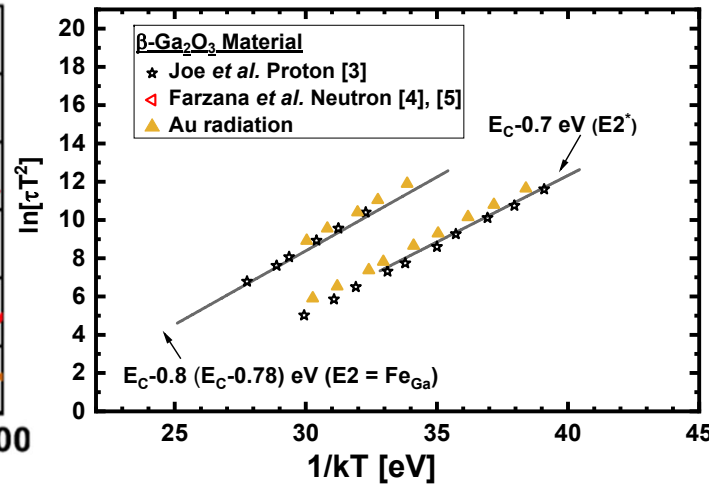
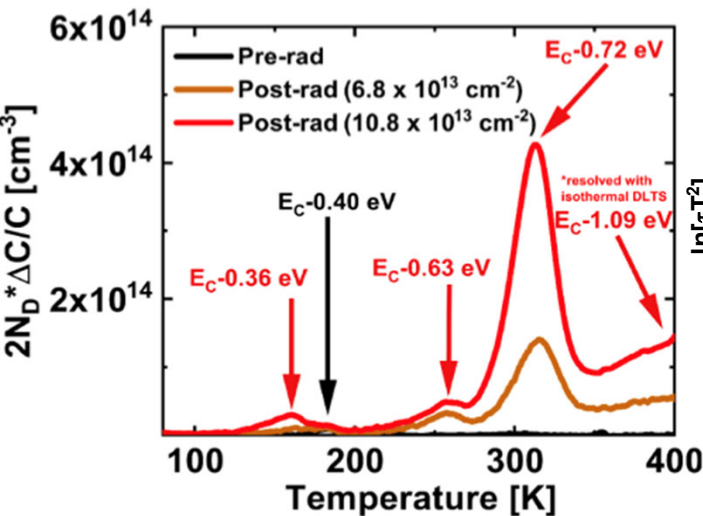
- 2 traps observed ( $E_C - 0.70/E2^*$  and  $E_C - 0.80$  eV/ $E2$ )
  - Both are unchanged with Au irradiation
  - $E_C - 0.8$  eV is attributed to be  $Fe_{Ga}$  [1]
  - $E_C - 0.7$  eV was proposed to be  $V_{Ga}$  or  $V_{Ga}$  related [2]
    - In this case, might expect radiation response
    - Indeed, did respond to neutrons and protons [3, 4]
      - More next...

- [1] J. F. McGlone, Appl. Phys. Lett. 115 (15) (2019)
- [2] J. B Varley et al 2011 J. Phys.: Condens. Matter 23 334212
- [3] J. McGlone et al J. Appl. Phys. 133 (4): 045702. (2023)
- [4] E. Farzana, APL Mater 7 (2) (2019)
- [5] E. Farzana, J. Appl. Phys. 123 (16) (2018)

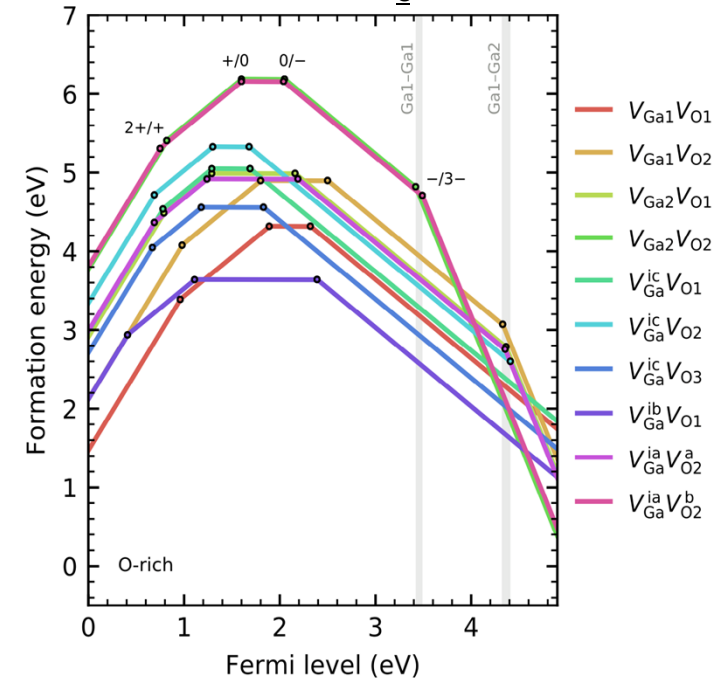




## Proton Radiation on MOCVD $\text{Ga}_2\text{O}_3$ Response

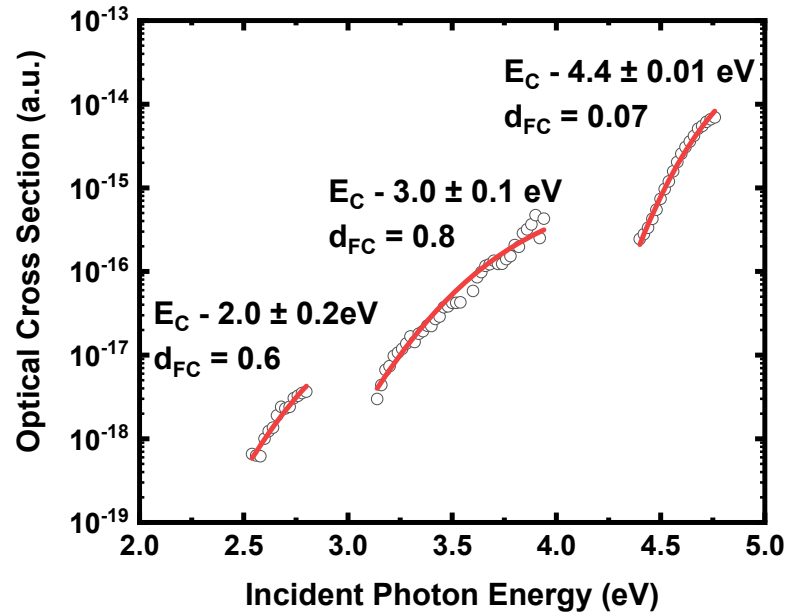
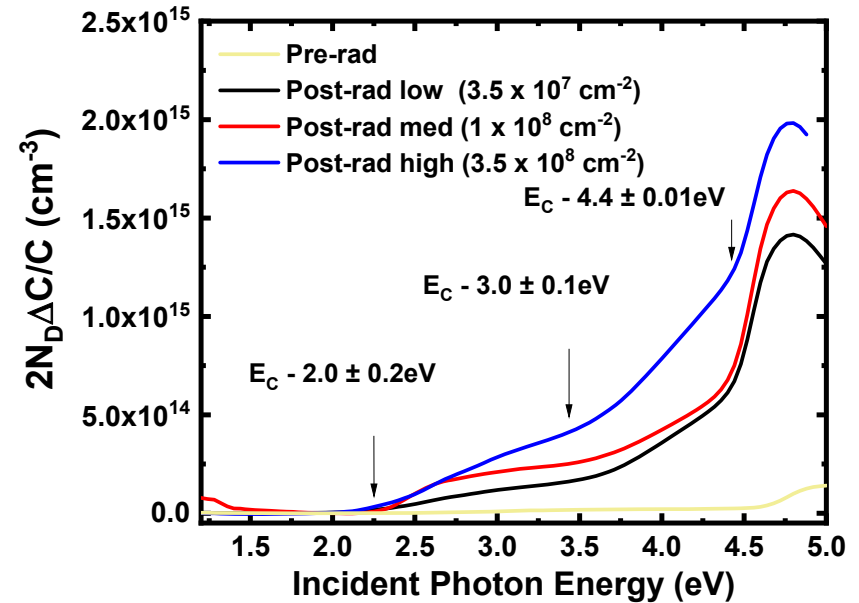


## DFT simulation on $E_c - 0.7\text{eV}$ Trap



- Clear radiation response to protons and neutrons
- Arrhenius overlapping, so unlikely different traps
- Recent DFT simulations suggest it could be  $V_{\text{Ga}}\text{-}V_{\text{O}}$  complex [1]
- Still cannot easily explain p+, n response and not to Au
  - Could be annihilating in heavy ion due to local heating
  - More work is needed & heavy ion experiments being repeated

- [1] Y. K. Frodason et al *Phys. Rev. Materials* 5, 025402 (2021)
- [2] C Zimmermann et al *J. Phys. D: Appl. Phys.* **53** 464001 (2020)
- [3] J. McGlone et al *J. Appl. Phys.* 133 (4): 045702. (2023)
- [4] E. Farzana, *APL Mater* 7 (2) (2019)
- [5] E. Farzana, *J. Appl. Phys.* 123 (16) (2018)

DLOS results on different radiation fluenceSSPC results on different radiation fluence

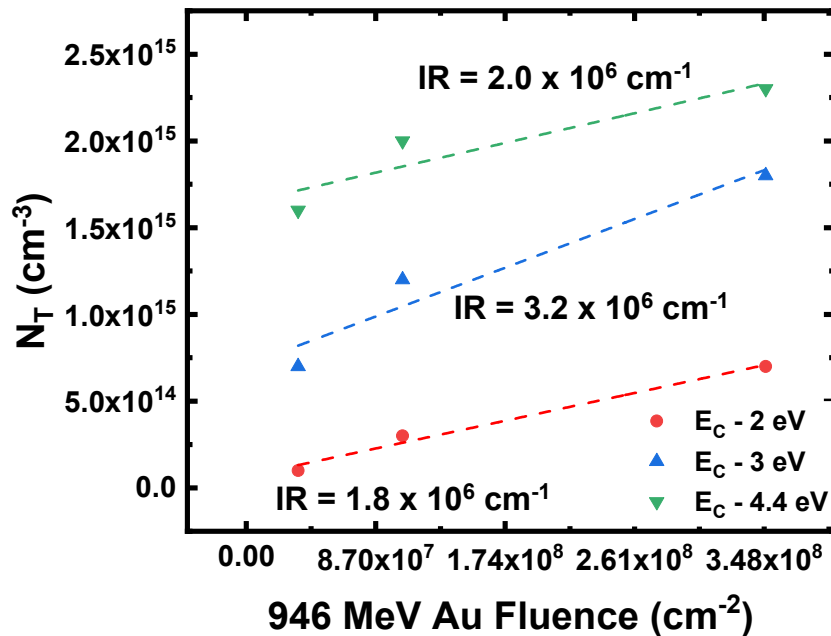
- 3 traps observed via DLOS
  - $E_C - 2.0$  ( $2V_{Ga} - Ga_i$ ) and  $E_C - 4.4 \text{ eV}$  (Hole polaron, intrinsic origin) traps commonly observed [1, 2]
  - $E_C - 3.0 \text{ eV}$  trap previously seen in PAMBE Ge-doped  $Ga_2O_3$ 
    - Source not known
  - All 3 traps respond to Au irradiation

[1] J. M. Johnson et al. Phys. Rev. X 9, 041027 (2019)

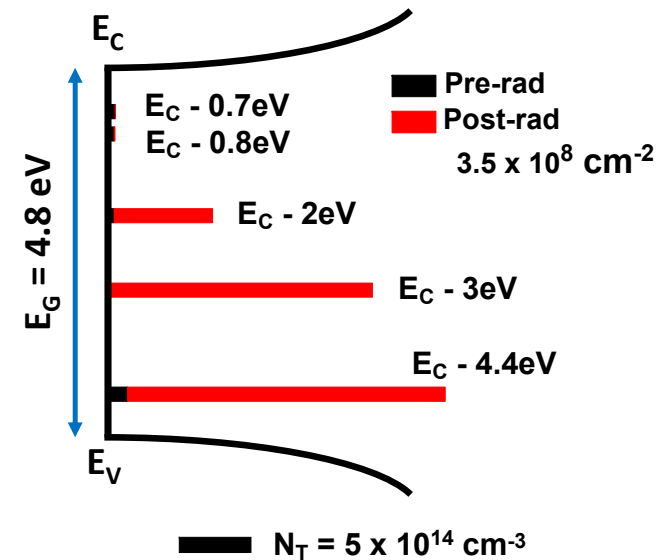
[2] Y. K. Frodason et al J. Appl. Phys. 127 (7): 075701. (2020)



## Au-induced trap introduction



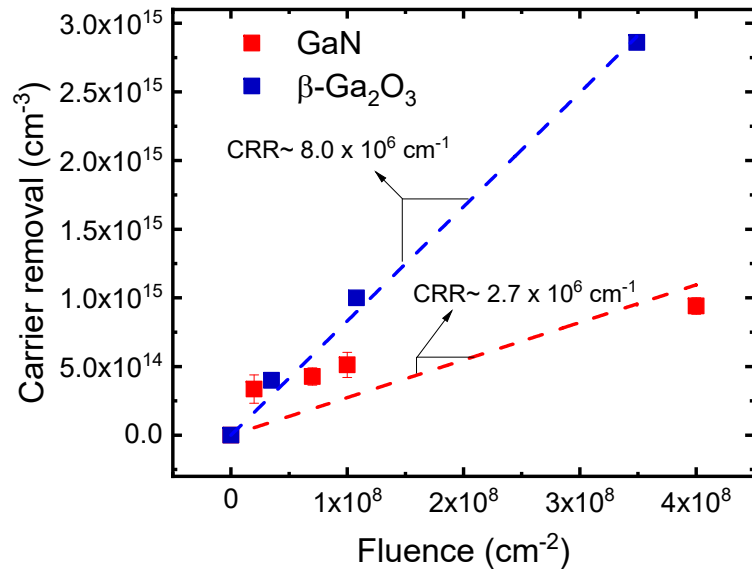
## Trap summary pre-rad and post- $3.5 \times 10^8 \text{ cm}^{-2}$ fluence



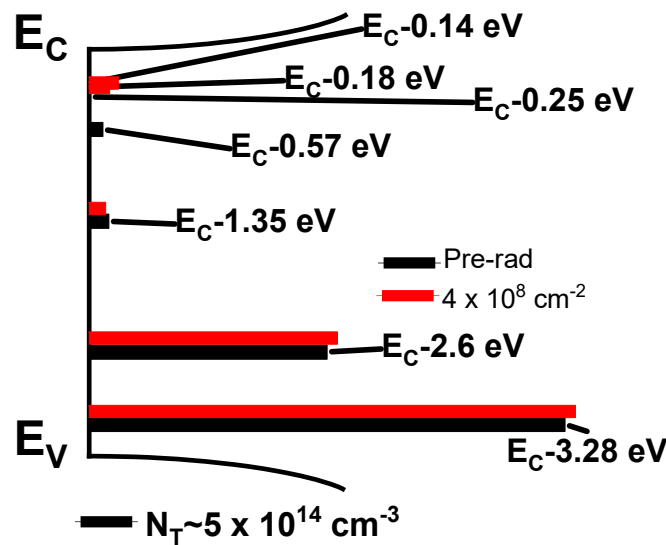
- Total trap introduction rate detected by DLOS is  $7.0 \times 10^6 \text{ cm}^{-1}$  (close to carrier removal rate)
- DLTS detected traps has a low response to the swift Au radiation
- $E_C - 2 \text{ eV}$  and  $E_C - 4.4 \text{ eV}$  trap shows comparable ramping rate
- $E_C - 3 \text{ eV}$  trap is newly introduced by radiation and possesses the highest ramping rate
  - Did not respond to proton and neutron radiation
  - More work need to be done to identify its source



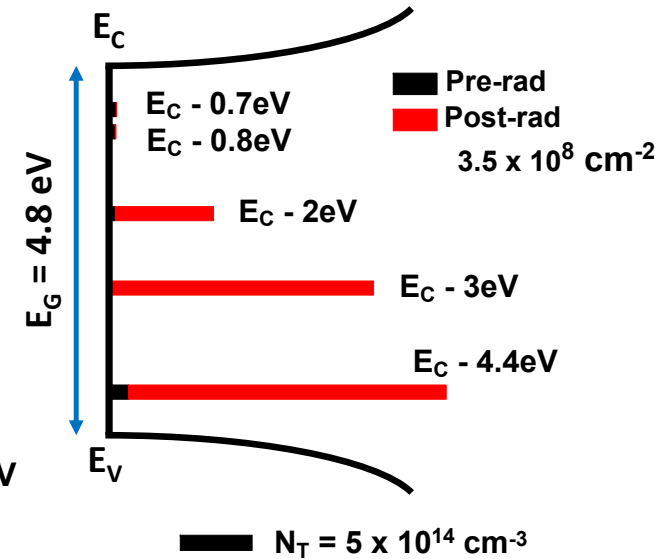
### Carrier removal vs. Au fluence



### Au-irradiated GaN



### Au-irradiated $\beta\text{-Ga}_2\text{O}_3$



- GaN CRR non-linear/ $\text{Ga}_2\text{O}_3$  nearly linear
- $\text{Ga}_2\text{O}_3$  CRR > GaN CRR, voltage/electric field will affect this difference
- GaN defects form mostly near  $E_C$
- $\text{Ga}_2\text{O}_3$  defects form mid-gap and near  $E_V$
- So very different material responses, much different than proton-induced traps as well



- Repeat some GaN and Ga<sub>2</sub>O<sub>3</sub> diode irradiation experiments (to confirm carrier removal, for instance)
- Same investigations with lower LET (Ar, 10 keV/nm, no open tracks) to compare with 70 keV/nm Au
- Received high-Al AlGaN diodes from UCSB(Speck) for defect studies
- Just received GaN transistors/diodes from MURI (Chu)
  - Common structures for comparison with Lenahan and others
- Currently fabricating Ga<sub>2</sub>O<sub>3</sub> transistors grown at OSU for defect-induced degradation (e.g. SELC)
- More comparisons with low energy ion, protons, and other irradiation

## Simulated radiation damage from heavy ion in GaN & AlN [1]

