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Radiation Effects Ctr of Excellence 10-2024 Review

Impact of proton and x-ray irradiation on trap behavior in Ga_2O_3 materials and devices and the influence of electric fields using defect spectroscopies

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Ohio State focus areas, acknowledgements & collaborations in the COE

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Prof. Steve Ringel

Defect spectroscopies of β-Ga_2O_3 and GaN materials/devices and space PV

Prof. Aaron Arehart

Transistor-based defect spectroscopy studies of rad-fx in WBG/UWBG

Prof. Tyler Grassman

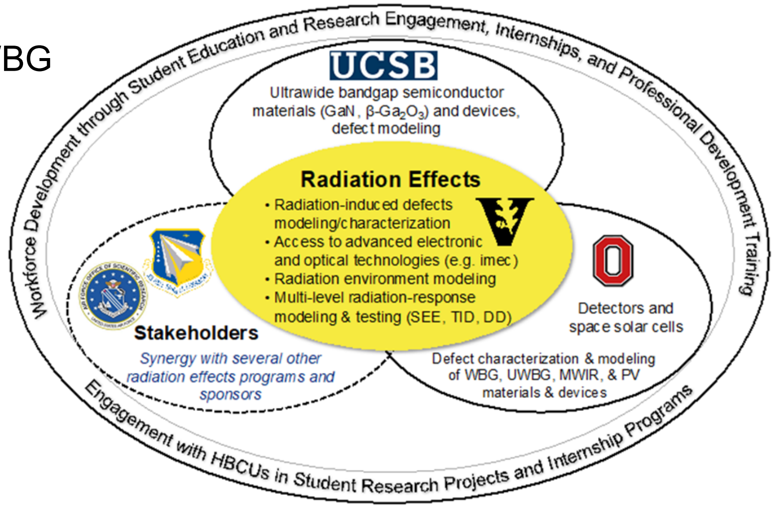
Space solar cell growth, fabrication, electron microscopy

Prof. Siddharth Rajan

MBE growth, transistor design, fabrication and modeling

Prof. Hongping Zhao (unfunded collaborator)

MOCVD growth and materials studies



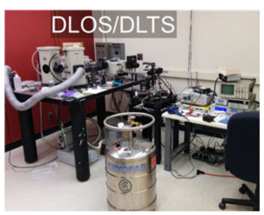
<u>COE Interactions</u>

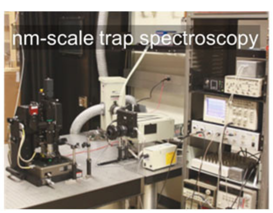
Theory, modeling: Van de Walle, Pantelidis

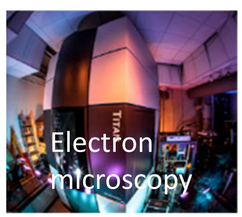
Radiation/characterization: Fleetwood, Schrimpf, Lang

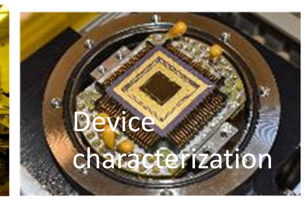
Materials/devices: Speck and industry/AFRL

External: Sandia IBL (Ed Bielejec, Chris Smyth, Eric Smith, Bas Vaandrager), Solaero/RocketLab (Zach Bittner, Daniel Derkacs, Nate Miller)









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Outline

A. Quick summary of last year to level-set

B. Current year highlights and progress

I. Systematic study of factors affecting carrier removal/recovery dynamics in proton irradiated β-Ga_2O_3 Schottky diodes

a) Doping concentration, depletion depth and spatial damage profile
b) Ex-situ (post) and in-situ (during irradiation) applied E-fields

II. Ionizing and Displacement Damage of Ni/Al_2O_3/β-Ga_2O_3 MIS Capacitors

a. TID and DD under bias: creation of a TID equivalency relation between xrays and protons
b. X-ray charge generation rate study for unifying and predicting TID damage

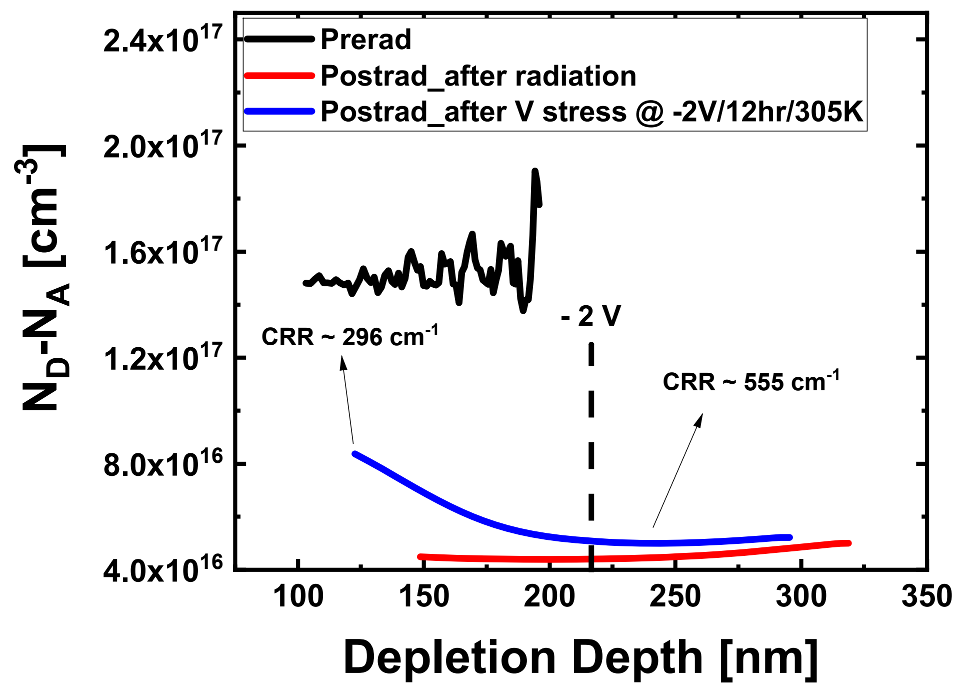
III. [Heavy ions (Au) studies on GaN and β-Ga_2O_3 are presented by Aaron Arehart, next]

C. Summary and near-term plans

Recap from last year and basis for part I today

Proton-irradiated β-Ga_2O_3 Schottky diodes

- Identified the primary sources of carrier compensation at E_C-0.7 eV, E_C-1.2 eV and **E_C-2.0 eV (dominant)** using DLTS and DLOS
- Revealed impact of post-rad applied voltage on carrier removal rate (CRR)
  - Observed **depth dependent CRR**
  - Presented carrier **recovery** model related to an apparent field-assisted defect diffusion process within Schottky depletion region based on time & depth-dependent carrier recovery measurements – **basis for today's presentation on root causes**



H. Ghadi, et al. Manuscript in preparation

Additional motivation: significant variation observed for carrier removal rates (CRR) in proton irradiated β-Ga_2O_3

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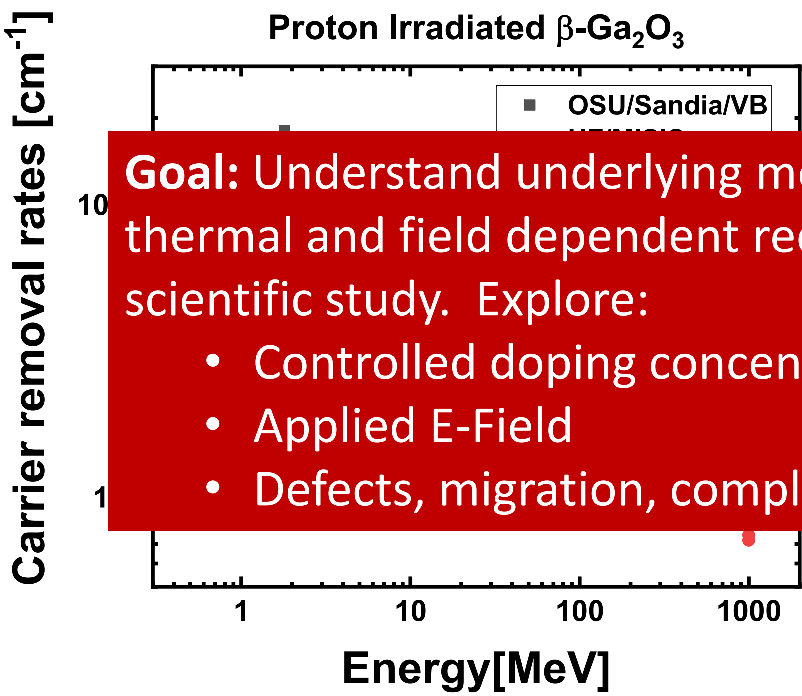
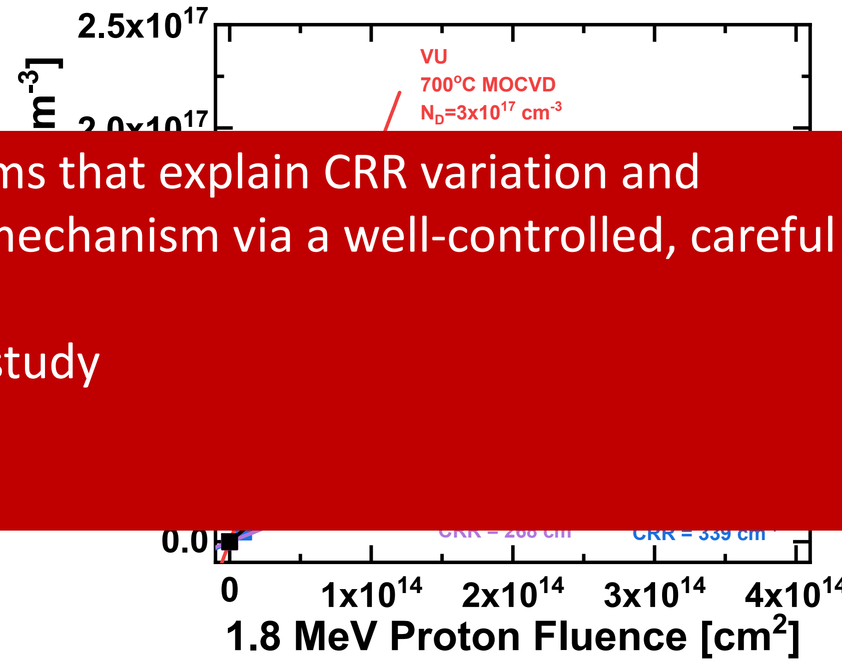
Significantly inconsistent CRR rates in literature

…and even in this COE!!!



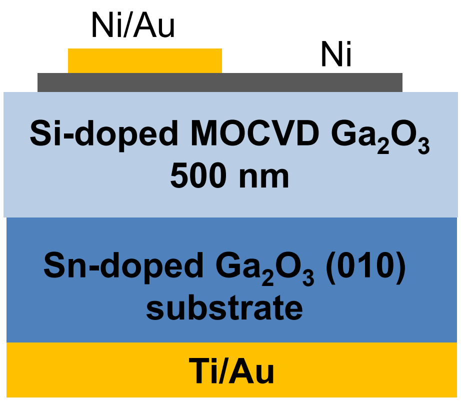


Goal: Understand underlying mechanisms that explain CRR variation and thermal and field dependent recovery mechanism via a well-controlled, careful scientific study. Explore:

- Controlled doping concentration study
- Applied E-Field
- Defects, migration, complexes

1. Mcglone et al, J. Appl. Phys. 133, 045702 (2023)
2. Ingebrigsten et al, APL Mater. 7, 022510 (2019)
3. Kim et al, J. Mater. Chem. C, 2019, 7, 10—24.
4. Pearton et al, Gallium Oxide Technology, Devices and Applications Metal Oxides, 2019, Pages i-ii
5. Li et al, J. Phys. Mater. 6 (2023) 045003.
6. Polyakov et al, J. Appl. Phys. 123 115702
7. Polyakov et al, APL Mater. 6 096102
8. Polyakov et al 2018 Appl. Phys. Lett. 113 092102

Controlled doping sample series for CRR studies



Device Schematic

MOCVD Growth (Hongping Zhao)

Constant Growth Conditions

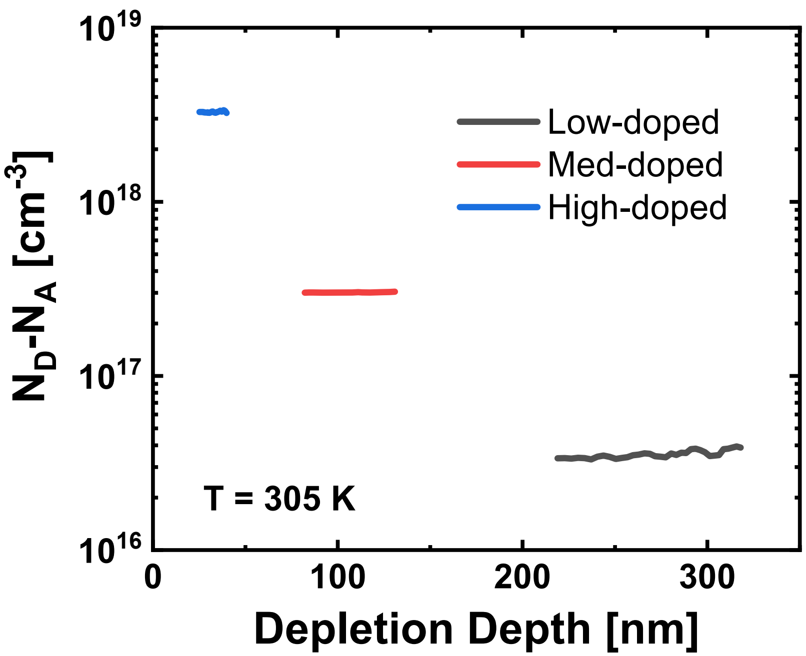
Growth temp: 880°C
Chamber pressure: 60 torr
Growth rate: 650 nm/hr
Growth thickness: 500 nm

Variable Silane Flow

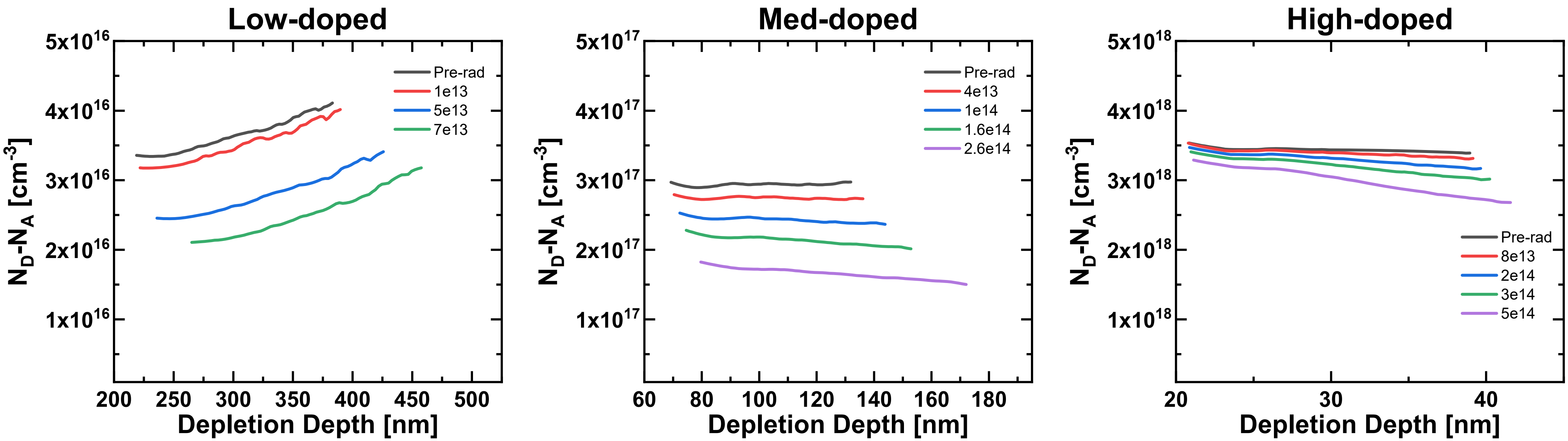
Silane Flowrate (nmol/min):
Low doped: 0.0275
Med doped: 0.248
High doped: 2.56

Sandia Ion Beam Lab - 3 MeV Pelletron

- Packaged and wire bonded
- in-situ biasing and testing
- Variable range of fluences for each sample
- Proton beam flux ~1×10^{11} $p^+/cm^2/s$

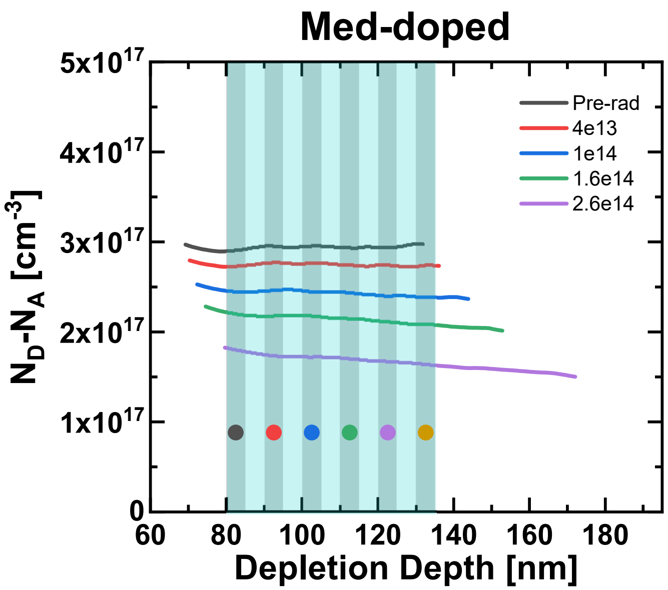


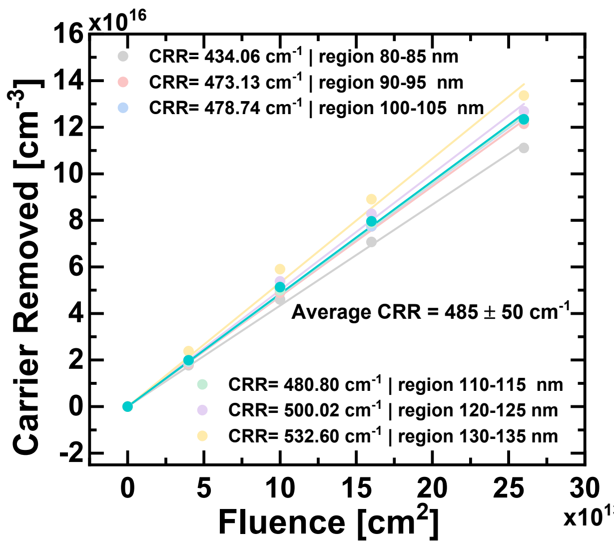
Irradiation Damage Observed on Grounded Devices

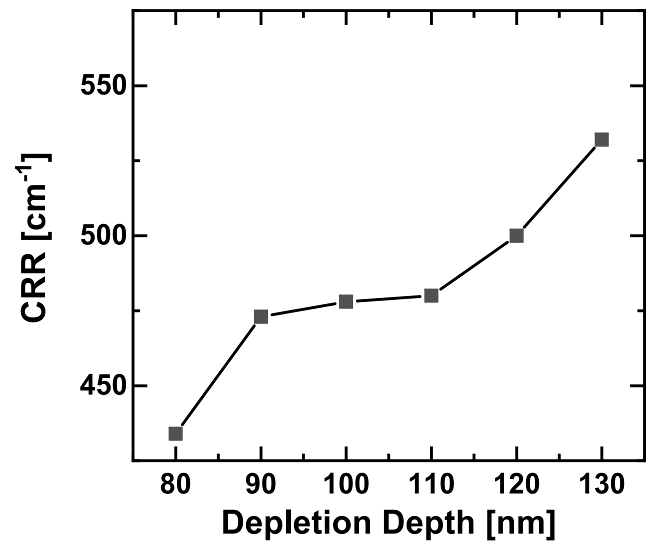


- In-situ C-V measurements enable a rapid study with multiple fluences
- Evidence of non-uniform changes in N_D-N_A profile that increases for higher (Si) doping concentrations
  - ***Need to look at changes in N_D-N_A as a function of fluence and depth (next slides)***

Calculating depth-dependent carrier removal rate

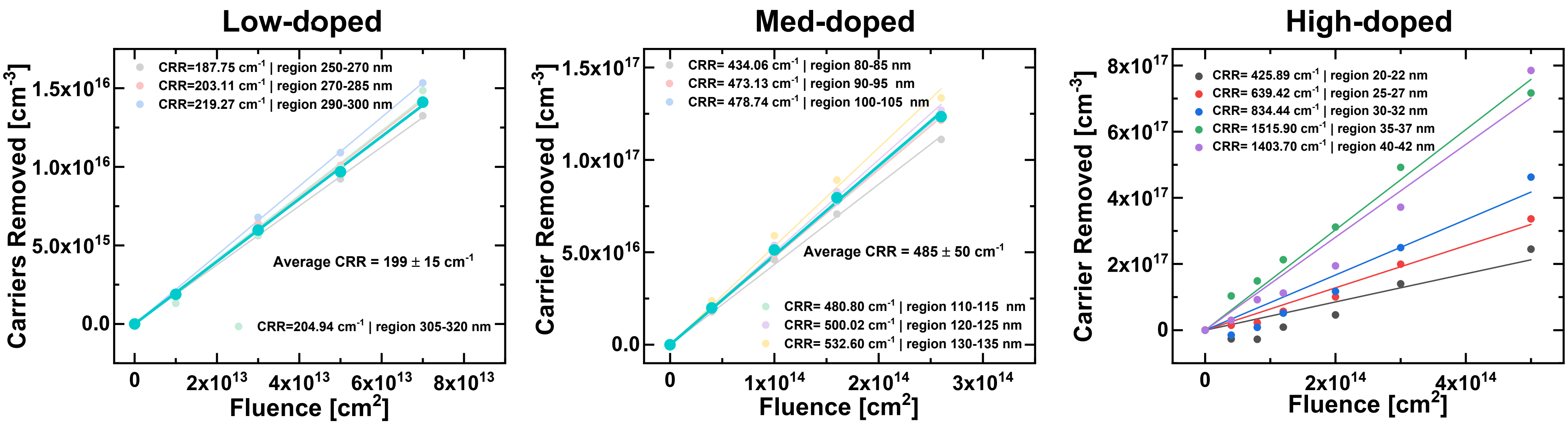






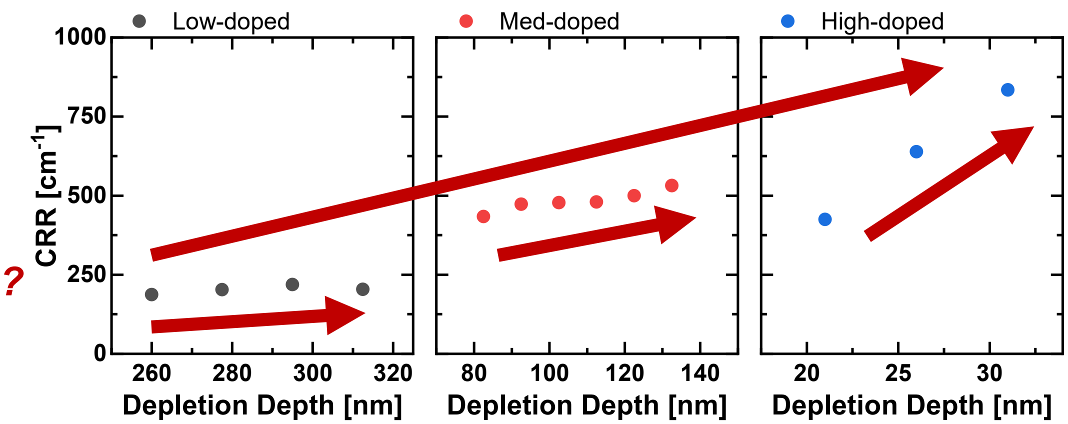
1. Average each fluence's N_D-N_A value within the shaded window
2. Calculate the difference from pre-rad
3. Plot carrier removal vs. fluence
4. Linear fit
5. Repeat in additional windows

Carrier removal rates in Grounded Devices



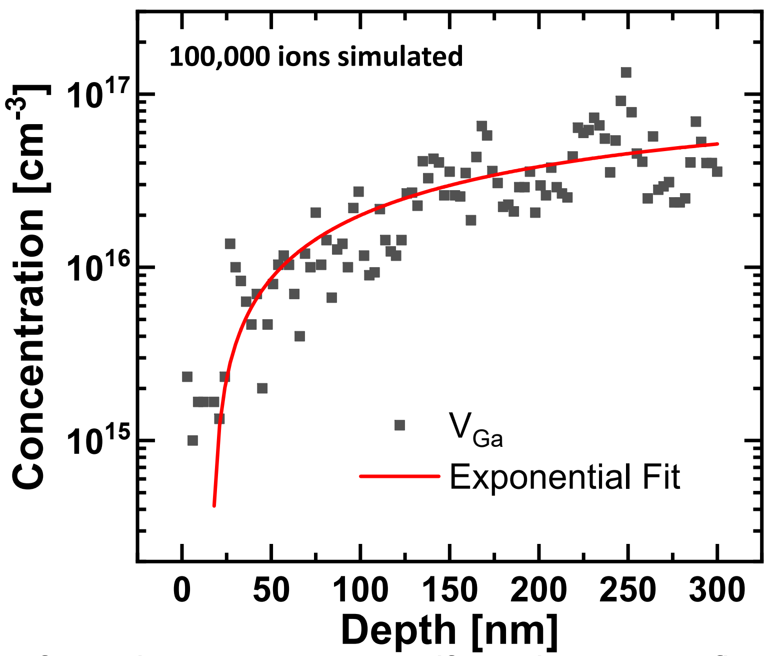
Two major observations:

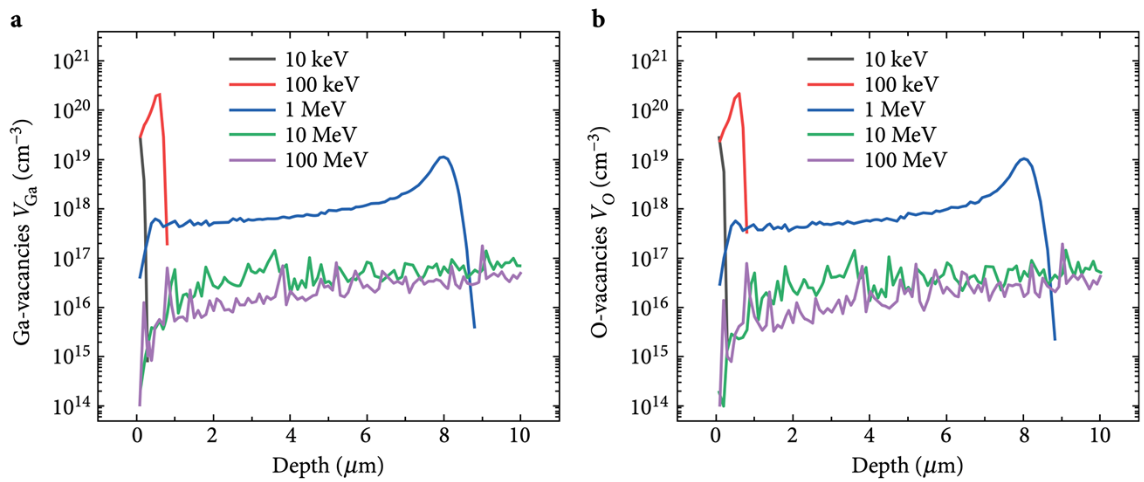
- CRR magnitude increases with increase in doping concentration
  - ***Interaction between damage and donors?***
- Depth dependence of CRR increases with doping
  - ***More variation near surface – damage profile?***



Exploring Source of Depth Dependence

Vacancies profile simulated from SRIM/TRIM





Expecting more uniform damage deeper into the material

[1] H. J. Ghadi, J. F. McGlone, E. Farzana, A. R. Arehart, and S. A. Ringel, "Radiation Effects on β-Ga2O3 Materials and Devices," in Ultrawide Bandgap β-Ga2O3 Semiconductor: Theory and Applications, AIP Publishing LLC, 2023, pp. 12-1–12-26. DOI: 10.1063/9780735425033_012

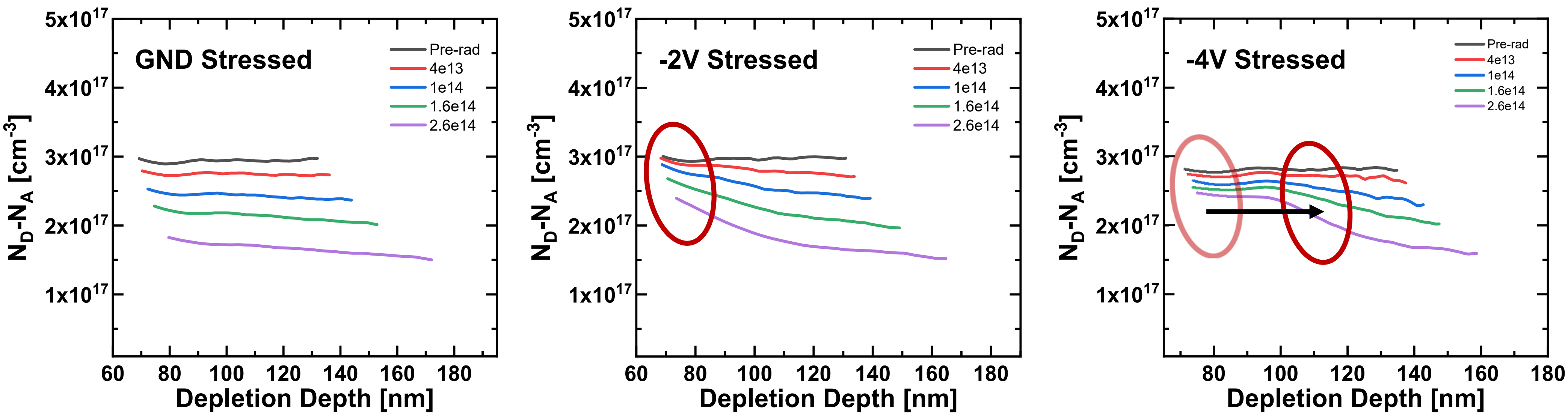
10^{16} 0 100 200 300 400 500

Depletion Depth [nm]

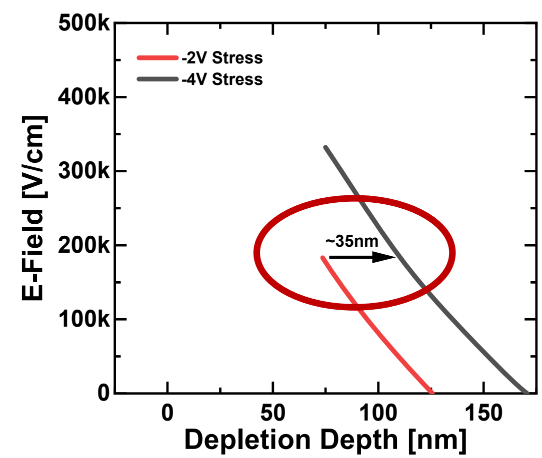
- Vacancy formation suggest non-uniform damage profiles near surface
- Less damage is expected in front compared to back
  - Seems to be consistent for CRR profile within each sample
  - BUT, implies a low CRR in high-doped sample compared to med and low-doped from measured C-V
    - ***Opposite of observed – need another explanation?***

Depth dependence of CRR in each sample is roughly consistent with exponential damage profile

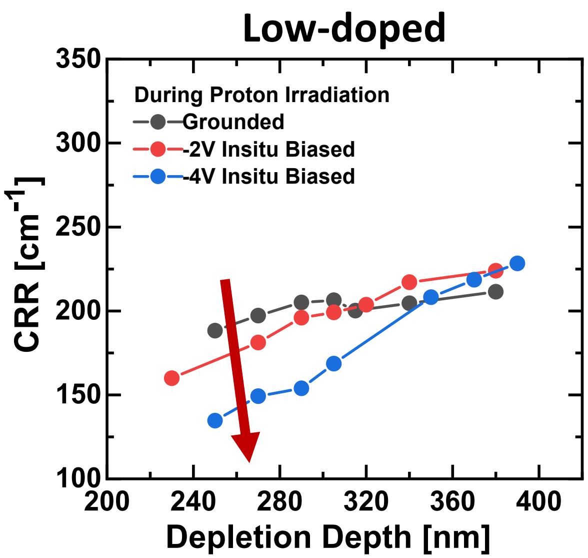
Impact of in-situ Biasing – Med-doped Example

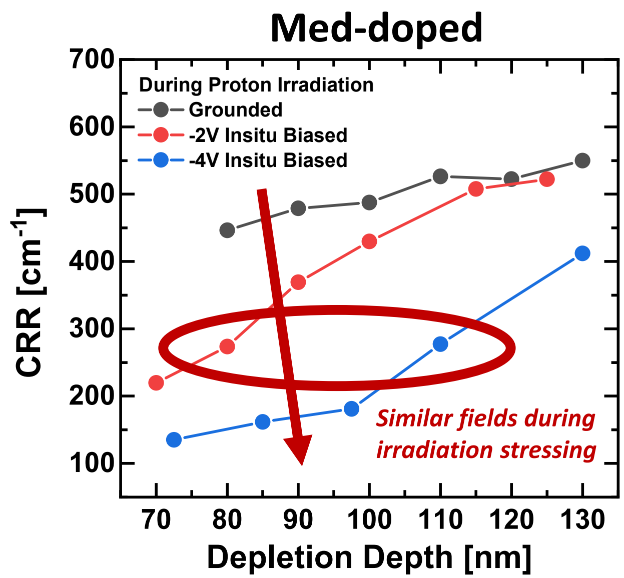


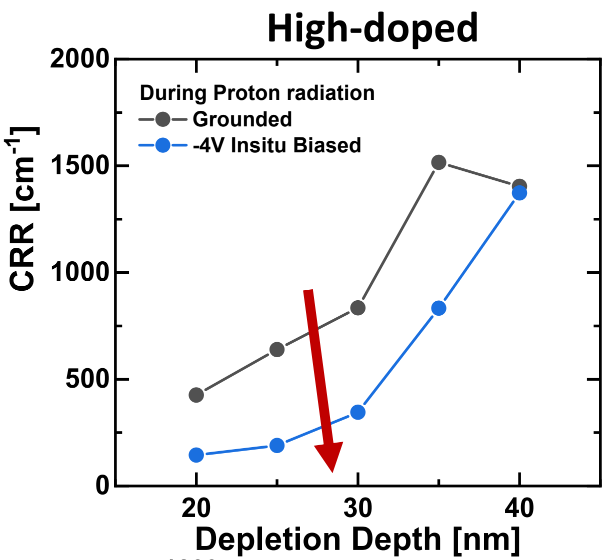
- **In-situ biasing enhances carrier recovery (curves coming close together)**
  - No field in measured region during irradiation in GND condition
  - More recovery where E field is larger – nearer to surface
  - Recovery is same for both biases in regions where field strength is same
    - recovery depends on field, not voltage, in this range
    - Example on right: similar carrier recovery at ~180 kV/cm in both devices



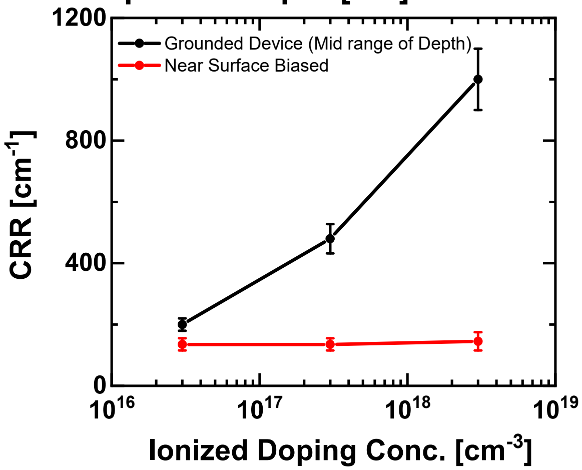
Investigating the role of in-situ E field in CRR improvement







- **Regions with similar applied field during irradiation recover to similar CRR**
- Monotonic decrease in CRR with increasing biasing
- Minimum CRR of 130-150 cm^{-1} where the electric field is highest near the surface
  - ***Applied field during irradiation results in predictable CRR for all samples***
  - ***Devices in operation with applied fields should have higher radiation tolerance***
- Need to consult with theorists to understand the underlying mechanism of these observations



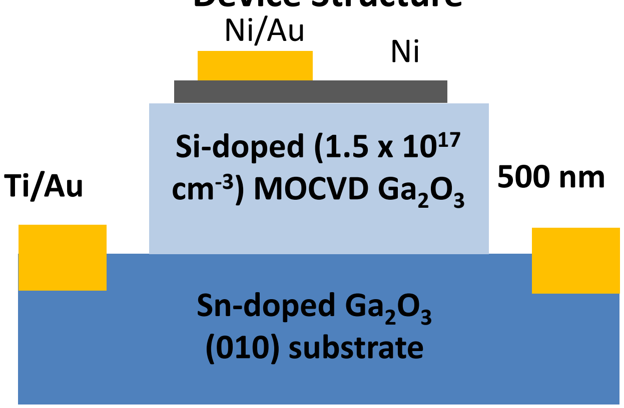
Now, let's explore the thermal activation with no field

Proton Irradiation Conditions (VU):

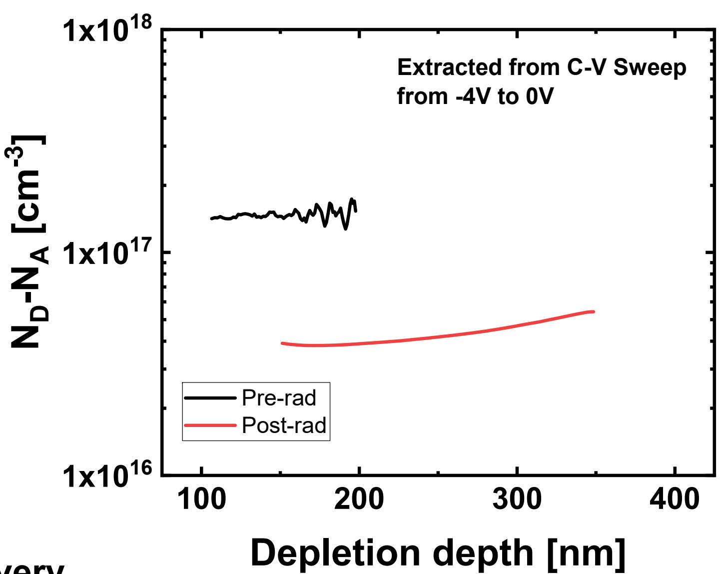
- Energy: 1.8 MeV
- Fluence: 2×10^{14} cm^2

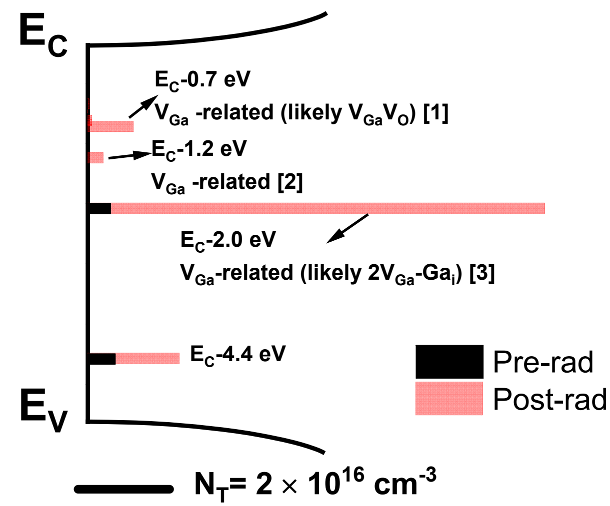
Doping concentration profiles (CV) and defect distributions using deep level thermal/optical transient spectroscopy (DLTS/DLOS), and Lighted CV (LCV)

Device Structure



Sample



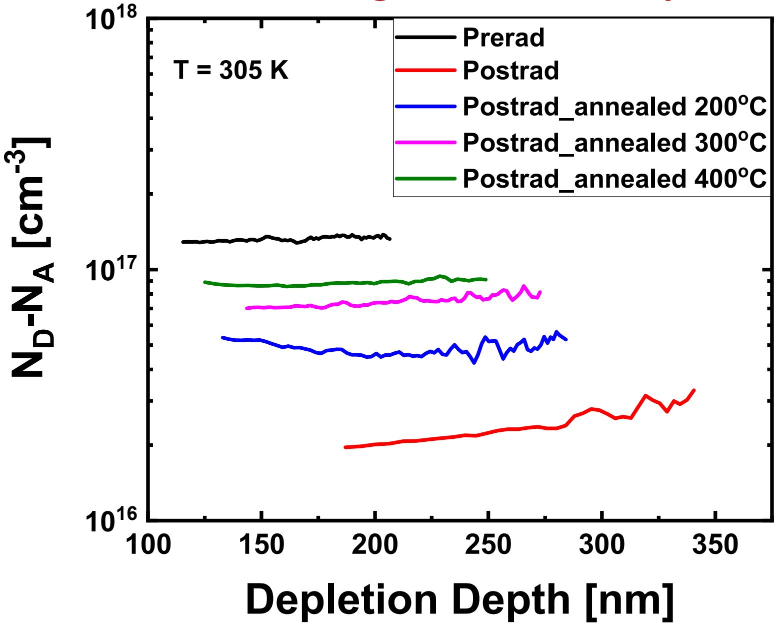


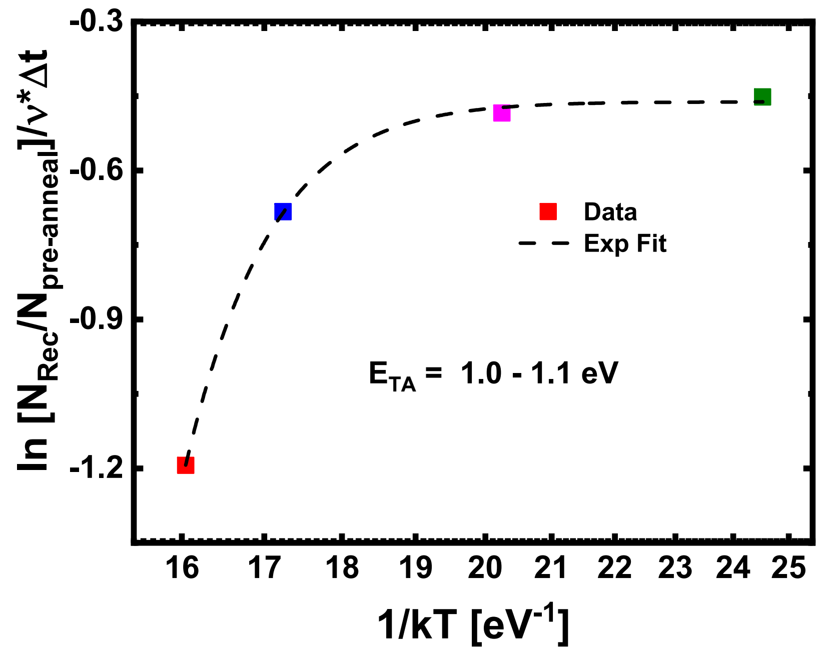
- **Multiple sample sets prepared**
- **Multiple devices measured for every experiment**

1. Frodason et al, Physical review materials 5, 025402 (2021)
2. Mcglone et al, J. Appl. Phys. 133, 045702 (2023)
3. Johnson et al, PHYS. REV. X 9, 041027 (2019)

Modeling the carrier recovery to a single activation energy

No bias stressing on devices; impact can be considered only from thermal annealing





- **Annealing in N_2 ambient.**
- **Anneal time: 5 mins.**

$$\frac{N(recovered)}{N(Pre\ anneal)} = \exp(-\nu t * \exp\left(-\frac{qE_{TA}}{kT}\right)\ [1,2]$$

ν = attempt frequency, k= Boltzmann const, t= time, T = temperature

- A single activation energy for carrier recovery with temperature as a variable.
- Literature reported the thermal activation energy of CRR between 1.0-1.2 eV [3].

[1] Zhang et al, Journal of applied physics 118, 155701 (2015) [2] Umana-membrano, J. Appl. Phys. 101, 054511 2007 [3] M. Ingebrigsten et al, APL 112, 042104 (2018).

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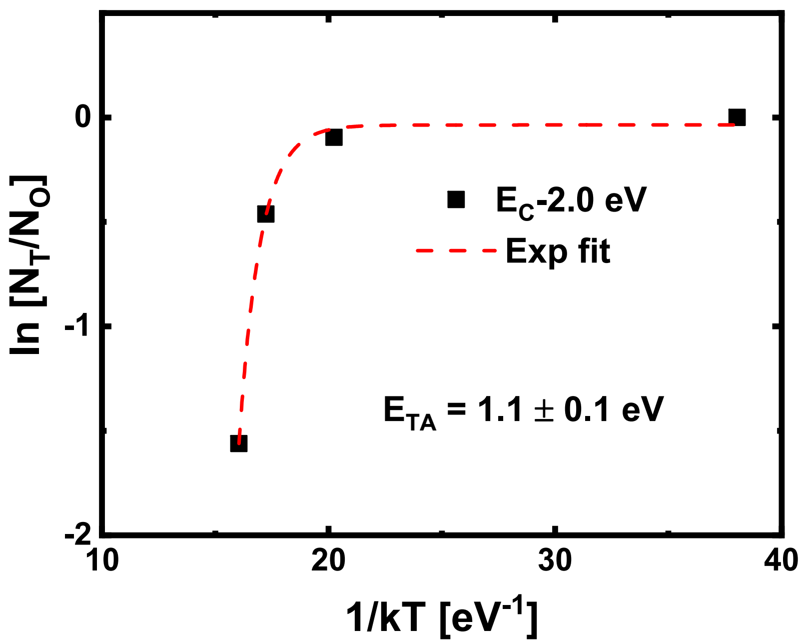
Modeled thermal annealing of individual defect states

Trap Concentration Annealing Kinetics
(from DLOS and DLTS results]



$$\frac{N_T}{N_O} = \exp(-vt * \exp\left(-\frac{qE_{TA}}{kT}\right) \text{ [1,2]}$$

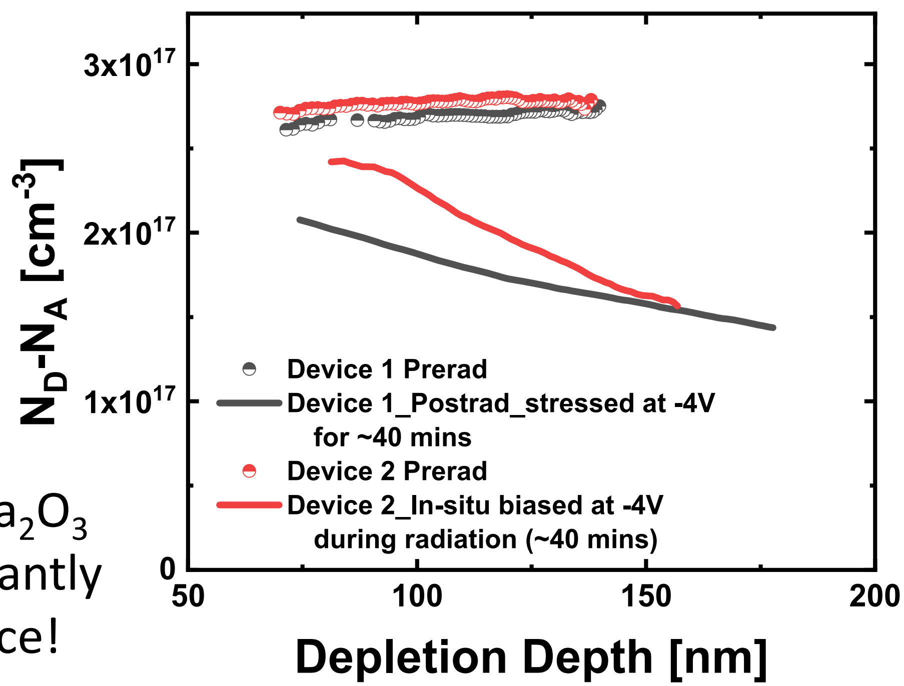
1. Zhang et al, Journal of applied physics 118, 155701 (2015)
2. Umana-membrano, J. Appl. Phys. 101, 054511 2007

Defect	annealing activation energy [eV]	% contribution to carrier compensation
E_C-0.34	0.5 ± 0.1	0.002
E_C-0.6	0.3 ± 0.05	0.001
E_C-0.7	0.85 ± 0.05	7
E_C-1.2	1.2 ± 0.1	3
E_C-2.0	1.1 ± 0.1	75

- **E_C-2.0 eV is the primary compensating defect, with 75% contribution**
- **The E_C-2.0 eV activation energy for annealing matches the overall carrier recovery activation energy**

Proton irradiation damage and recovery summary for β-Ga_2O_3

- CRR varies with doping concentration, depth, and electric field strength
- E-field increases carrier recovery
  - Further enhanced when *biasing during irradiation*
  - Implications for operating vs off/grounded conditions
- Apparent minimum CRR ~ 150 identified for β Ga_2O_3
  - Applying bias when determining CRR significantly addresses CRR scattered values – best practice!
- Carrier recovery by thermal annealing explained by annealing of E_C-2.0 eV trap related to V_{Ga}



Part II: Ionizing and Displacement Damage of $Ni/Al_2O_3/\beta$-Ga_2O_3 MIS Capacitors: recap from last year

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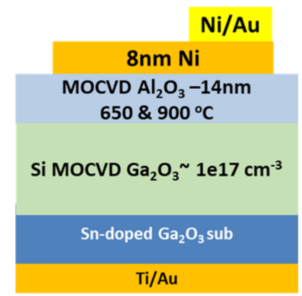
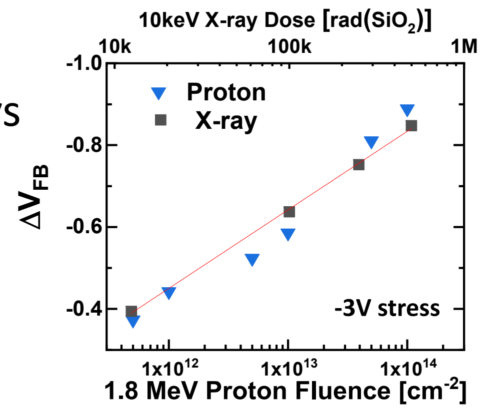
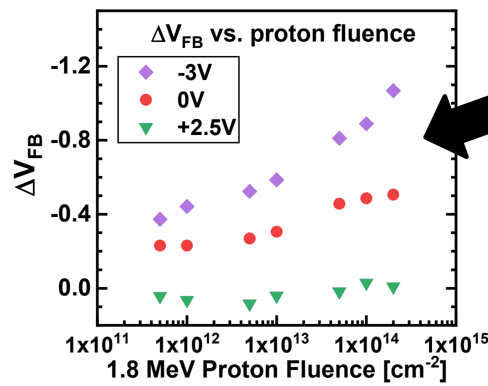
Initial x-ray vs proton irradiation studies on $Ni/Al_2O_3/\beta$-Ga_2O_3 MISCAPS

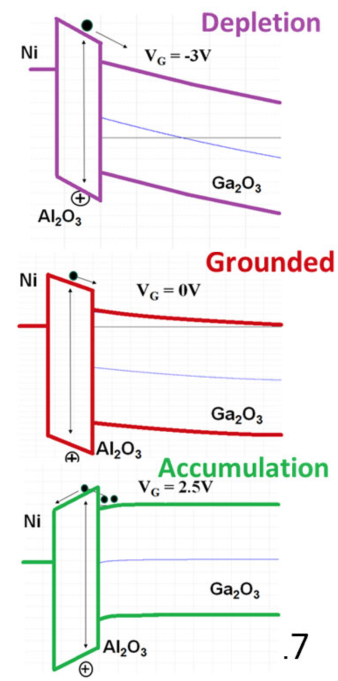


- Identified and quantitatively separated **TID** and **Displacement** for protons by comparing with x-rays
- Similar trends in TID response for both sources – introduced a TID-equivalency correlation between proton and x-ray sources



- In-situ biasing effects on TID response of β-Ga_2O_3 MISCAPS:
  - Increasing V_R inhibits EHP recombination and increases net + charge and **ΔV_{FB}**
  - Negligible **ΔV_{FB}** at forward bias

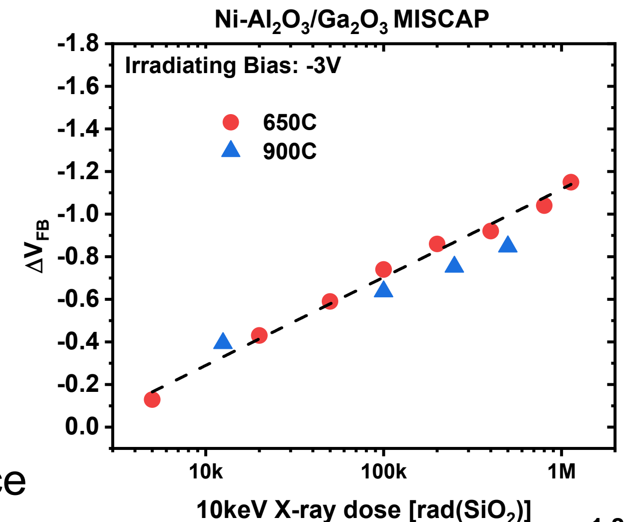


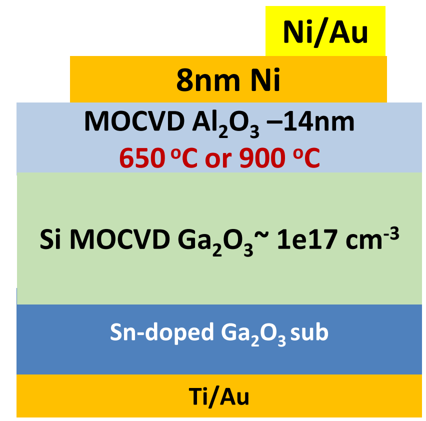


All done on 900 C Al2O3 MISCAPs

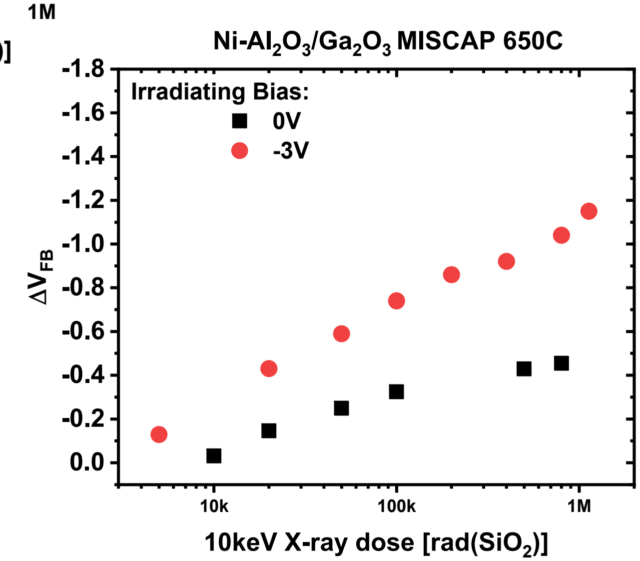
Investigating a model for TID effects

- Both Al_2O_3 growth temperatures show similar ΔV_{FB} under the same irradiating condition and similar bias dependence.





- Variable ΔV_{FB} with applied field and fluence
  - Results in wide range of values
  - Requires time-consuming testing at different biases and doses to map out the damage space
  - ***Would like to have a predictive model***

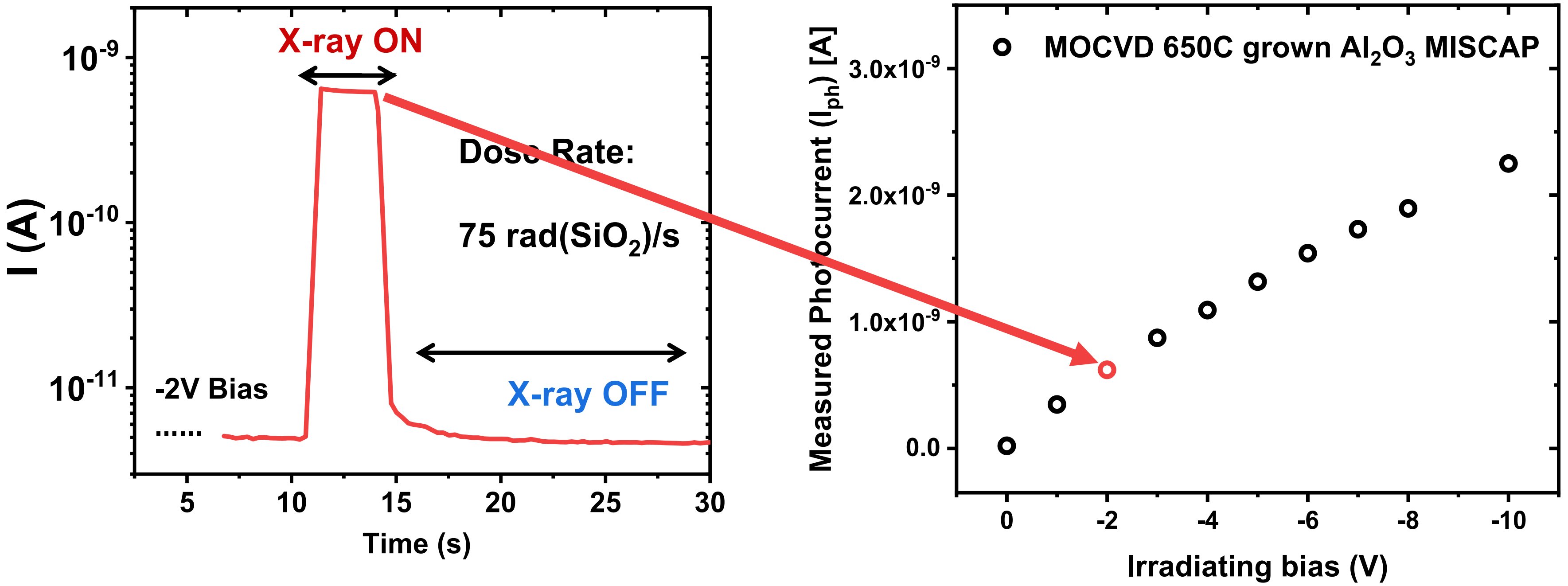


Focus: Model TID response by field dependent charge generation
- ***Obtained by observing changes in bias dependent photocurrent measurements [1]***

[1] J. M. Benedetto (1986) IEEE Transactions on Nuclear Science, Vol. NS-33, No. 6,

Experimental Setup

- Devices irradiated using 10keV X-ray (ARACOR 4100 at Vanderbilt University) at low dose rate of 75rad(SiO2)/s for short amount of time
- **In-situ** measurement example shown below. Recorded average current values on a range of different **in-situ** bias values



Approach for charge generation rate model

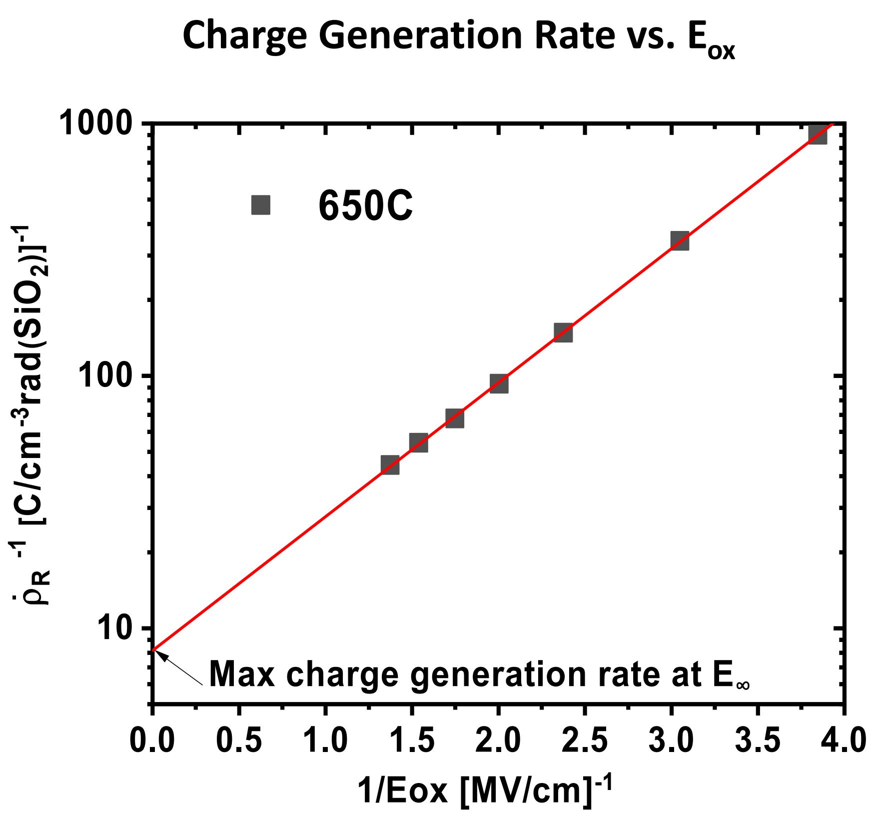
- Inverse photocurrent vs. inverse oxide field yields linear relation (columnar ionization model [1,2])
- charge generation rate:

$$\dot{\rho_R} = \frac{I_{ph}}{At_{ox}\,\dot{D}} \quad [C/cm^3\,rad(SiO_2)]$$

- The y-intercept indicates maximum possible charge generation rate (for 10keV X-rays used here)

➡ Can obtain charge generation rate for **any applied field**

➡ Net charge generated (C/cm^{-3}) = charge gen rate x **dose**

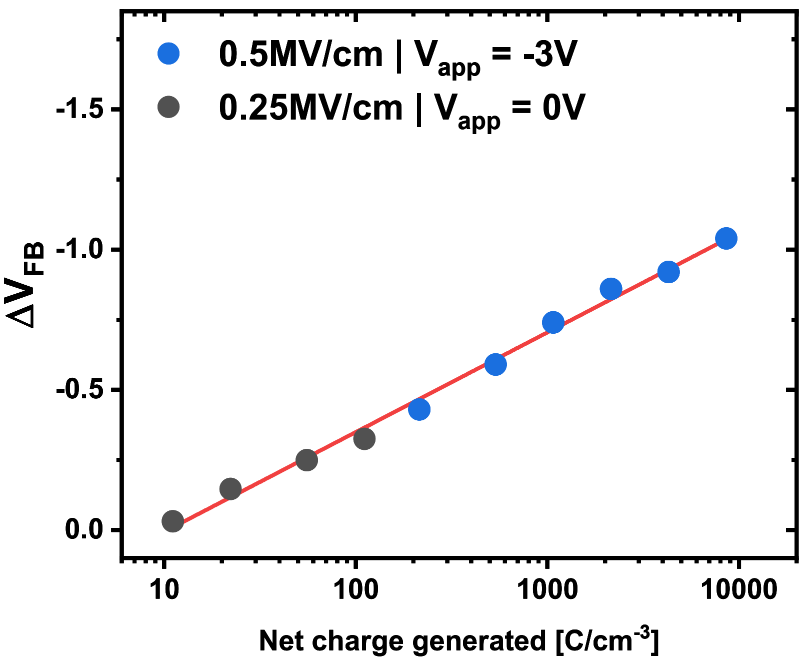


[1] J. M. Benedetto (1986) IEEE Transactions on Nuclear Science, Vol. NS-33, No. 6,

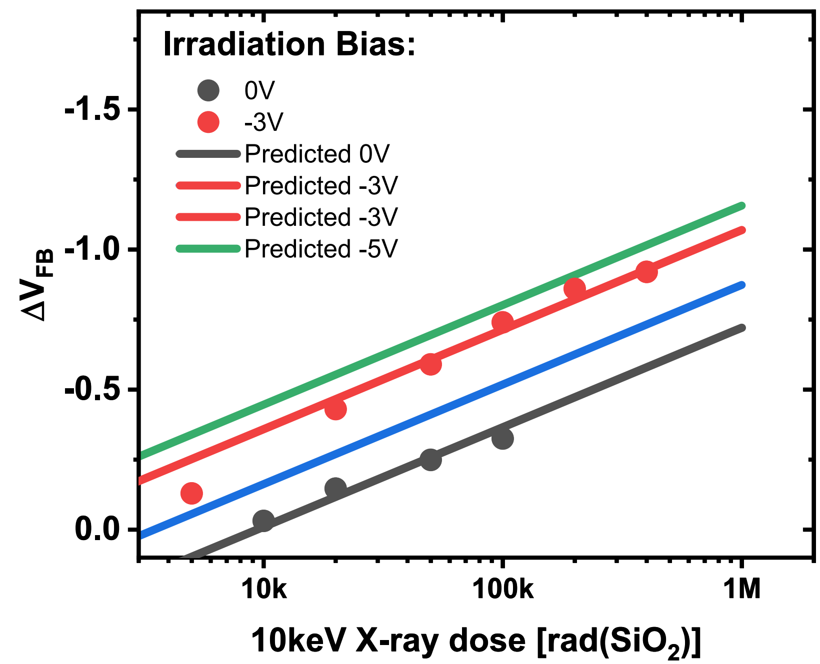
[2] G. A. Ausman, Jr., and F. B. McLean, Appl. Phys. Lett. 26 173-175 (1975).

Charge generation model to predict TID induced ΔV_{FB} for arbitrary biases and x-ray dose

ΔV_{FB} versus net charge generated



ΔV_{FB} vs x-ray dose as function of applied bias



- Work to verify is ongoing
- Can be used to predict proton-induced ΔV_{FB}

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Overall highlights and summary for year 3

Carrier removal & recovery dynamics for proton-irradiated b Ga_2O_3

- CRR varies with doping conc, depth, field strength for grounded devices
- In-situ bias can reconcile wide variations in reported CRR values & allow comparisons
- Apparent min CRR ~ 150 identified for β Ga_2O_3
- Carrier recovery by thermal annealing due to annealing of E_C-2.0 eV V_{Ga}-related trap

TID effects and predictive modeling for MIS β Ga_2O_3 devices

- Bias dependence & charging in MIS from TID similar for x-rays and protons
- X-ray - proton TID equivalence relation
- Initial predictive model used to quantify TID effects over wide range of biases and radiation doses for X-ray without exhaustive testing

Near-Term Plans

β-Ga_2O_3

- Continuing CRR - doping concentration study
  - Temp-dependent Hall, growth conditions, investigating doping effects in GaN
- Time/field dependence of post-rad recovery
- Continuing thermal annealing kinetics study
- *Consult with theorists on open questions*

Extend Studies to High Field Structures

- Investigate GaN and β-Ga_2O_3 high field structures and the impact of protons – ***thick drift layers***
- Move on to heavy ions to study SEE under off-state biases

MIS Structures

- Verify model at wider range of biasing conditions
- Apply methodology to different MIS
  - Al_2O_3 via ALD, Al_2O_3/BTO high-k
  - GaN MISCAPs

Radiation effects in III-V space solar cells

- 2.1 eV bandgap AlGaInP toll cell of 34% efficient multjunction – metamorphic vs lattice matched
  - Dislocation – rad induced defect interactions
  - Protons; heavy ions from 50 eV – 200 keV
  - Depth resolved DLTS/DLOS – point to cluster defect formation

THE OHIO STATE UNIVERSITY

List of publications with partial or full COE support for year 3

Journals

1. Hemant Ghadi, Evan Cornuelle, Joe F McGlone, Alexander Senckowski, Shivam Sharma, Uttam Singisetti, Man Hoi Wong, Ymir Kalmann Frodason, Hartwin Peelaers, John L. Lyons, Joel B. Varley, Chris G. Van de Walle, Aaron Arehart, Steven A Ringel, "Comprehensive characterization of nitrogen-related defect states in β-Ga_2O_3 using quantitative optical and thermal defect spectroscopy methods", APL Mater. 12, 091111 (2024).
2. Hemant Ghadi, Evan Cornuelle, Joe F McGlone, Alexander Senckowski, Shivam Sharma, Uttam Singisetti, Man Hoi Wong, Ymir Kalmann Frodason, Hartwin Peelaers, John L. Lyons, Joel B. Varley, Chris G. Van de Walle, Aaron Arehart, Steven A Ringel, "Identification and characterization of deep nitrogen acceptors in β-Ga_2O_3 using defect spectroscopies", APL Mater. 11, 111110 (2023).
3. H. Lee, J. F. McGlone, S. Ifatur Rahman, C. Chae, C. Joishi, J. Hwang, and S. Rajan, "Investigation of Interlayer Dielectric in $BaTiO_3$/III-Nitride Transistors," *physica status solidi (RRL) – Rapid Research Letters*, vol. 18, no. 8, p. 2400042, 2024. DOI: 10.1002/pssr.202400042

Conferences

1. **(Invited)** Steve Ringel, Hemant Ghadi, Joe F. McGlone, Ashok Dhenena, Siddharth Rajan, Aaron Arehart, Alexander Senckowski, Shivam Sharma, Lingyu Meng, Hongping Zhao, Man Hoi Wong and Uttam Singisetti, Defect spectroscopies studies of Deep Acceptors in β-Ga_2O_3 GOX 2024, Columbus, OH.
2. Hemant Ghadi, Tal Kasher, Randy Carver, Joe McGlone, Lingyu Meng, Dong S Yu, Mike McCurdy, Hongping Zhao, Daniel Fleetwood, Ronal Schrimpf, and Steven A. Ringel, Investigating Thermal Stability and Influence of Electric Field on Radiation Induced Defects in β-Ga_2O_3, GOX 2024, Columbus, OH.
3. **(Invited)** Joe F. McGlone, Hemant Ghadi, Hyunsoo Lee, Daniel M. Fleetwood, Aaron Arehart, Siddharth Rajan, Steven A. Ringel, "Impact of Radiation on Wide and Ultrawide Bandgap Materials and Devices", National Aerospace and Electronics Conference (NAECON), Dayton, OH, July 2024.
4. Tal Kasher, Hemant Ghadi, John T. Hart, Zachary S. Bittner, Andrew Espenlaub, Daniel Derkacs, Nate Miller, Tyler J. Grassman, Steven A. Ringel, "Trap Analysis of Zn- vs. C-doped 2.1eV AlGaInP Irradiated by 3MeV Protons," Space Photovoltaics Research and Technology Conference, Cleveland, OH, 2024.
5. Tal Kasher, Hemant Ghadi, John T. Hart, Zachary S. Bittner, Andrew Espenlaub, Daniel Derkacs, Nate Miller, Tyler J. Grassman, Steven A. Ringel, "Trap Analysis of Zn- vs. C-doped 2.1eV AlGaInP Irradiated by 3 MeV Protons," Photovoltaics Specialist Conference, Seattle, WA.