Performance Degradation of Neutron Irradiated 4H-SiC LGADs

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Outline

- Introducing the Team
- Background
- Fabrication Process of 4H-SiC LGADs
- Electrical Characteristics of Irradiated 4H-SiC LGADs
- Charge Collection Characteristics of Irradiated 4H-SiC LGADs
- Conclusion

NCSU-L(BNL)^2 Collaboration

- **NC State University**
  - Expertise
    - Fabrication, characterization, and simulation of (ultra-) wide bandgap semiconductor devices
    - Members: Dr. John Muth, Dr. Spyridon Pavlidis, Dr. Gil Atar, Dr. Philip Barletta, Dr. Ben Sekely, Greg Allion, Yashas Satapathy

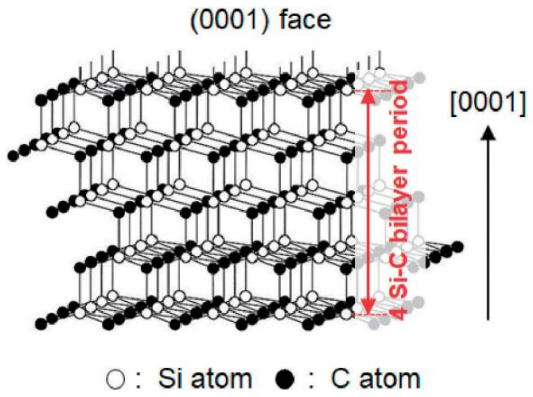
- **Lawrence Berkeley National Laboratory**
  - Expertise
    - Detector and electronics development and characterization for high energy physics
    - Members: Dr. Carl Haber, Dr. Steve Holland, Dr. Tao Yang, Dr. Haichen Wang (UC Berkeley), Chenxi Yang (UC Berkeley)

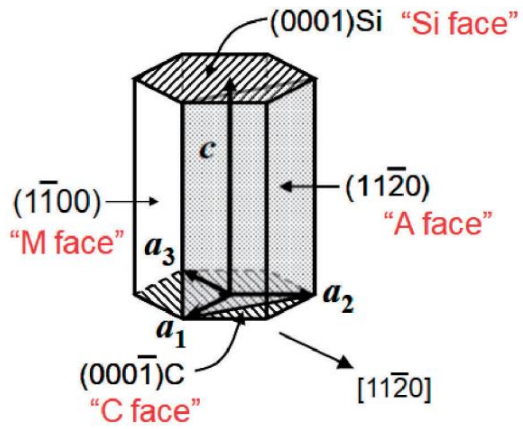
- **Brookhaven National Laboratory**
  - Expertise
    - Fabrication, characterization, and simulation of Si LGADs
    - Detector and electronics development and characterization for high energy physics
    - Members: Dr. Stefania Stucci, Dr. Abraham Tishelman-Charny

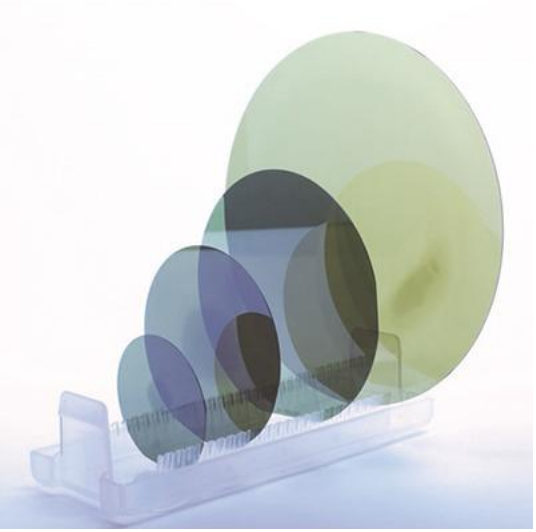
- **Supporting Institutions and Organizations**
  - Brown University
  - UC Berkeley
  - Rice University
  - NASA Space Radiation Laboratory (NSRL)
  - Rhode Island Nuclear Science Center (RINSC)
  - NCSU Nanofabrication Facility (NNF)
  - NCSU PULSTAR Reactor

Incorporating 4H-SiC into LGAD Technology

- Properties
  - Hexagonal crystal structure w/ an ABAC stacking sequence
  - Indirect bandgap of 3.26 eV
- Current status
  - Large substrates (up to 200 mm)
  - Mature processing technologies
- Advantages over Si-based devices
  - Potentially higher radiation hardness
  - Reduces need for extensive cooling systems
- **Objective**
  - Fabricate a functional 4H-SiC LGAD and determine its radiation hardness



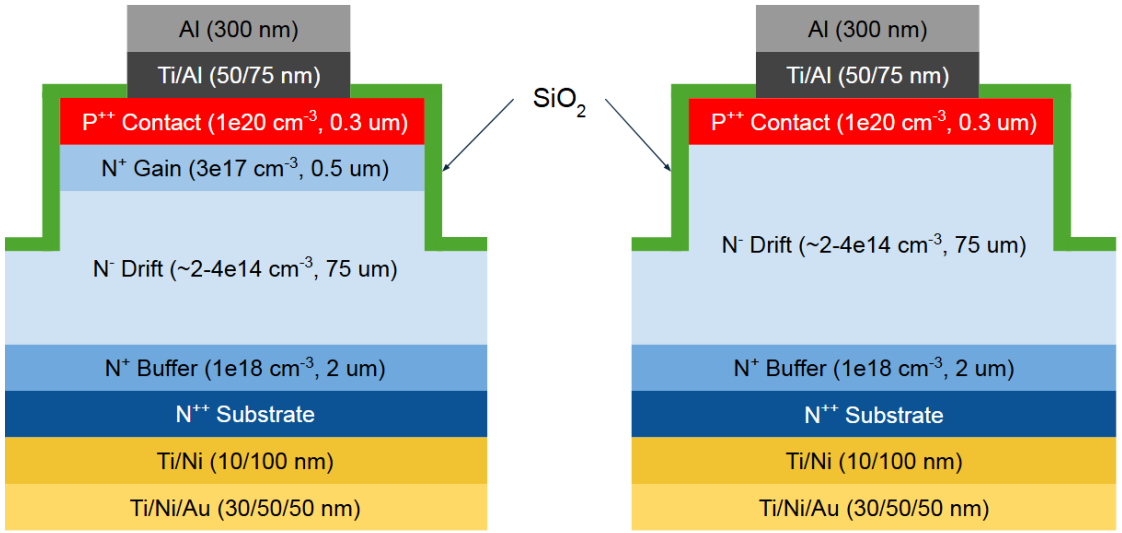




Kimoto, T. and Cooper, J. A. (2014). Fundamentals of Silicon Carbide Technology: Growth, Characterization, Devices and Applications. John Wiley & Sons. Google- Books-ID: 586iBAAAQBAJ.
Kimoto T. High-voltage SiC power devices for improved energy efficiency. Proc Jpn Acad Ser B Phys Biol Sci. 2022;98(4):161-189. doi: 10.2183/pjab.98.011. PMID: 35400694; PMCID: PMC9071924.
https://www.plutosemi.net/show-105-426-1.html

Neutron Irradiation Campaign

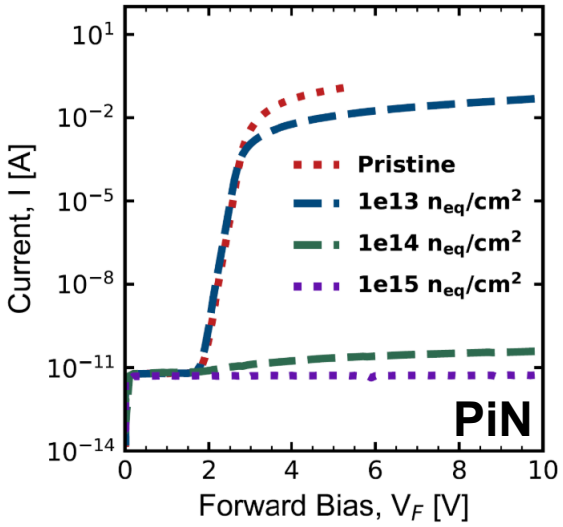
- LGADs and complementary PiN diodes were irradiated at the Rhode Island Nuclear Science Center (RINSC)
- Fluences: Non-irradiated (pristine), 1e13, 1e14, 1e15 n_{eq}/cm^2
- Gamma ray exposure: 0.0097 kGy, 0.097 kGy, and 0.97 kGy
- **Goals:**
  - Investigate the electrical and charge collection characteristics of an irradiated LGAD
  - Begin developing a model to explain the performance of an irradiated LGAD

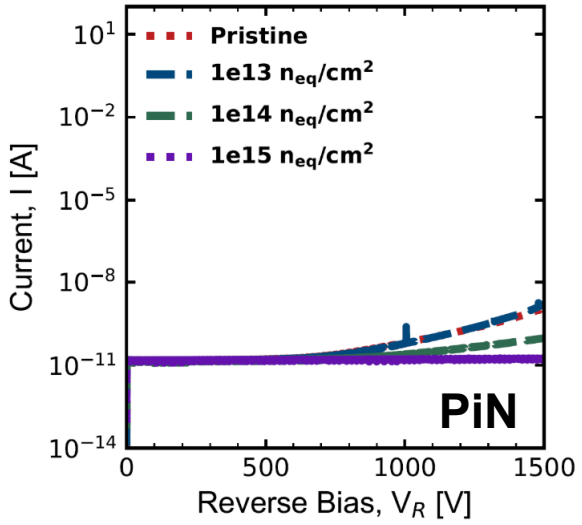


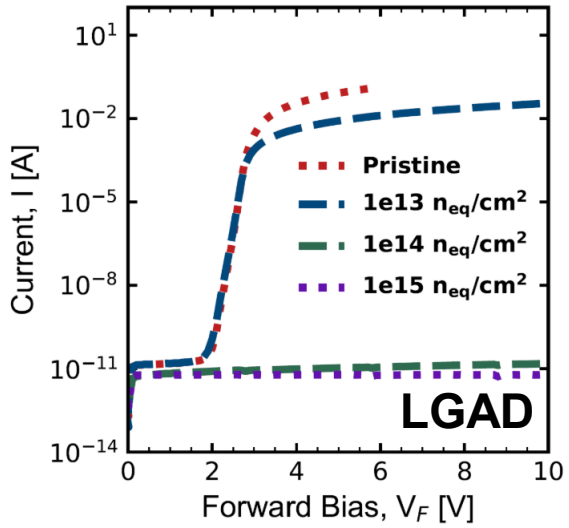
LGAD **PiN Diode**

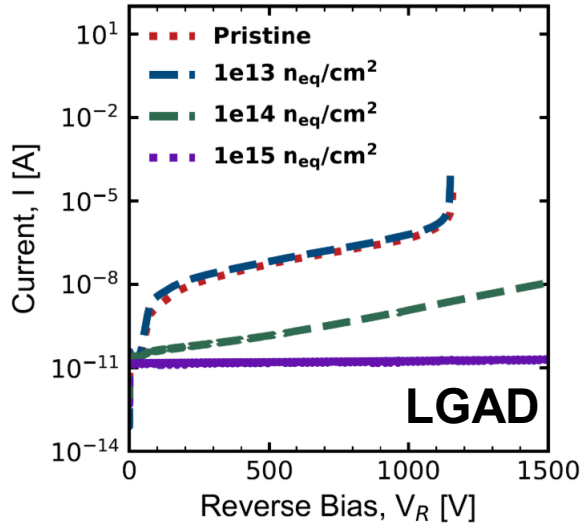
Credit: Jennifer Roloff
Dylan Ponman

I-V Characteristics of Irradiated Devices







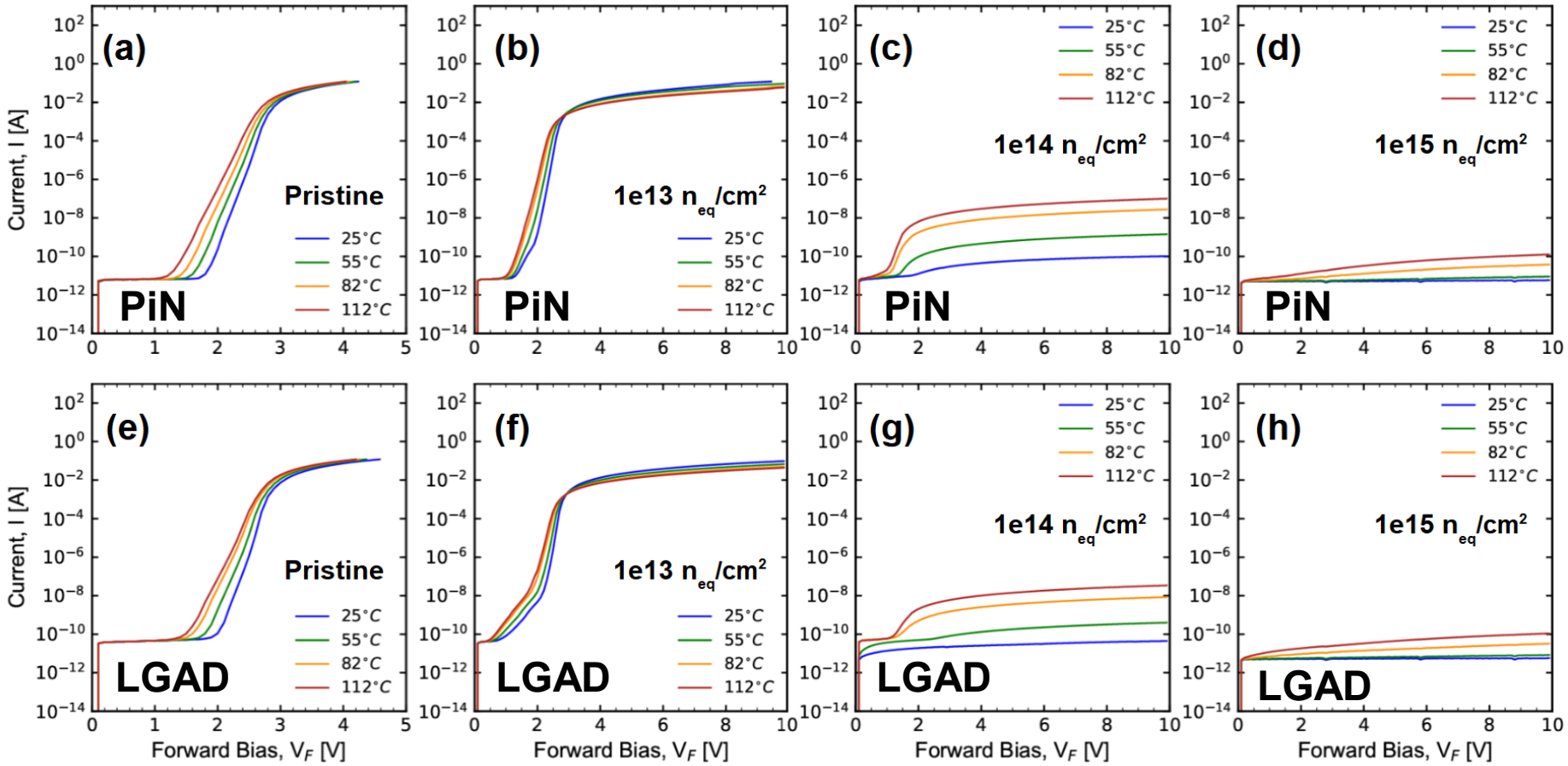


- Device specs.: 300 um diameter
- Increasing neutron fluence leads to…
  - Higher ON-state resistance
  - Lower leakage currents
  - Higher breakdown voltages
  - Loss in rectification (RR → 1)
  - Removal of characteristic “step” feature (in the LGAD)

Key Takeaways: Radiation-induced defects are compensating epi- layers which result in degrading I-V performance.

I-V-T Characteristics of Irradiated Devices

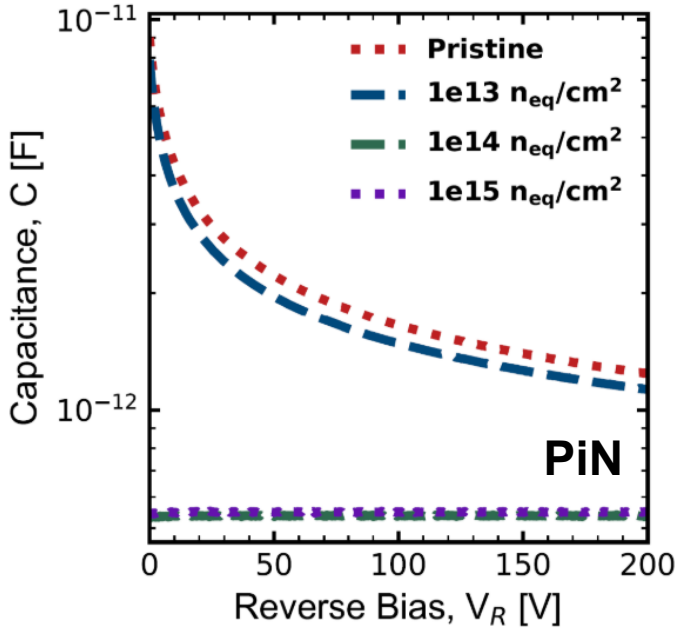
- Device specs.: 600 um diameter
- At low fluences…
  - Increasing temp. leads to decreasing ON-state current
  - ON-state current is limited by phonon scattering
- At high fluences…
  - Increasing temp. leads to increasing ON-state current
  - ON-state current is limited by radiation-induced defects

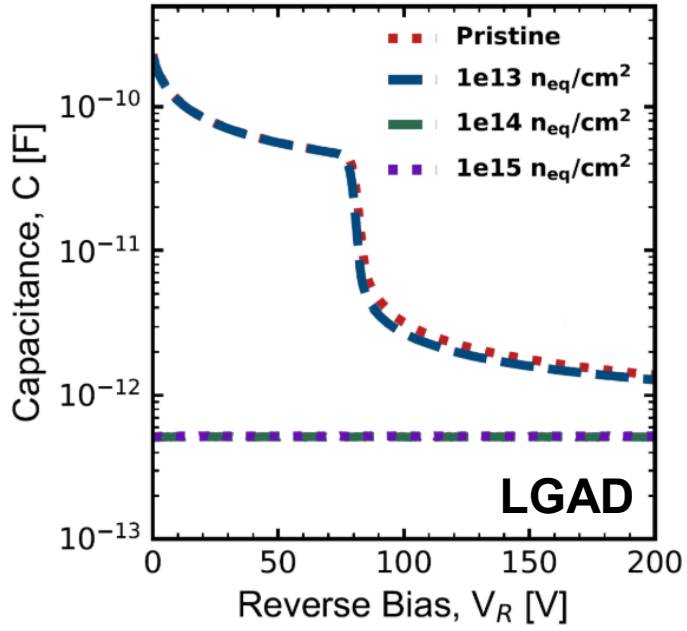


Key Takeaways: Interactions between mobile carriers and the lattice change with increasing incorporation of radiation-induced defects.

C-V Characteristics of Irradiated Devices

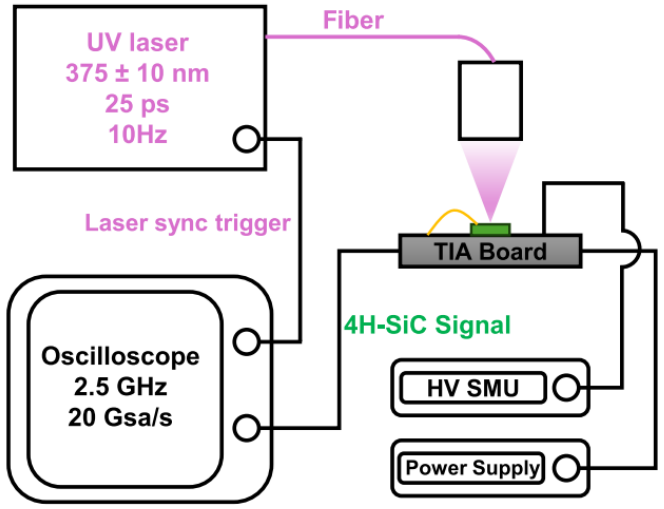
- Device specs.: 600 um diameter
- At low fluences…
  - Capacitance decreases slightly in the voltage regime where the drift layer is being depleted
- At high fluences…
  - Capacitance loses its voltage-dependence
- Observations:
  - Gain and drift layer become “electrically indistinguishable” at high fluences

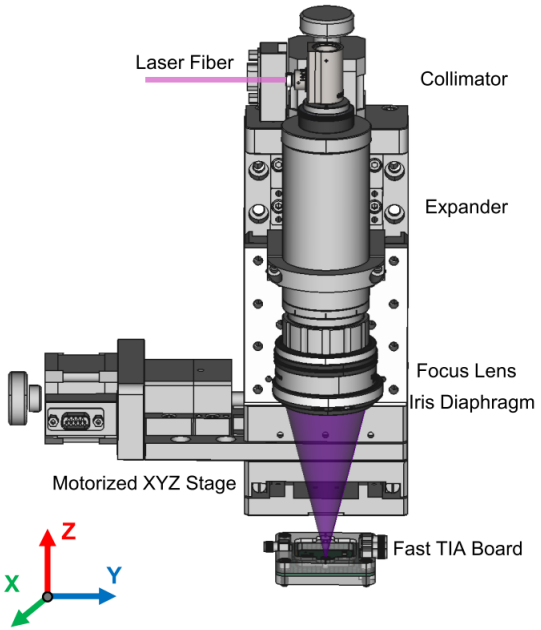




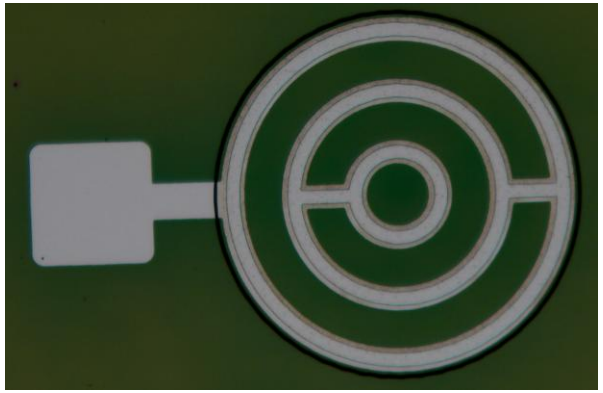
Question: Is the gain layer completely compensated?

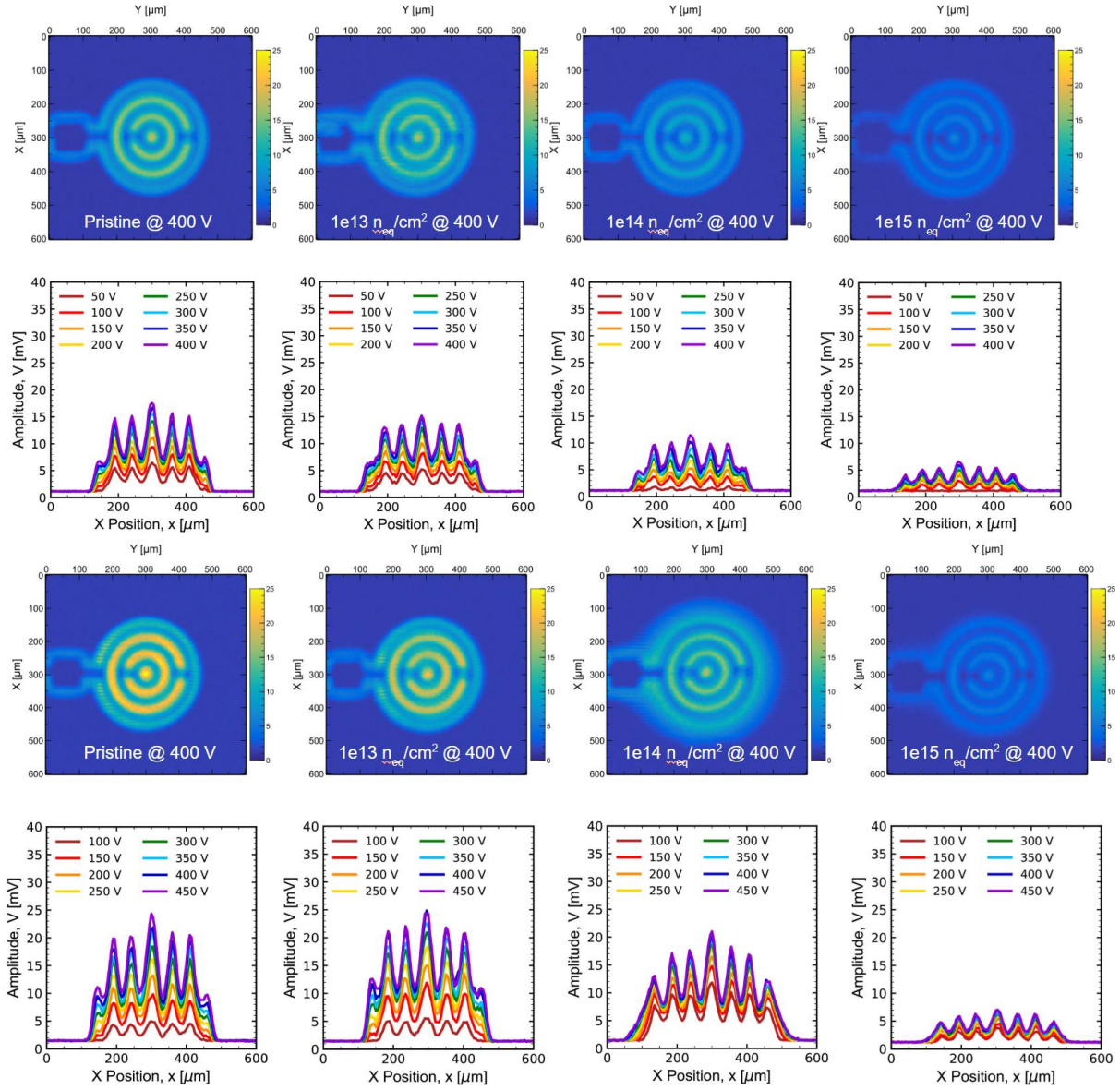
UV-TCT Characterization





- Laser specs.
  - λ = 375 ± 10 nm
  - Spot size ~ 24 um
  - Pulse width: 25 ps
  - Rep rate: 10 Hz
- Oscilloscope specs.
  - 2.5 GHz
  - 20 Gsa/s



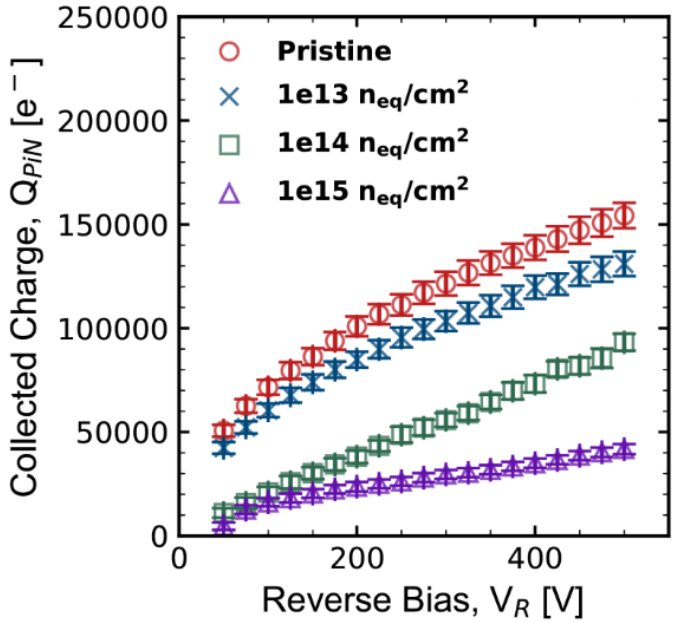


Credit: Tao Yang

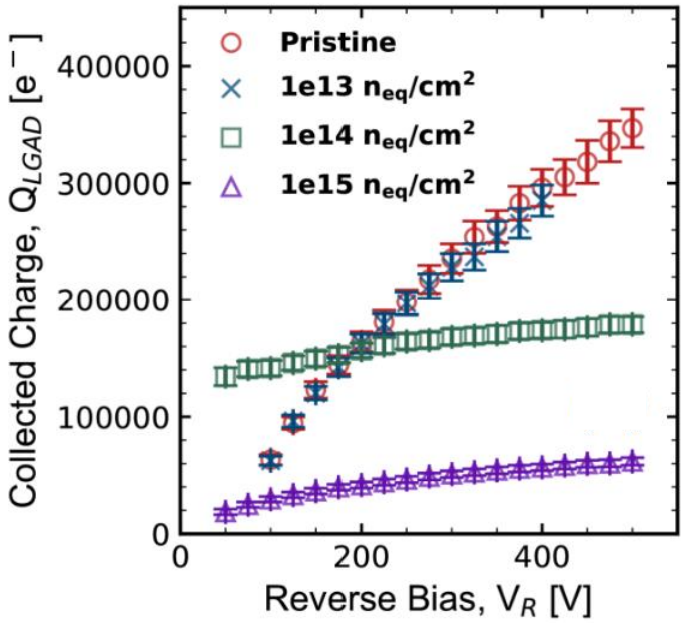
Tao Yang et al.. "Ultra-Fast 4H-SiC LGAD with Etched Termination and Field Plate," in IEEE Electron Device Letters, doi: 10.1109/LED.2025.3548509.

Charge Collection Characteristics

- Increasing neutron fluence leads to decreasing charge collection in both the LGAD and PiN diode
- Charge collection is enhanced in low voltage regime for 1e14 n_{eq}/cm^2 LGAD
- Gain degradation is clear, however quantifying it is tricky due to changing depletion region volumes



PiN Diode



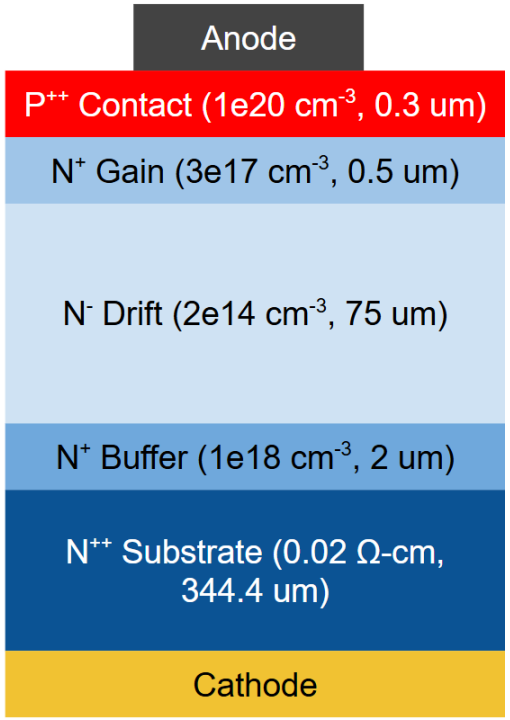
LGAD

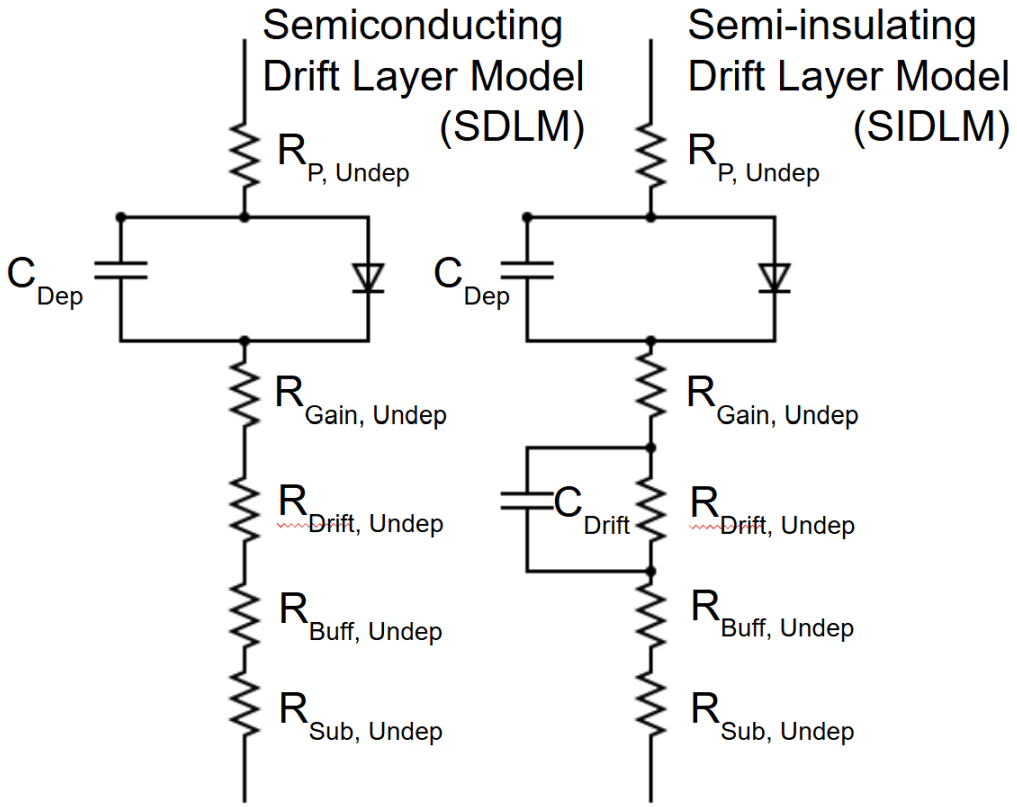
Key Takeaways: Gain degradation appears to be severe.

Question: Can we predict the degradation of the irradiated 4H-SiC LGAD's performance?

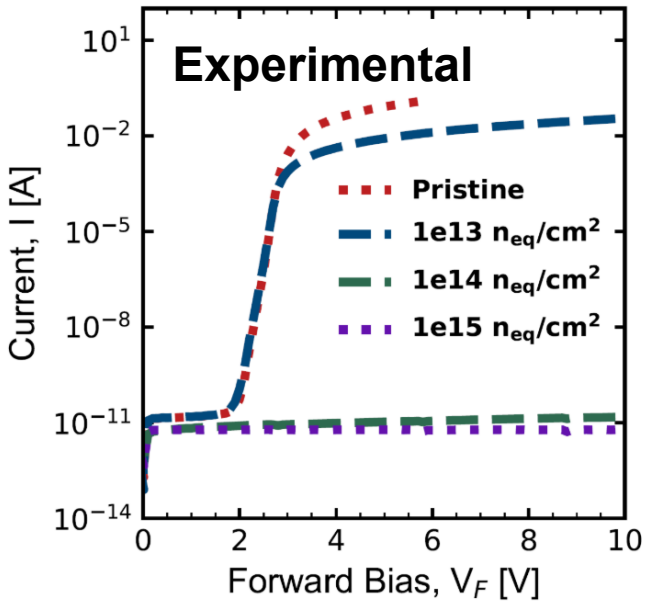
Equivalent Circuit Model of LGAD

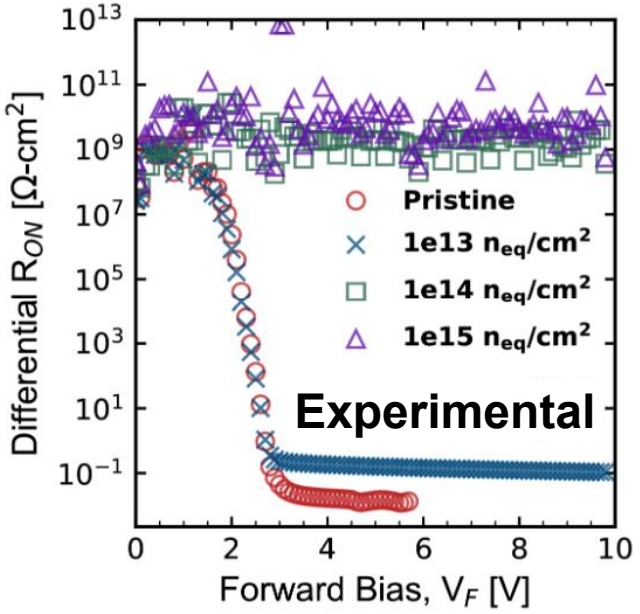
- Hypothesis
  - For pristine and “lightly” irradiated LGADs…
    - Every layer is lightly compensated
    - Drift layer acts as a semiconductor w/ a finite resistance
  - For “highly” irradiated LGADs…
    - Drift layer is heavily compensated, other layers are comparatively not as affected
    - Drift layer acts as a semi-insulating layer with a non-negligible capacitance

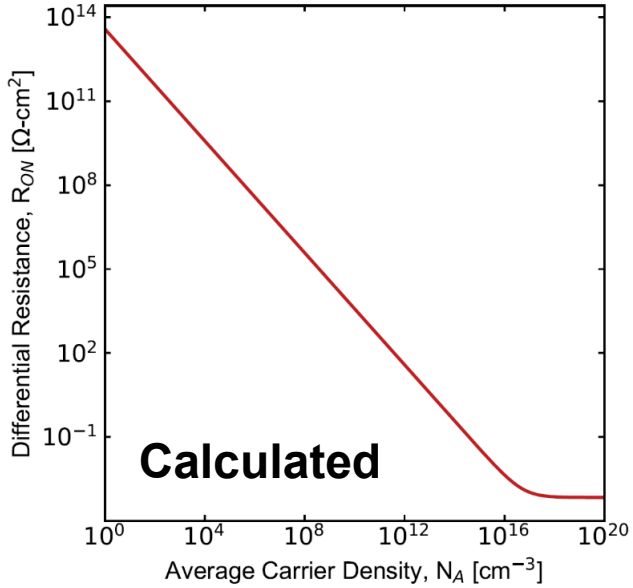




Equivalent Circuit Model (I-V Comparison)





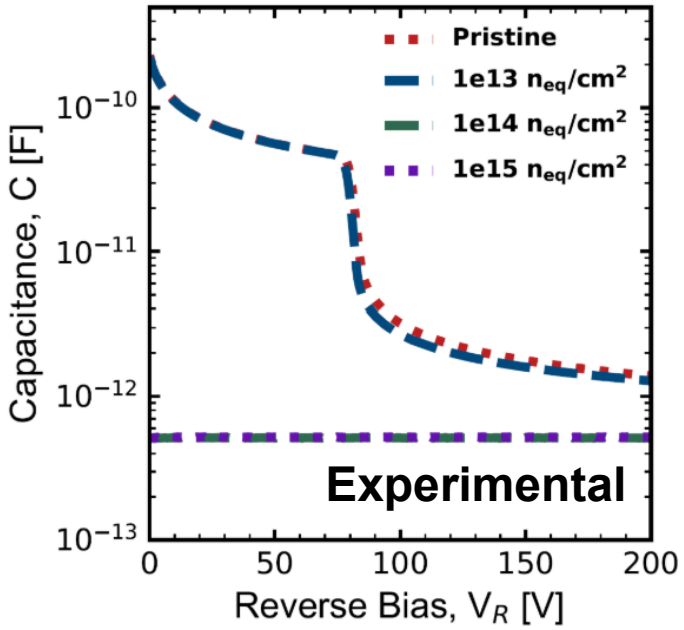


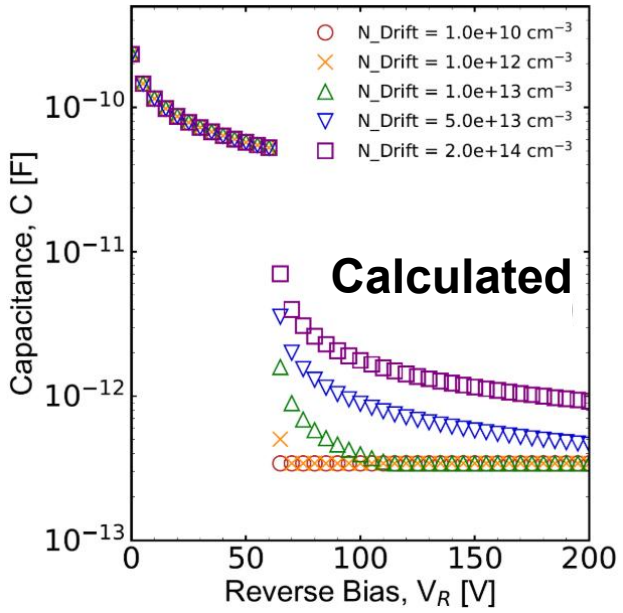
- High differential ON-state resistance values results from average carrier density reduction in the drift layer.
- This is due to radiation-induced defects causing compensation and a reduction in carrier lifetime.

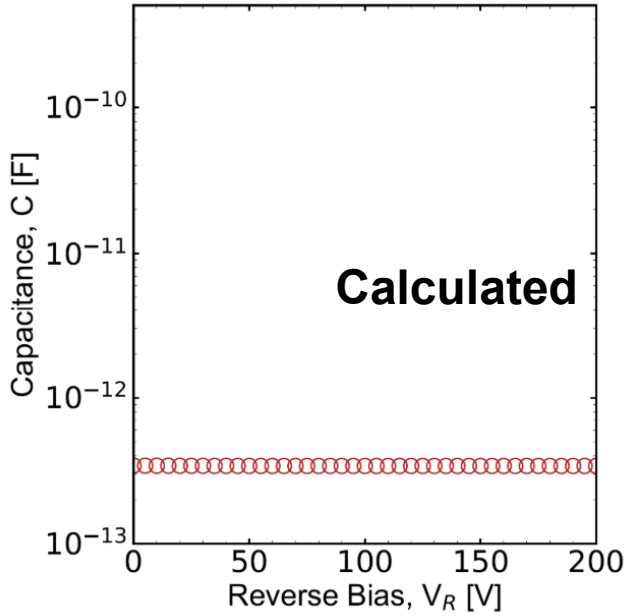
$$R_{ON} = (R_{P,Undep} + R_{Gain,Undep} + R_{Drift,Undep} + R_{Buff,Undep} + R_{Sub,Undep})A$$

$$R_{Drift,Undep} = \frac{t_{Drift}}{Aq(\mu_n + \mu_p)N_A}$$

Equivalent Circuit Model (C-V Comparison)







- SDLM model is more accurate in describing C-V characteristics of pristine and “lightly” irradiated LGADs
- SIDLM model is more accurate in describing C-V characteristics of “heavily” irradiated LGADs

$$C_{eff} = \left(\frac{1}{C_{Dep}(V_R)} + \frac{1}{C_{Drift}} \right)^{-1}$$

Conclusion

- Electrical (I-V, I-V-T, and C-V) characteristics show degradation due to introduction of radiation-induced defects which lead to compensation.
- Charge collection characteristics show significant gain reduction
- Equivalent circuit models can be used to describe the device physics of an irradiated 4H-SiC LGAD
- **Important Question:** Is the 4H-SiC LGAD more radiation-hard than its Si counterpart?
- **Areas of research:**
  - Use TCAD to predict 4H-SiC LGAD degradation due to radiation-induced defect incorporation.
  - Determine compensation of n-type and p-type SiC w/ varying doping levels at varying radiation fluences.
  - Determine methods to make 4H-SiC LGAD more radiation-hard. Defect engineering?
  - Establish a figure-of-merit to compare Si LGAD and 4H-SiC LGAD performance (need to consider timing resolution, operating temperature, radiation hardness, etc.)

Questions?

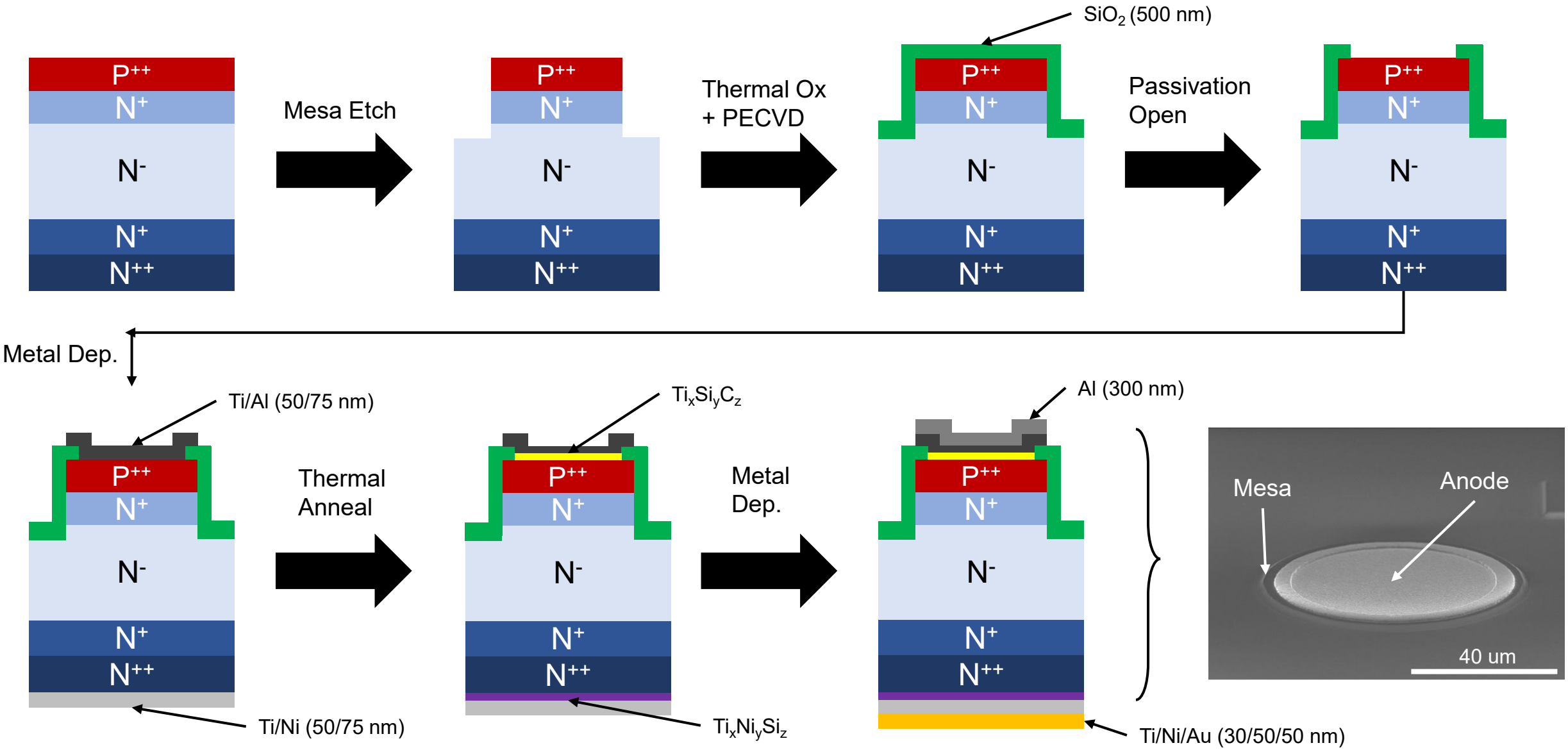
Backup Slides

Si vs. 4H-SiC

Property	Si	4H-SiC	Consequences
Bandgap (eV)	1.12	3.26	Larger operating voltage range and lower leakage/higher temp. operation
Thermal Conductivity ($W\ m^{-1}\ K^{-1}$)	130	370	Lower thermal impedance
Threshold Displacement Energy (eV)	13-20	22-35	Higher radiation hardness
Saturation Velocity ($10^7\ cm\ s^{-1}$)	1	2	Faster collection time and timing resolution
EHPs per μm	75	55	Less ionization in SiC LGAD
Impact Ionization Coefficient	$\alpha_e > \alpha_h$	$\alpha_e < \alpha_h$	Device polarity is changed (NPiP→PNiN)

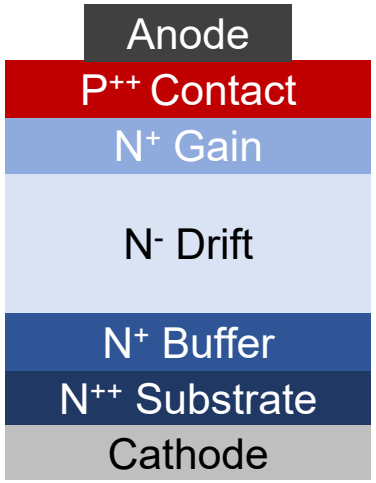
P. Barletta, M. Cerullo, C. Haber, S.E. Holland, J. F. Muth, B. Sekely, "Fast Timing With Silicon Carbide Low Gain Avalanche Detectors', (2022) Proceedings of the US Community Study on the Future of Particle Physics (Snowmass 2021)

4H-SiC LGAD Fabrication Process



Effects of Irradiating 4H-SiC

- Defects generated
  - Point/cluster defect generation
  - Neutron transmutation doping
  - Nuclear spallation
- Consequences of radiation induced defects
  - Compensation in p-type and n-type SiC
    - V_C, V_{Si}^+, V_C+V_{Si} are acceptor-like and have been seen compensate n-SiC
    - Al_{Si} -V_C complex has been seen to compensate p-SiC
  - Reduced carrier lifetime
    - $Z_{1/2}$ (carbon vacancy) is a well-known lifetime killer
- Expected effects to proton irradiating 4H-SiC LGADs
  - N-type gain and drift layers will experience compensation
  - Carrier lifetime will decrease due to increasing $Z_{1/2}$ concentration



4H-SiC LGAD

V.V. Kozlovski, A.A. Lebedev, E.V. Bogdanova and N.V. Seredova, Effect of irradiation with MeV protons and electrons on the conductivity compensation and photoluminescence of moderately doped p-4H-SiC (CVD), Semiconductors 49 (2015) 1163
H. Matsuura, S. Kagamihara, Y. Itoh, T. Ohshima and H. Itoh, Mechanisms of reduction in hole concentration in Al-doped 4H-SiC by electron irradiation, Microelectronic Engineering 83258(2006) 17.
T. Kimoto, K. Danno and J. Suda, Lifetime-killing defects in 4H-SiC epilayers and lifetime control by low-energy electron irradiation, physica status solidi (b) 245 (2008) 1327.
V. Kažukauskas, R. Jasiulionis, V. Kalendra and J.V. Vaitkus, The effect of irradiation with high-energy protons on 4H-SiC detectors, Semiconductors 41 (2007) 345.