The research of 4H-SiC LGAD after proton radiation

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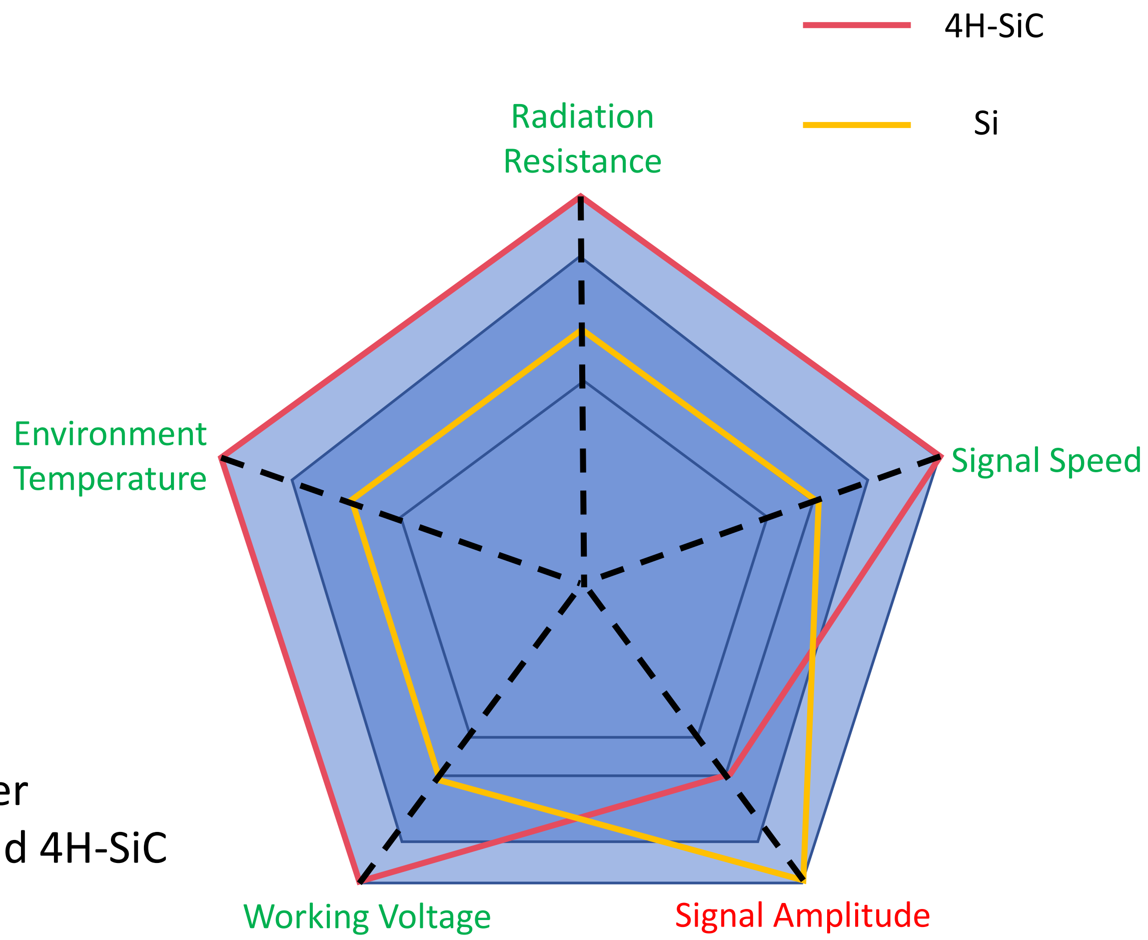
Why do we need 4H-SiC?

Characteristic	Si	4H-SiC
Eg (eV)	1.12	3.26
Thermal conductivity	1.5	4.9
$E_{breakdown}$ (V/cm)	0.5	3
Saturated electron velocity (cm/s)	1×10^7	2×10^7
ionization energy for e-h pair (eV)	3.64	7.8
displacement energy	13	21.8



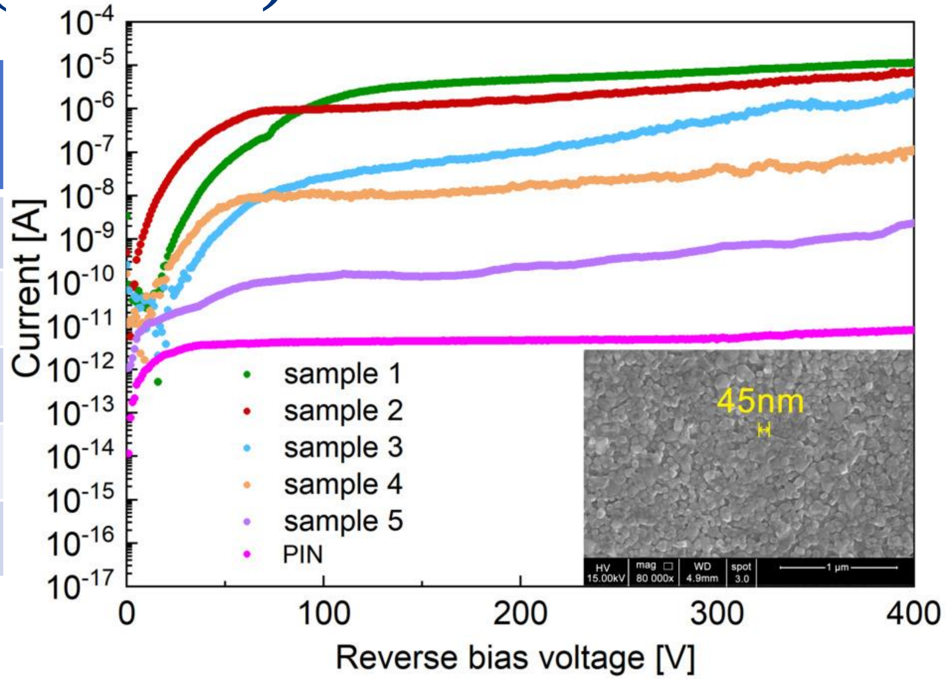
Compared with Si, 4H-SiC can standard higher radiation and work at room temperature. And 4H-SiC can generate a faster signal.

But it needs more energy to generate one e-h pair.

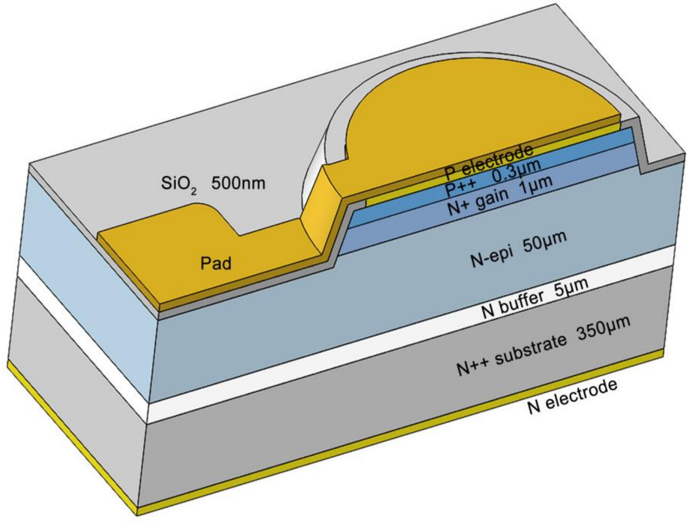
One way to close the gap: inner amplification of signal by avalanche.

Choice of electrodes of 4H-SiC LGAD (SICAR)

SICAR samples	Thickness of Ni/Ti/Al (nm)	Anneaing Temperature (°C)
Sample 1	60/30/80	850
Sample 2	60/30/80	950
Sample 3	60/30/80	1050
Sample 4	60/20/80	1050
Sample 5	50/15/80	1050

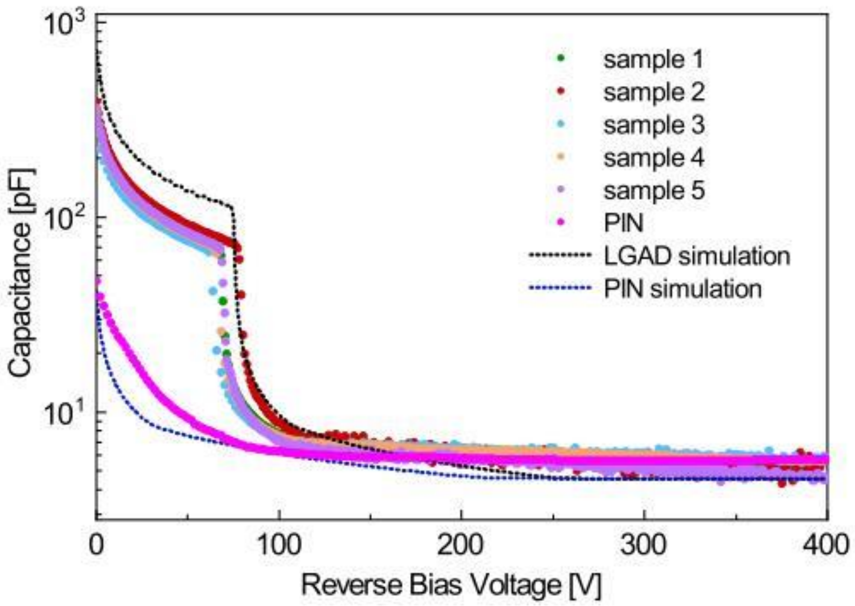


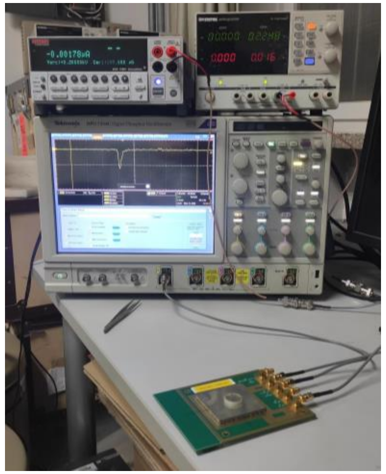
All samples will not be broken down at 400V.



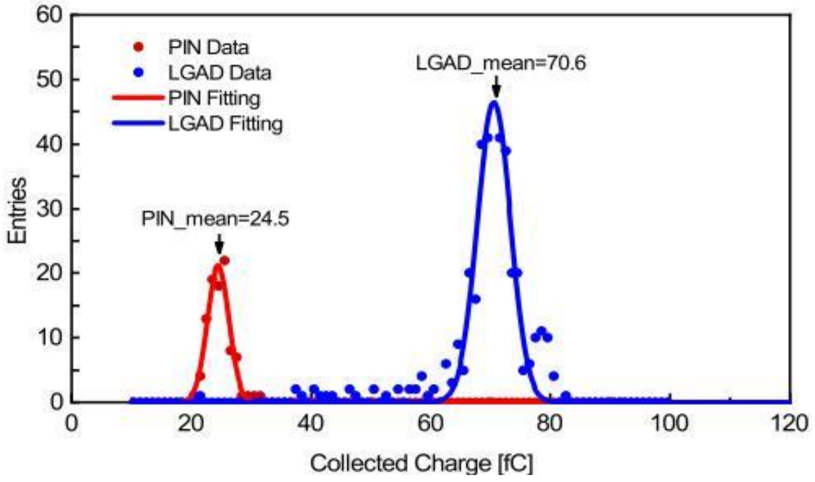
- 50/15/80 (nm) of Ni/Ti/Al
- Annealing temperature of 1050 °C

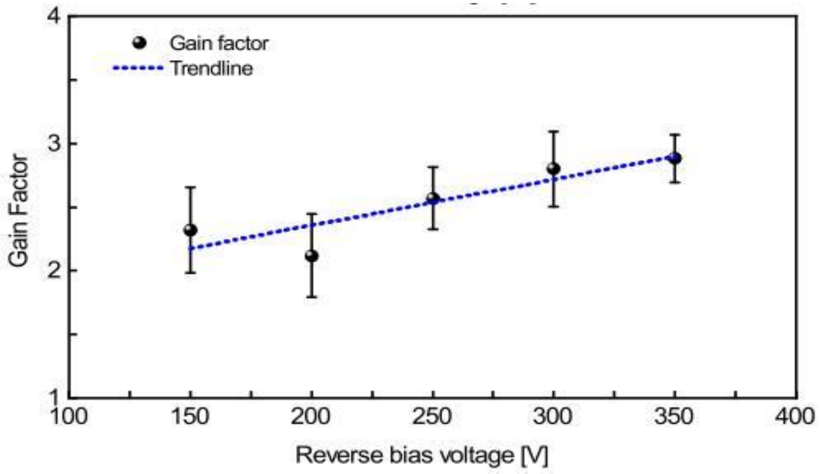
Gain factor of SICAR





gain test setup





- The effective doping of gain layer:8.6 $\times 10^{16}$ cm^{-3}
- Depletion depth of the gain layer :1 *u*m
- Gain structure does exist

4H-SiC devices with a gain factor of 3 have been successfully prepared.

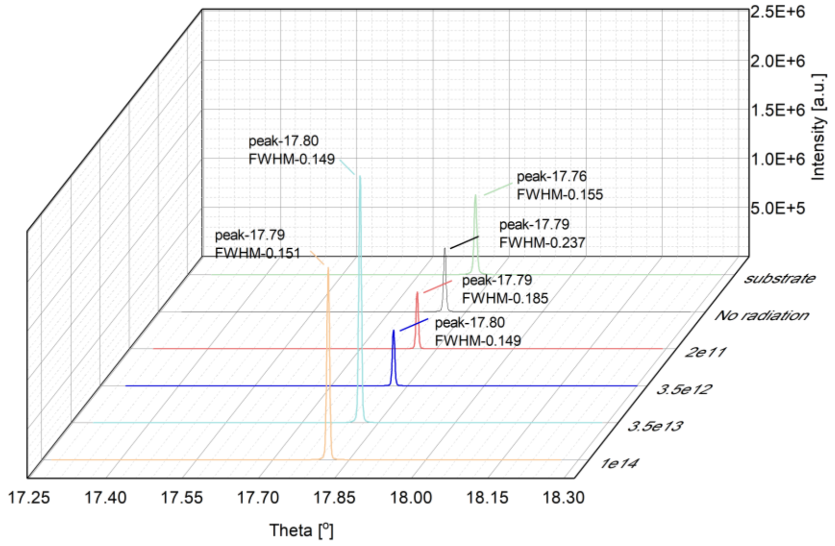
More details in
S. Zhao et al., "Electrical Properties and Gain Performance of 4H-SiC LGAD (SICAR)," in IEEE Transactions on Nuclear Science, doi: 10.1109/TNS.2024.3471863.

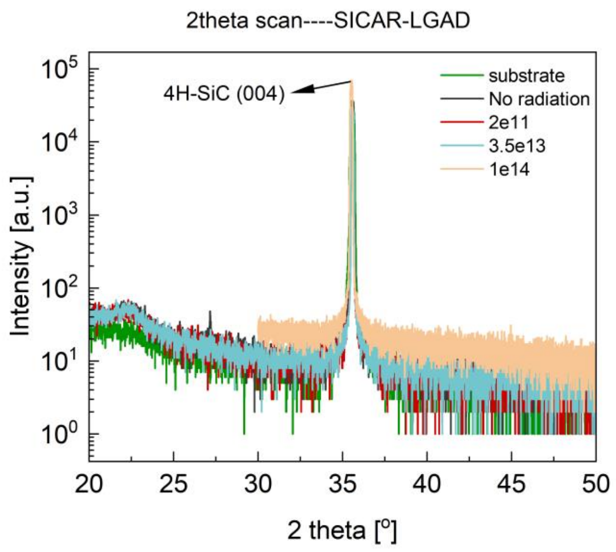
Radiation setup

- 80 MeV proton radiation
- Flux:2e11 n_{eq}/cm^2, 3e12 n_{eq}/cm^2 , 3.5e13 n_{eq}/cm^2 , 1e14 n_{eq}/cm^2
- Size: rectangle of 2 cm × 2 cm

China Spallation Neutron Source

Defect Characterization
----XRD test

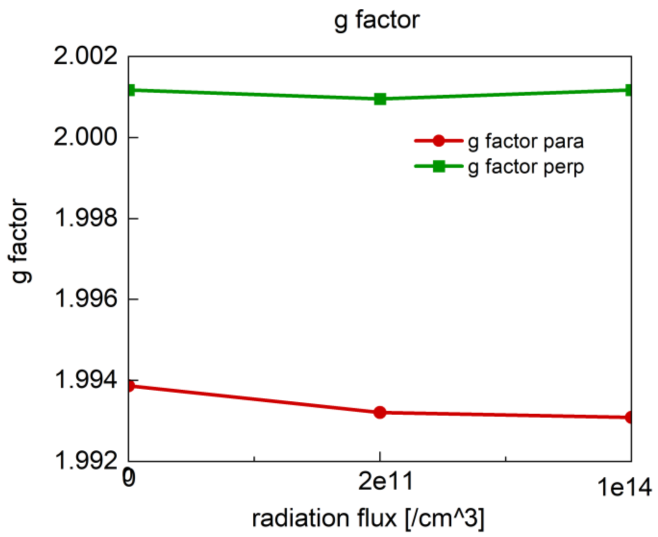




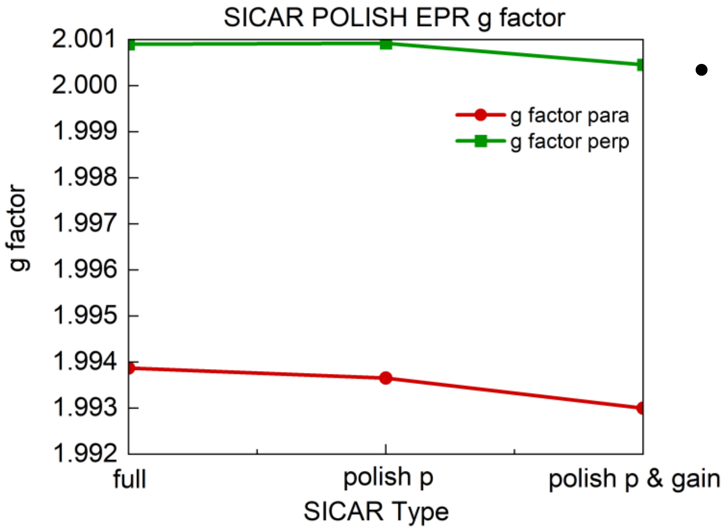
	Substrate	No radiation	2e11	3.5e13	1e14
peak(2θ) [°]	35.5188	35.587	35.589	35.597	35.587
FWHM(β) [°]	0.155	0.237	0.185	0.149	0.151
Size (D) [A]	6.076	7.7839	9.1137	9.5365	9.2887

- Good quality of single crystal
- No out-of-plane lattice distortion and twinning due to proton irradiation
- Crystallinity even improved with the increase of irradiation

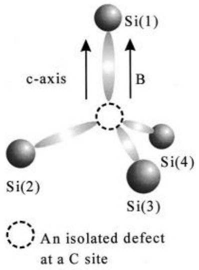
Defect Characterization
----EPR test



- The defects exhibit obvious anisotropies, and the symmetry of the unit cell changes



- The type of defect is generally consistent within the device



Symmetry from C_{3v} to C_{1h}

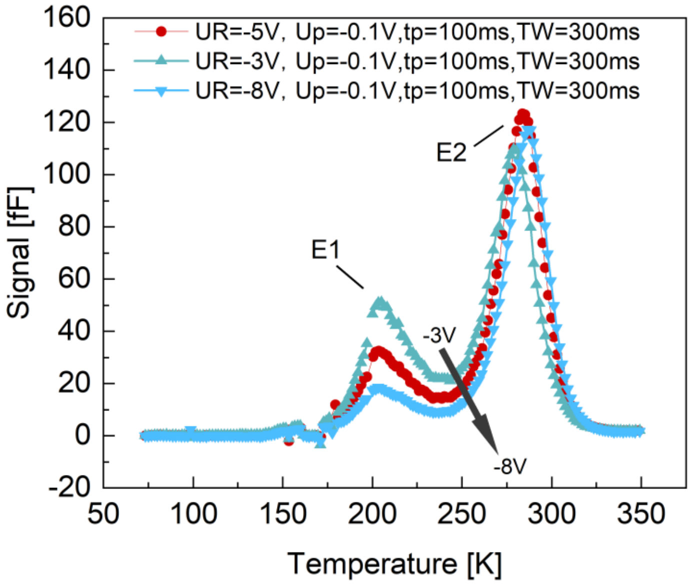
$$H=\mu_B \mathbf{B}\cdot\mathbf{g}\cdot\mathbf{S}+\sum_{j=1-4}\mathbf{S}\cdot\mathbf{A}^{(j)}\cdot\mathbf{I}_{Si}$$

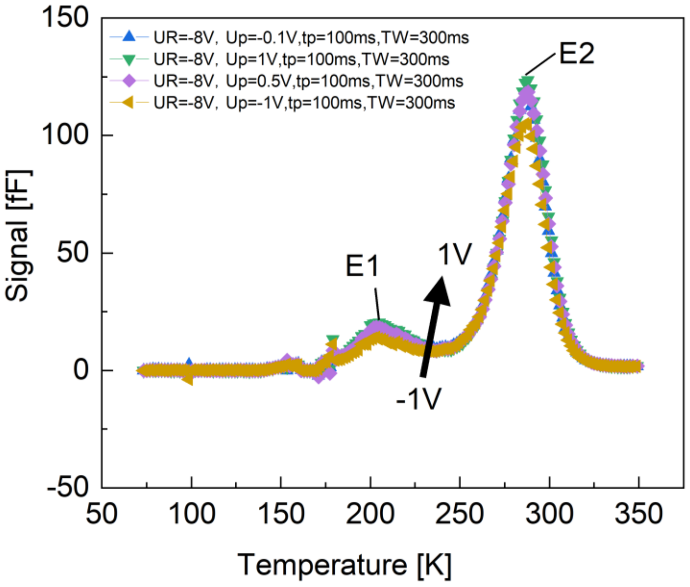
The tensor A can be used to describe the anisotropy of the vacancy

It should be guessed that the symmetry contains the vacancy at the C_{1h} position

A portion of this work was performed on the Steady High Magnetic Field Facilities, High Magnetic Field Laboratory, CAS

Defect Characterization
----DLTS test : No radiation

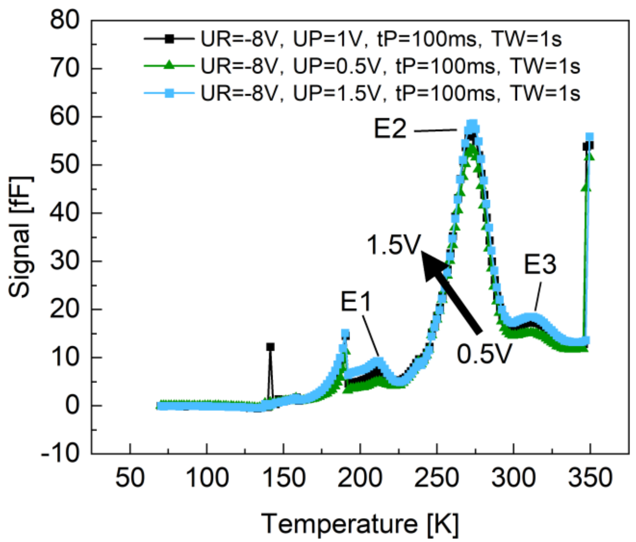


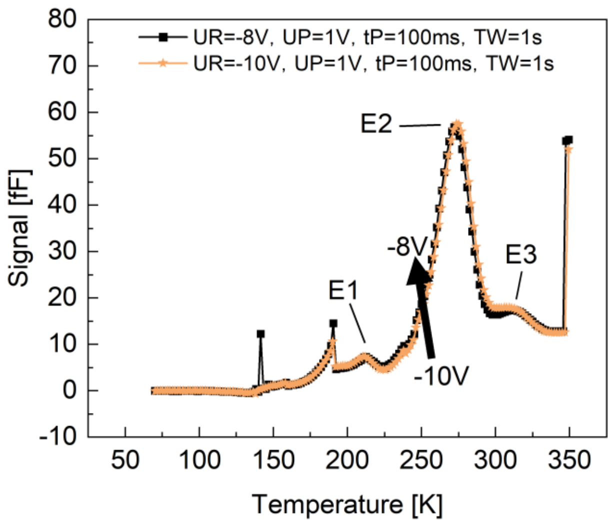


- E2 defect is sensitive to electric field （position of E2 peak move to the higher temperature）
- After the E1 emits carriers, the electrical properties of the trap are neutral.

	Trap	Activation energy(eV)	Capture cross-section (cm^2)	Trap concentration NT (cm^{-3})
EH_1 ←	E1	0.44	1.88E-14	1.01E+12
$Z_{1/2}$ ←	E2	0.63	1.07E-14	6.74E+12

Defect Characterization
----DLTS test : 2e11





- E3 is a new trap after irradiation.

	Trap	Activation energy(eV)	Capture cross-section (cm^2)	Trap concentration NT (cm^{-3})
EH_1 ←	E1	0.46	1.66E-15	1.38E+12
$Z_{1/2}$ ←	E2	0.61	1.27E-15	1.07E+13
EH_3 ←	E3	0.70	1.30E-15	3.48E+12

Defect Characterization

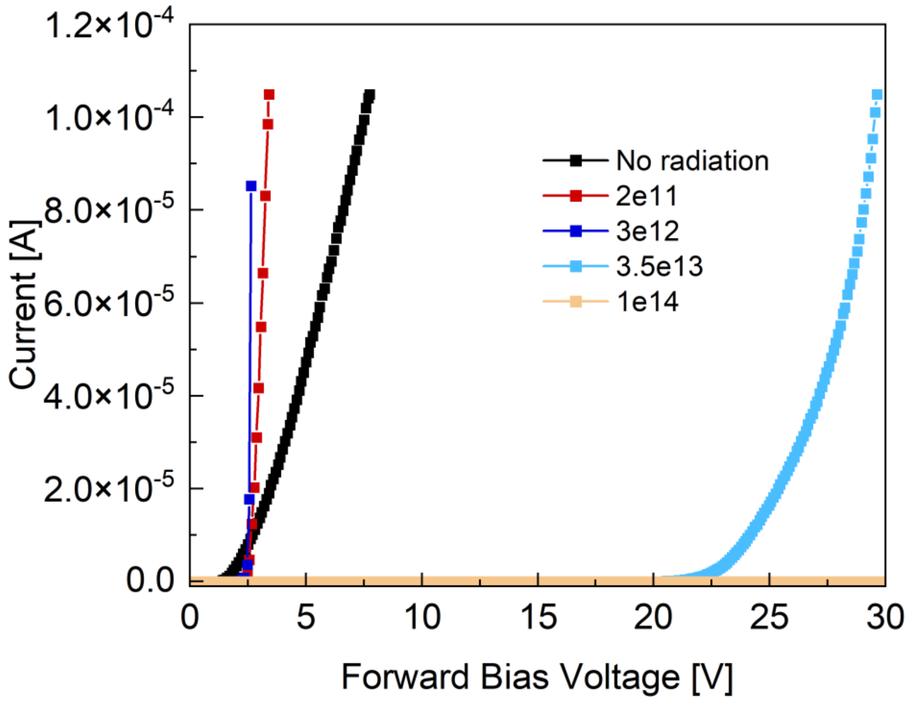
Conclusion

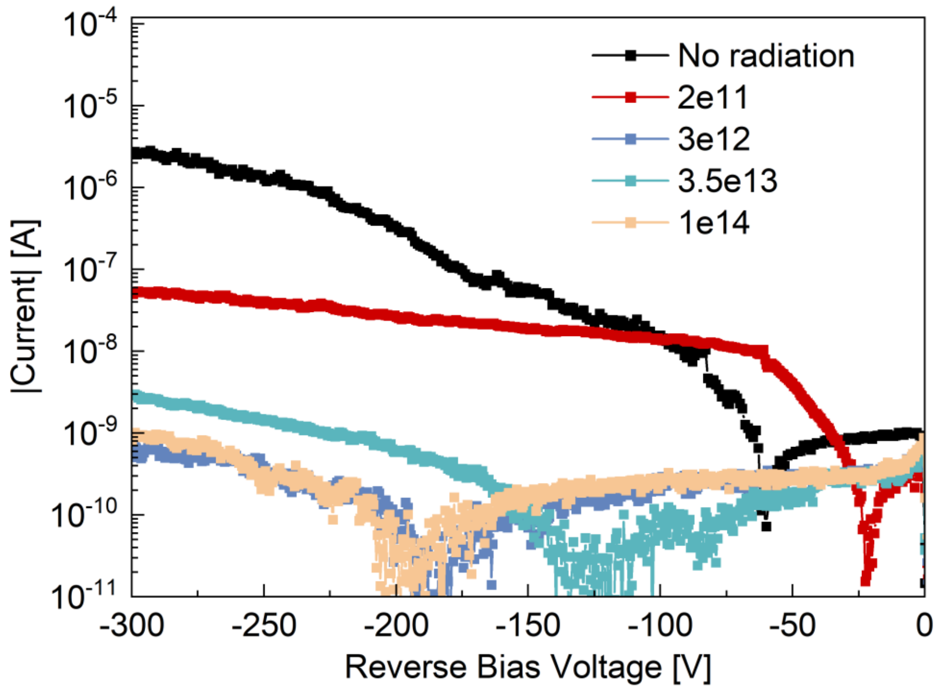
	Trap	Activation energy(eV)	Origin
EH_1	E1	0.46	$V_{Si}(3-/=)$
$Z_{1/2}$	E2	0.61	$V_c(=/0)$
EH_3	E3	0.70	$V_{Si}(=/-)$

- E1 and E2 were intrinsic defects introduced during the 4H-SiC growth process.
  E3 was introduced by 80MeV proton radiation.
- The capture cross-sections of E1 and E2 were reduced by an order of magnitude after irradiation.
- The trap concentration of E1 irradiation was almost unchanged
  The trap concentration of E2 irradiation increased, indicating that the radiation has a greater impact on carbon than silicon atoms.

Electrical performance of SICAR after proton irradiation

Current vs Voltage

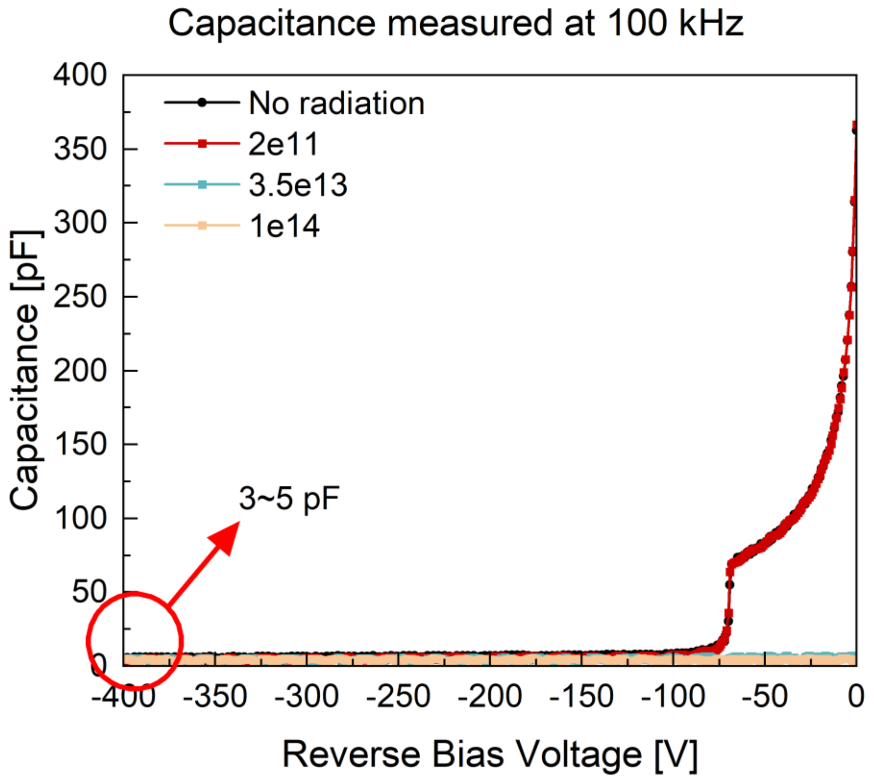




- Threshold voltage increases with radiation flux
- The leakage current reduced by 2-4 orders of magnitude

Electrical performance of SICAR after proton irradiation

Capacitance vs Voltage



- Capacitive properties disappear at irradiation flux of 3.5e13 and 1e14.
- The total miscellaneous capacitance of the entire test system is approximately 3 to 5 picofarads (pF).

Defect concentration

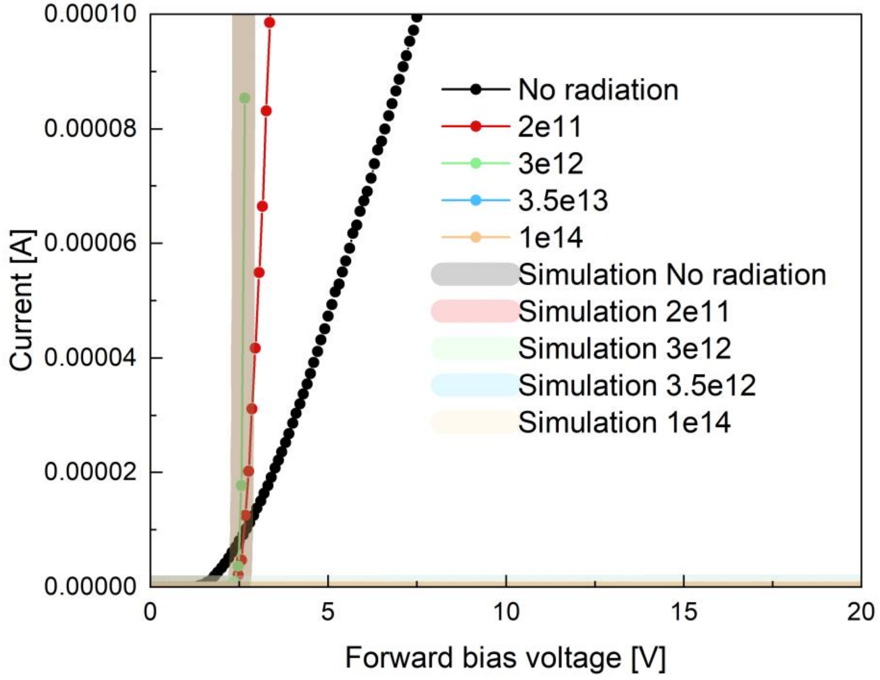
Assuming the concentration of defects changes linearly with the radiation flux：

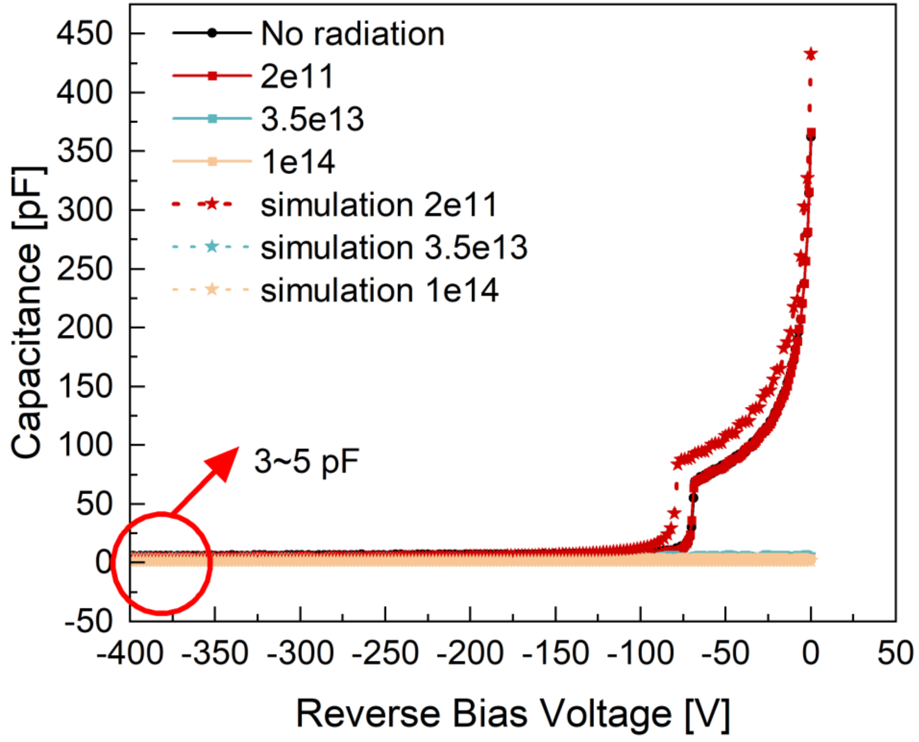
- $N_{EH3} = g_{EH3} * \Phi_{flux}$ ($g_{EH3} = 17.4\ cm^{-1}$)
- $N_{Z1/2} = g_{Z1/2} * \Phi_{flux}$ ($g_{Z1/2} = 19.8\ cm^{-1}$)

Trap concentration	No radiation	2e11	3e12	3.5e13	1e14
$Z_{1/2}$ (η=19.8)	6.74e+12	1.07e+13	6.6e13	7.0e14	1.98e15
EH1 (η=1.75)	1.01e+12	1.38e+12	6.26e12	6.23e13	1.75e14
EH3 (η=17.4)	0	3.48e+12	5.2e13	6.09e14	1.7e15

Simulation

Add the defects to the simulation

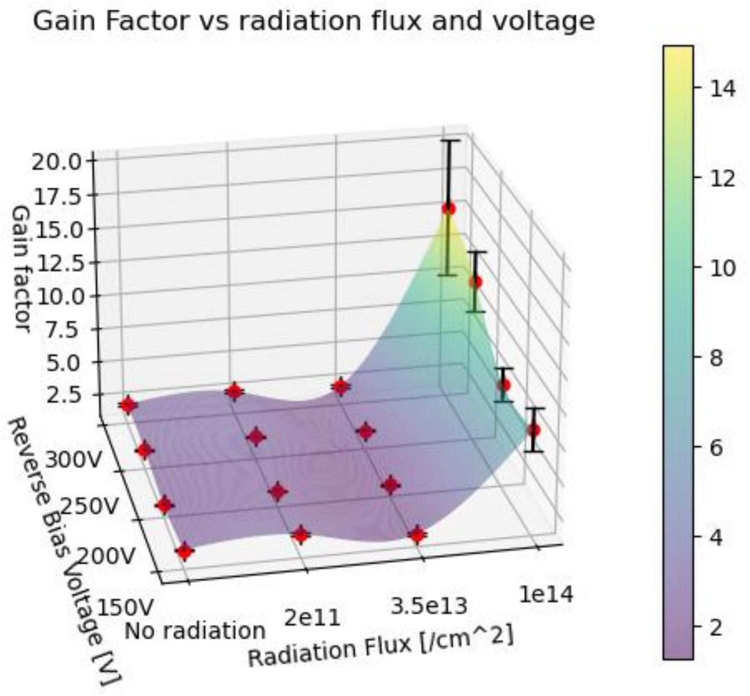


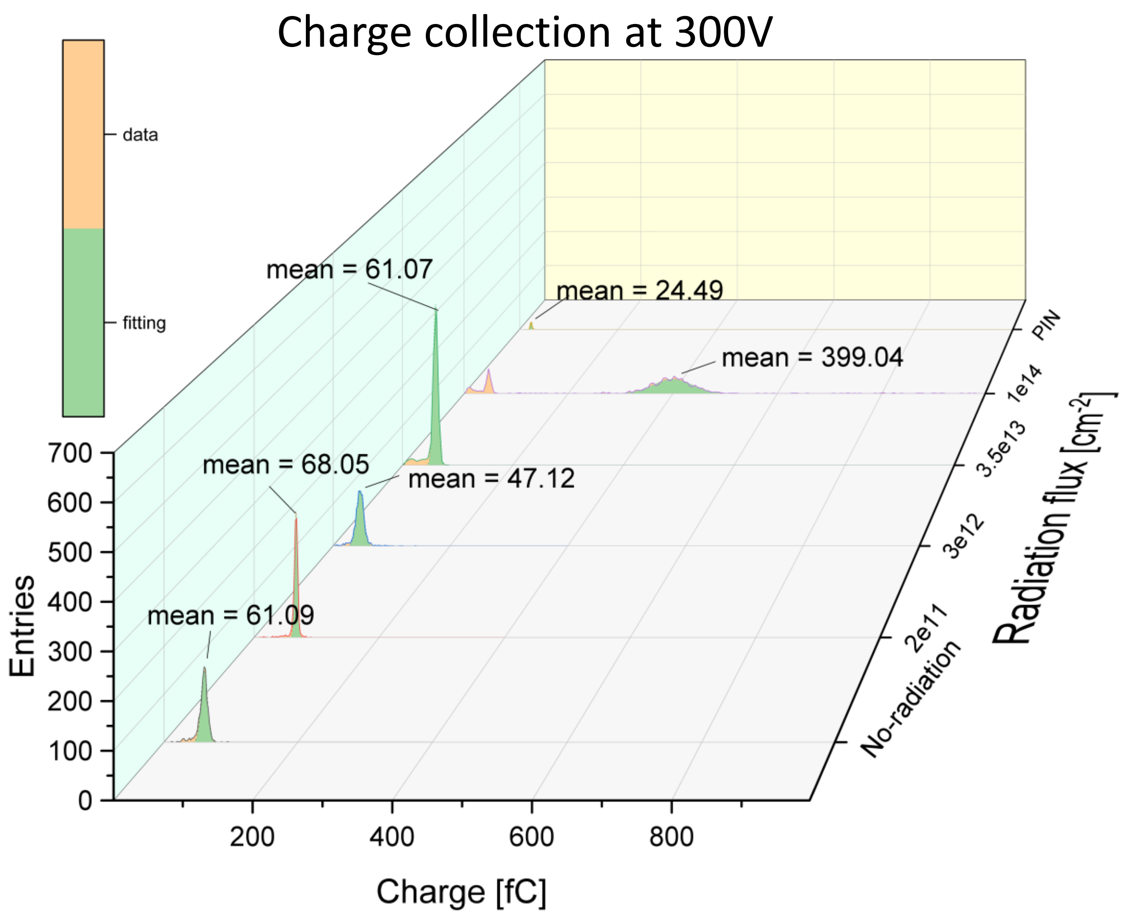


The simulation results are in good agreement with the experimental results.

$Z_{1/2}$ and EH_3 are the critical reason of the impact on IV and CV curves.

Gain factor





- Gain factor increases slowly with the reverse bias voltage
- The gain factor increases at a radiation flux of 1e14

- We speculate that the uneven distribution of defects within the high-dose irradiated device changes the gain path of the carriers, leading to the appearance of higher charge collection.

Summary and Plan

Summary

- Proton irradiation introduces additional vacancy defects that are key points of the influence of IV and CV.

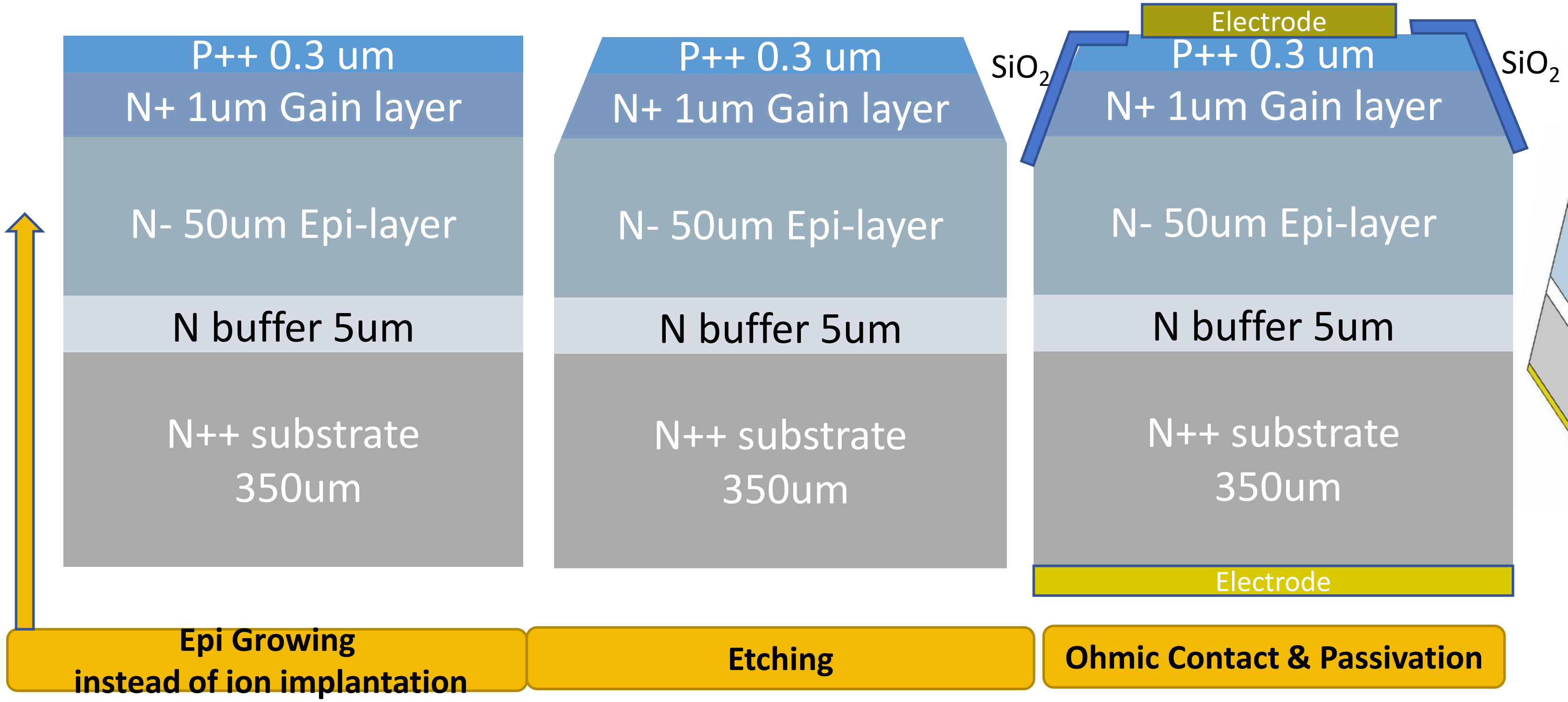
- At high irradiance levels, the gain factor of the SICAR device increases from 2.3 to 15.

Plan

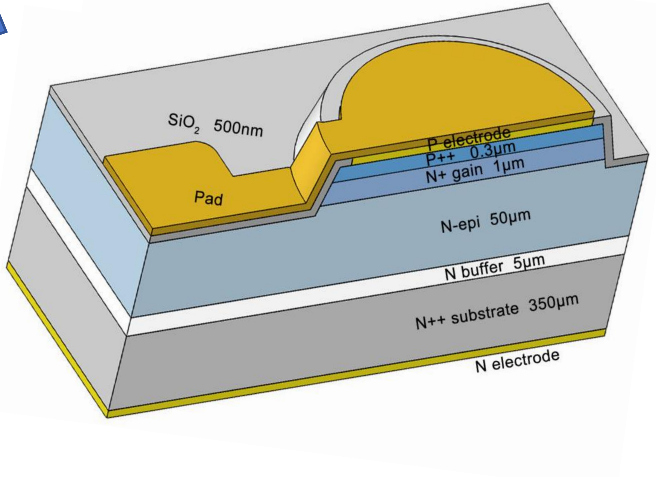
- Higher flux of proton radiation
- Electron and neutron radiation
- Physical analysis of EPR and DLTS
- Modeling and Physical Interpretation of Irradiation for LGAD Devices

Backup

Process of 4H-SiC LGAD

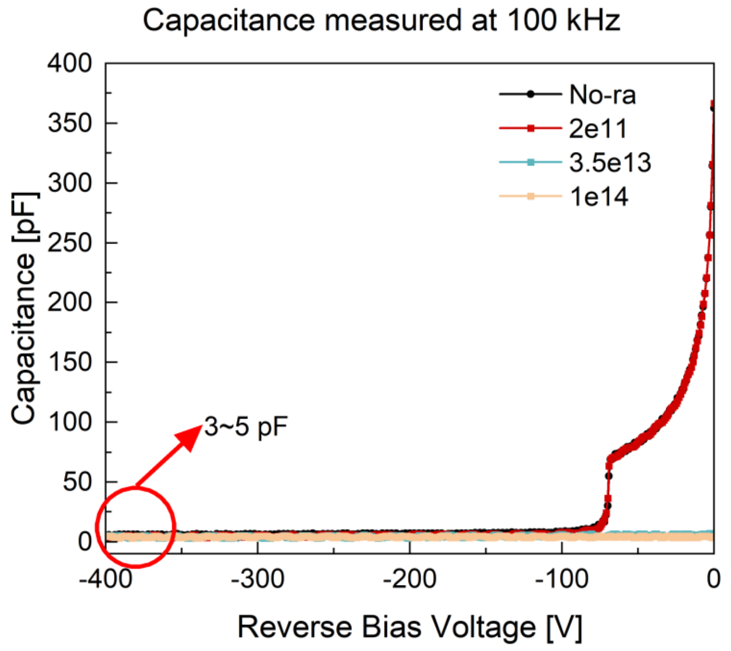


Cross-section of LGAD



Electrical performance of 4H-SiC LGAD after proton irradiation

Capacitance vs Voltage



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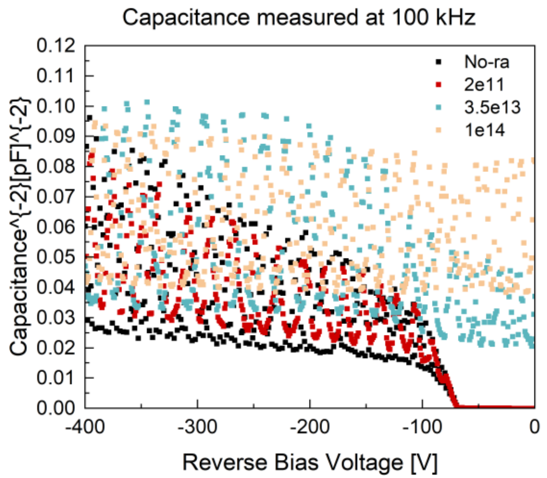
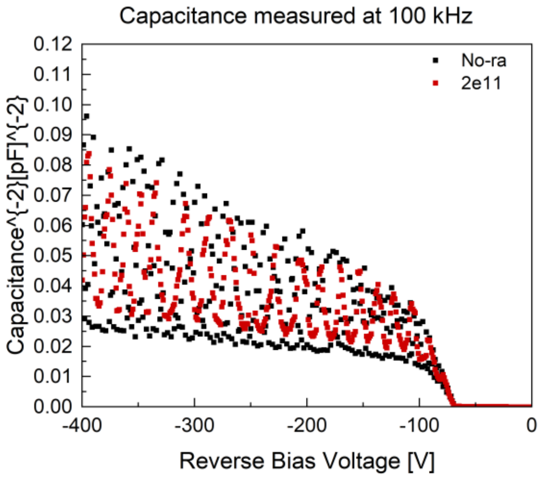
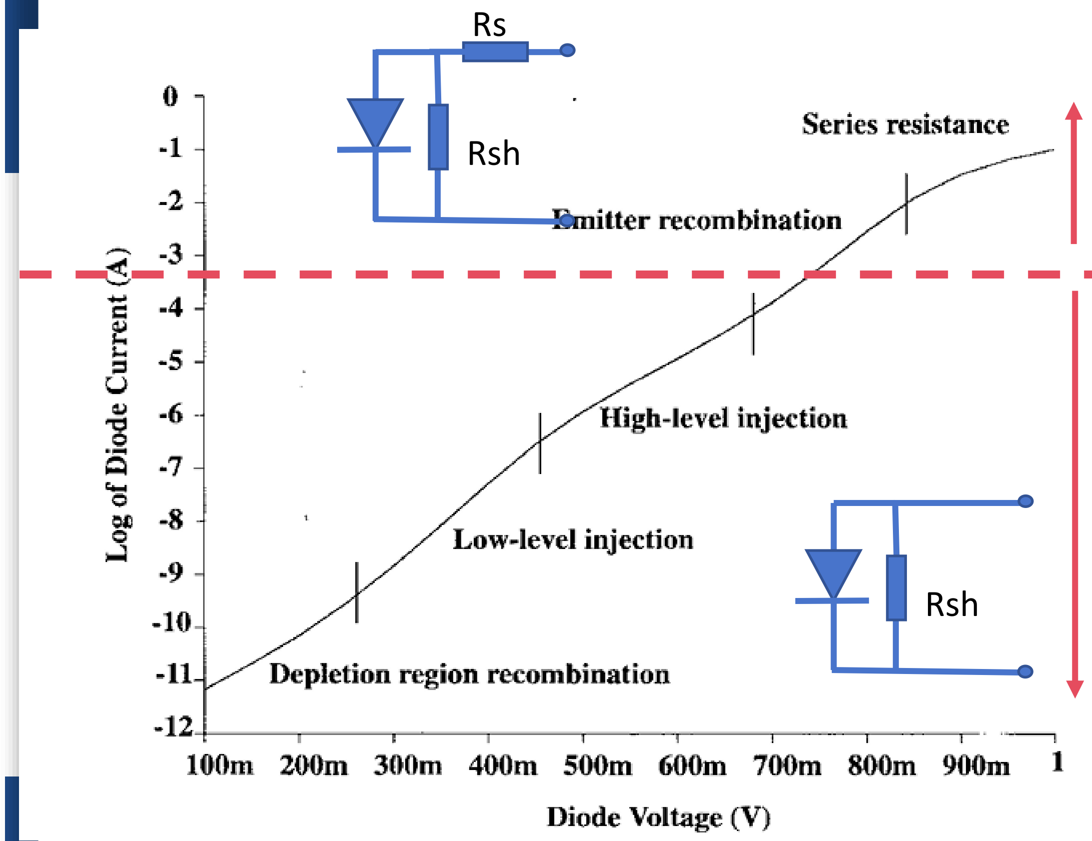


- The capacitance of radiation flux at 3.5e13 and 1e14 change to be constant.



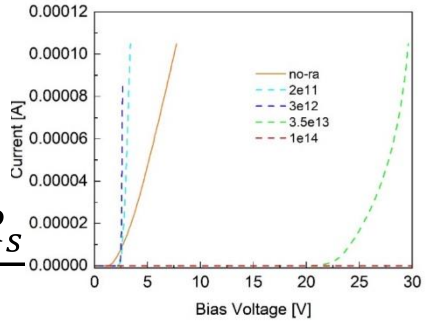
- The capacitance of radiation flux at 2e11 even has no change.

n and Rsh analysis



H. A. Mantooth and J. L. Duliere, "A unified diode model for circuit simulation," in *IEEE Transactions on Power Electronics*, vol. 12, no. 5, pp. 816-823, Sept. 1997, doi: 10.1109/63.622999.

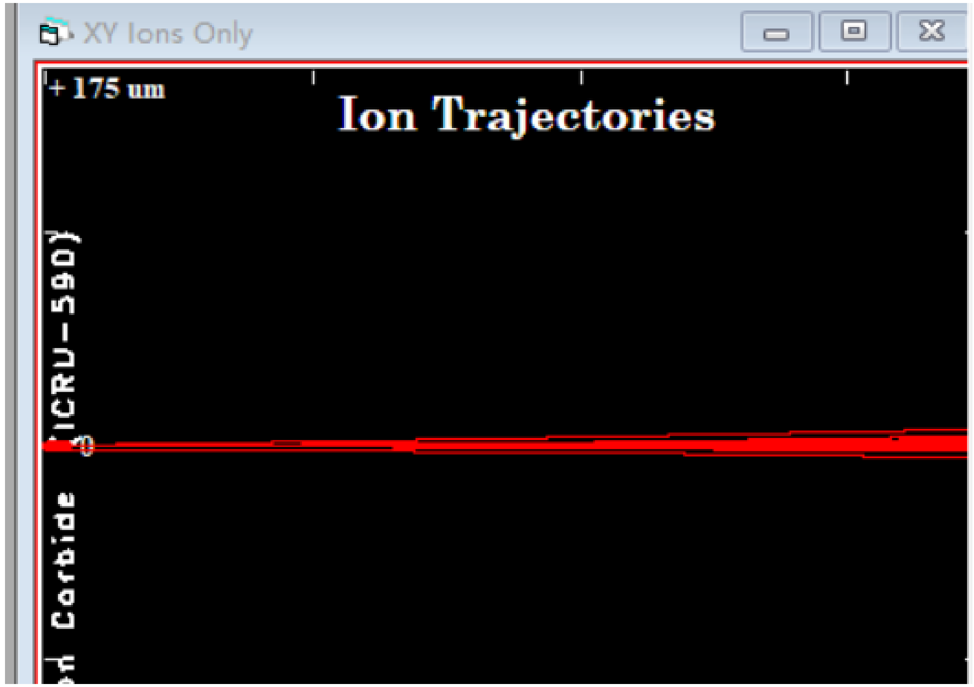
Rs $$I = I_s * \left(e^{\frac{qV - I*R_s}{nkt}} - 1\right) + \frac{V - I*R_s}{R_{sh}}$$



Rsh $$I = I_s * \left(e^{\frac{qv}{nkt}} - 1\right) + \frac{V}{R_{sh}}$$

- Higher n → low conductivity: dominated by recombination in the depletion region
- Lower n → high conductivity: dominated by diffusion in the depletion region
- Need higher current to find out the value of Rs

What happened inside the LGAD

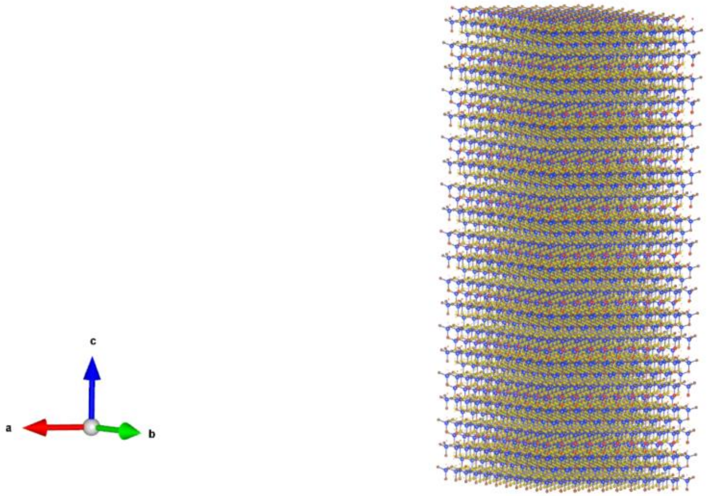


Simulation of the proton injection by SRIM

- Only **vacancies by injection**

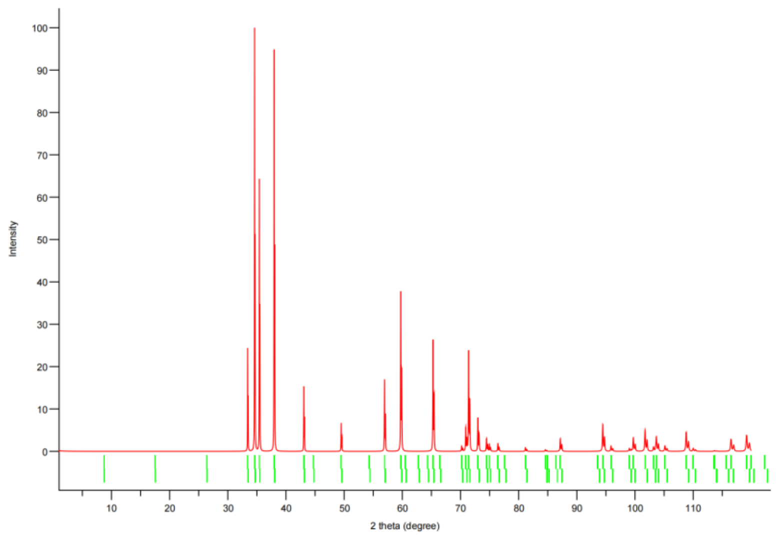
- We tested XRD, EPR, and DLTS to find out whether which defect is in the LGAD.

What happened inside the LGAD
----XRD test



The structure put into the simulation.

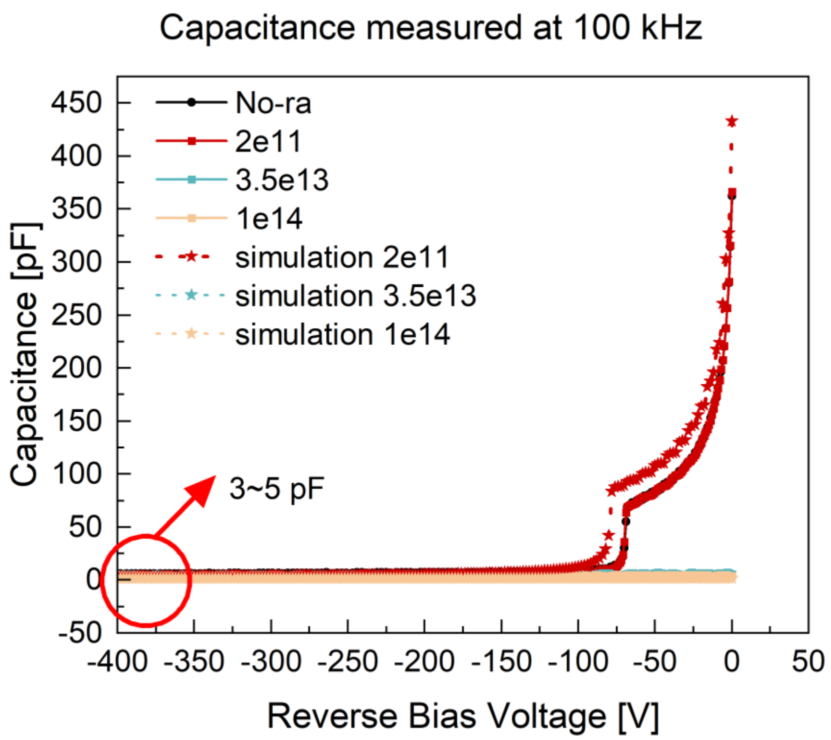
The internal microstructure changes.



1	0	1	2.59036	-12.4569	-16.3344	20.5423	34.6859	11.9891
-1	1	-1	2.59036	13.52	-15.8652	20.8445	34.6859	12.3444
-1	1	1	2.59036	-12.4568	-16.3344	20.5422	34.6859	11.9890
1	-1	1	2.59036	12.4568	16.3344	20.5422	34.6859	11.9890
1	-1	-1	2.59036	-13.52	15.8652	20.8445	34.6859	12.3444
0	0	-4	2.53195	13.4846	39.8791	42.0973	35.4237	96.1726
0	0	4	2.53195	16.1278	-39.7819	42.9268	35.4237	100.0000
0	0	-4	2.53195	13.4791	39.8818	42.098	35.5123	47.8258
0	0	4	2.53195	16.134	-39.7841	42.9311	35.5123	49.7374
0	-1	-2	2.36837	-9.74576	-21.2255	23.356	37.9606	25.4275
0	1	2	2.36837	-11.1412	19.8712	22.7813	37.9606	24.1916
-1	0	-2	2.36837	-9.74576	-21.2255	23.356	37.9606	25.4275

The simulation value of 2θ is different from test due to defects.

Simulation： Capacitance vs voltage



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- $N_{Z1/2} = \eta_{Z1/2} * \Phi_{flux}$ ($\eta_{Z1/2}$ = 19.8 cm^{-1})

When radiation flux reaches 3.5e13 or higher, the effective doping becomes 0.

$$n_{eff} = n_0 - \eta \times \phi_{flux}$$

$Z_{1/2}$ and EH_3 are the critical reason of the carrier removal effect.