山东高等技术研究院
SHANDONG INSTITUTE
OF ADVANCED TECHNOLOGY

Simulation of SiC detector

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2nd DRD3 Week on Solid State Detectors R&D

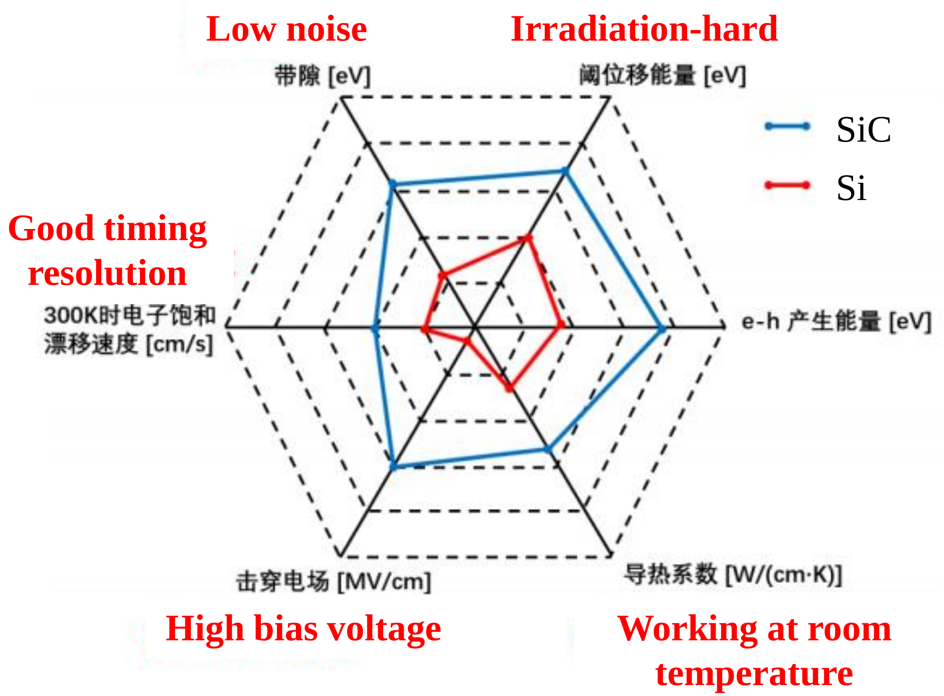
Advantages of silicon carbide

With the increase of collision brightness and detector size, silicon are facing two challenges:

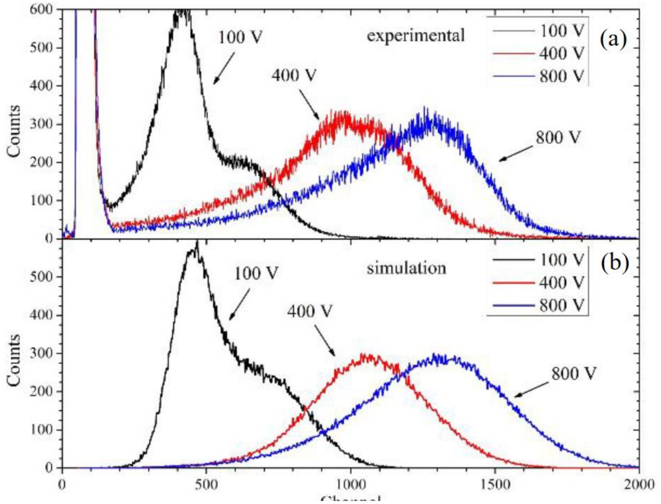
- **Near the limit of irradiation-hard → replace detector regularly**
- **Leakage current increases with irradiation → cooling equipment**

Silicon carbide is expected to achieve breakthroughs in the above two aspects.

物理量	Si	SiC
Bandgap[eV]	1.12	3.26
Thermal conductivity[W/K cm]	1.5	4.9
Breakdown[MV/cm]	0.3	2.0
Atomic displacement threshold energy[eV]	13	22
Average ionization energy[eV/e-h]	3.6	7.8
Electron saturation drift velocity[cm/s]	1×10^7	2×10^7
Hole saturation drift velocity[cm/s]	0.6×10^7	1.8×10^7



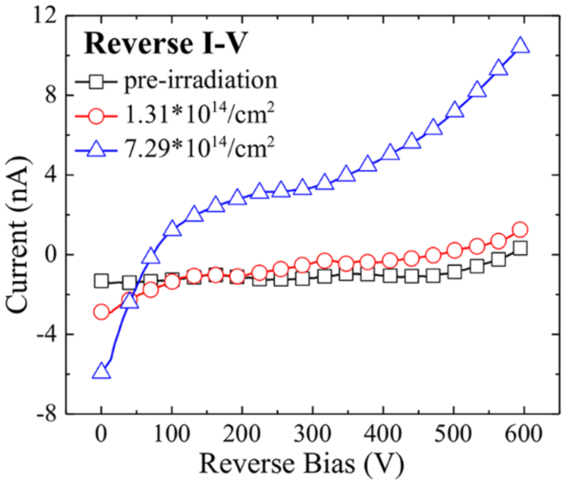
Irradiation studies of SiC



Comparison between the simulated values of the energy spectrum before device irradiation and the measured data.

Simulation on the performance degradation process and energy spectrum of the device use TCAD and FLUKA.

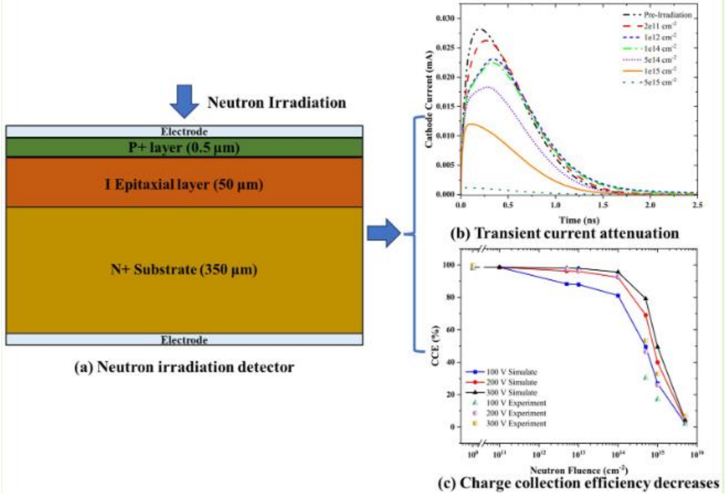
Huang Haili. Research on the Performance and Performance Degradation of SiC Particle Irradiation Detectors [D]. Xi'an University of Electronic Science and Technology , 2019.



Electric parameter measurement results of the SiC diodes before (black open blocks) and after neutron irradiation

The radiation resistance of 4H-SiC Schottky diode detectors was studied experimentally by carefully analyzing the detectors' properties before and after deuterium-tritium fusion neutron irradiation.

Liu L , Liu A , Bai S ,et al.Radiation Resistance of Silicon Carbide Schottky Diode Detectors in D-T Fusion Neutron Detection[J].Scientific Reports, 2017, 7(1):13376.

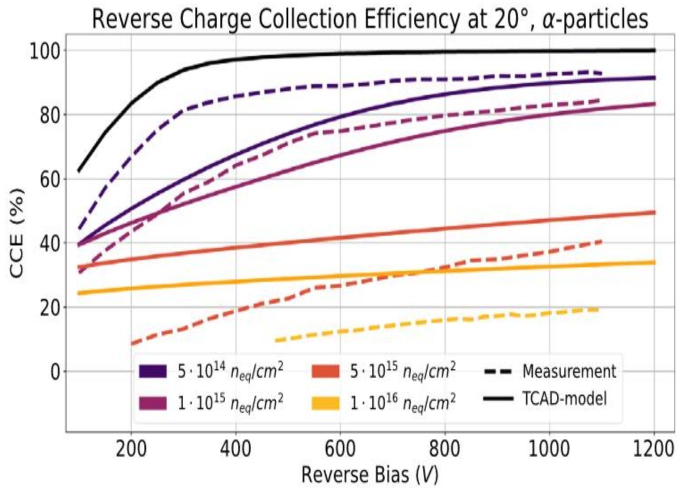


Transient current pulse response and charge collection efficiency after neutron irradiation under different neutron fluences

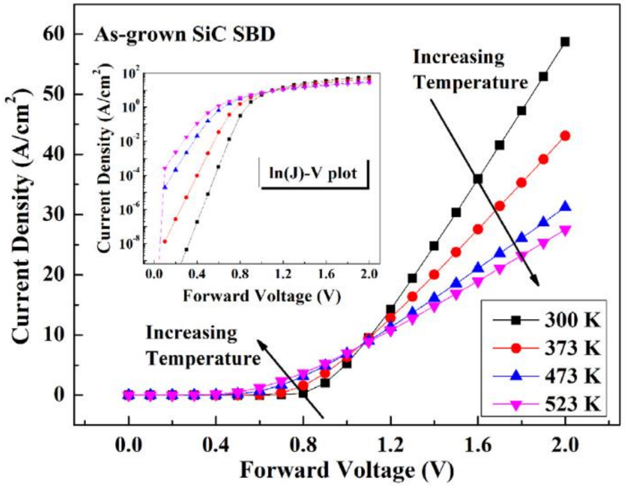
Simulations to investigate the output performance of 4H-SiC detectors due to high fluence of neutron damage by TCAD.

Y. Sun et al., "Investigation of the Performance Degradation of 4H-SiC Neutron Detectors Using MCNP and TCAD," in IEEE Sensors Journal, vol. 24, no. 4, pp. 4432-4441, 15 Feb.15, 2024.

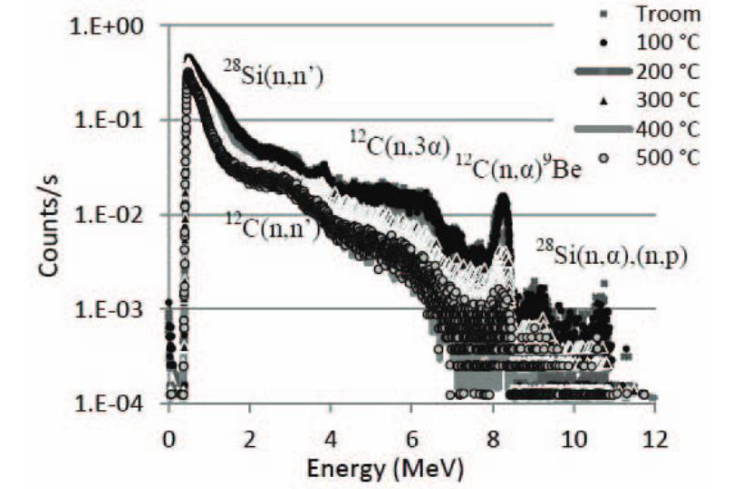
Irradiation studies of SiC



Reverse bias CCE measurements vs. simulation



Simulated forward J-V-T-characteristics of as-grown Ni/4H-SiC-based SBD



The resulted energy histograms recorded during irradiation tests with 14 MeV neutrons on different ambient temperatures

This work presents a bulk radiation damage model for TCAD simulation based on existing literature and optimized on measurement results of neutron-irradiated 4H-SiC pad diodes.

TCAD has been utilized to investigate the radiation-induced effects on the electrical characteristics of a SiC-based SBD detector.

F. Issa's group successfully completed the detection of 14 MeV neutrons using SiC detectors under the condition of 500° C.

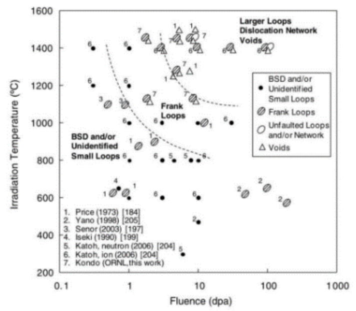
Gaggl P ,Burin, Jürgen, Gsponer A ,et al. TCAD modeling of radiation-induced defects in 4H-SiC diodes[J]. 2024.

Tripathi S , Upadhyay C , Nagaraj C P ,et al.The performance simulation of the LiH-SiC-based Fast Neutron Detector for harsh environment monitoring using Geant4 and TCAD[J].Nuclear Instruments and Methods in Physics Research A, 2019, 916.

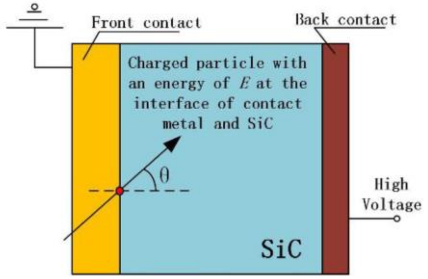
D. Szalkai et al., "Detection of 14 MeV neutrons in high temperature environment up to 500 °C using 4H-SiC based diode detector," 2015 4th International Conference on Advancements in Nuclear Instrumentation Measurement Methods and their Applications (ANIMMA), Lisbon, Portugal, 2015, pp. 1-6.

Challenges in SiC detector research

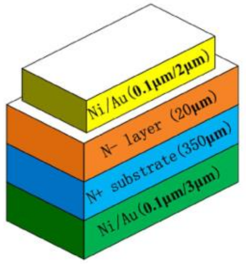
- **Irradiation damage mechanism of SiC materials not clear**
  - **The analysis of experimental results is more inclined to summarize the experimental results and qualitatively explain the device performance or the variation laws of the experimental results.**



- **Irradiation model of SiC detector incomplete**
  - **During the research process of SiC particle irradiation detectors, there is a lack of an analytical method that can comprehensively analyze the impacts of different factors on the final output of the detectors, as well as a series of physical models used to describe the damage to the devices.**



- **Lack of reliable detector with new structures**
  - **Extreme and complex radiation detection environments mean that the scale and structure of existing semiconductor detectors can no longer gradually meet future nuclear detection requirements. It is necessary to design new detector structures to fulfill the radiation detection needs of the future.**



Research goals

- **Study the defects generated during irradiation and the performance changes of SiC detector**

- **Improve the theoretical model to predict the performance of SiC detector after irradiation**

  ☆ **Focusing**

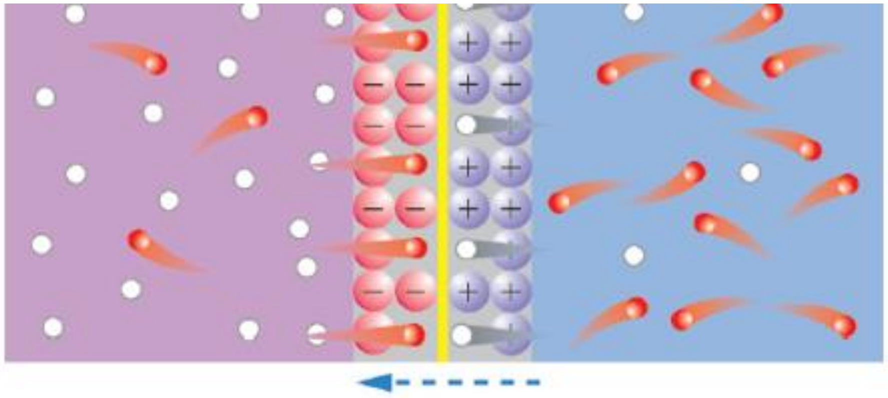
- **Develop SiC detector with new structures to improve its irradiation hardness**

Research content

- **Research on material characteristics to gain understanding of the physical changes of SiC after irradiation**
  - **Influence mechanism of carrier mobility**
  - **Transport: based on electric field, calculate the carrier mobility and diffusion coefficient using the diffusion and drift equations**
- **Improve theoretical model to explain and predict the behavior of SiC after irradiation**
  - **Recombination: such as scattering and trap recombination, establish rate equations to describe the disappearance process of carriers**
  - **Influence of different types of irradiation particles**
  - **Some empirical parameters from fitting**
- **Methods to reinforce detectors and improve service life**
  - **Materials: special doping**
  - **Process: annealing**
  - **Special structures: multilayer structures and heterojunctions**

Research plan

Influence mechanism of carrier mobility



- **Diffusion process: carriers move from regions of high concentration to low concentration due to the non-uniform carrier concentration in space caused by thermal motion**

$$\frac{\partial n(x,t)}{\partial t} = D_n \frac{\partial^2 n(x,t)}{\partial x^2} \qquad \frac{\partial p(x,t)}{\partial t} = D_p \frac{\partial^2 p(x,t)}{\partial x^2} \qquad D = \frac{kT}{q}\mu$$

- **Drift process: directional movement of carriers under the action of an electric field**

$$v_n = -\mu_n E \qquad v_p = \mu_p E$$

Research plan

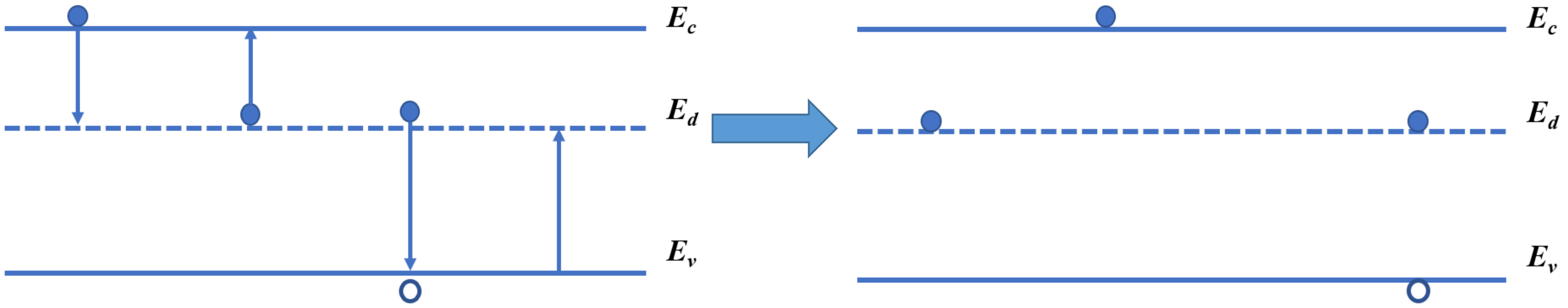
Recombination: such as scattering and trap recombination

- **Shockley-Read-Hall model: impurities and defects as recombination centers**

  recombination rate: $R_{SRH} = \frac{C_n C_p (np - n_i^2)}{C_n(n + n_1) + C_p(p + p_1)}$

- **Trap- recombination model: distribution of trap energy levels**

  recombination rate: $R_{trap} = \sum_i R_{trap,i}$



Research plan

Methods to reinforce detectors and improve service life

- **Materials: Special Doping**
  - Doping can change the band structure of semiconductors.
  - Impurity atoms can form stable defect complexes with irradiation-induced defects, suppressing the evolution of defects.
- **Process: Annealing**
  - Recovery of irradiation-induced defect damage.
- **Special Structures: Multilayer Structures or Heterojunctions**
  - Low Gain Avalanche Detector

Research foundation

An open-source fast simulation software RAdiation SEmi-conductoR(RASER)

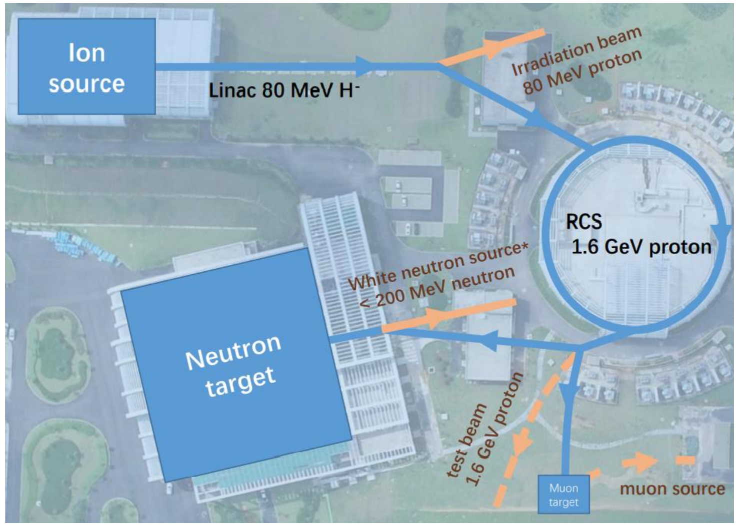
- **Particle incident path and deposition energy distribution: GEANT4**
- **Electric and weighting field from Poisson and Laplace equation: DEVSIM**

$$\nabla^2 \vec{U}(r) = -\frac{\rho}{\epsilon}, \quad \nabla^2 \vec{U}_w(r) = 0$$

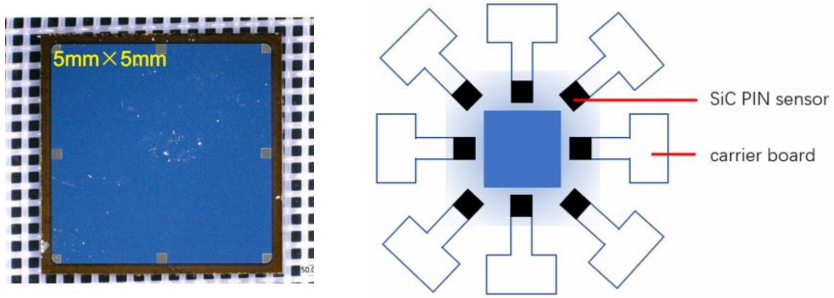
- **Electronic simulation: amplifier model, NGSpice**
- **Induced current:** $I(t) = -q\vec{v}(\vec{r}(t)) \cdot E_w(\vec{r}(t))$

Research foundation

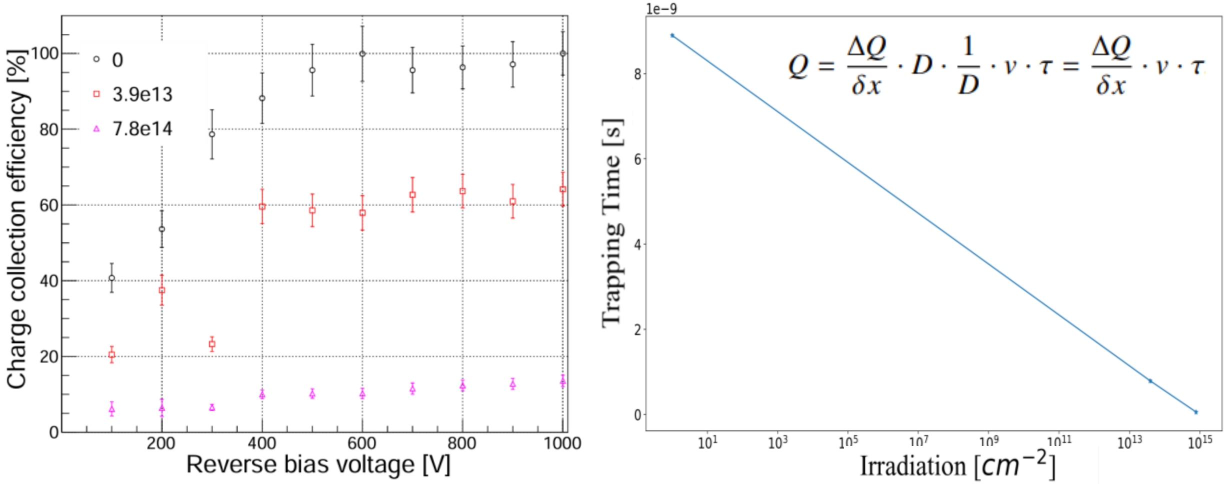
SiC PIN irradiation study as beam monitor for 1.6GeV proton beam line in China Spallation Neutron Source



New 1.6GeV proton beam line



SiC PIN(left) and detector placement in beam(right)

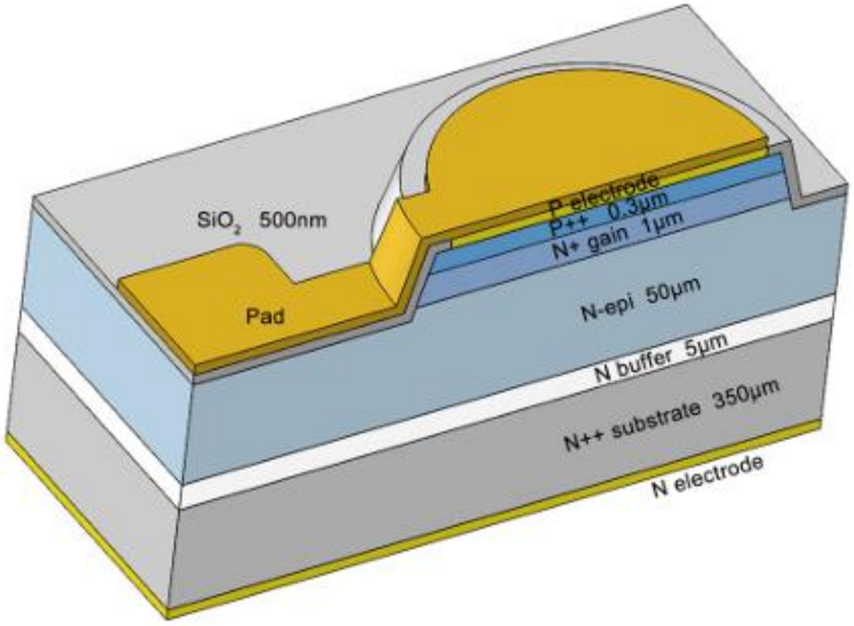


CCE(left) and carrier trapping time(right) before and after irradiation

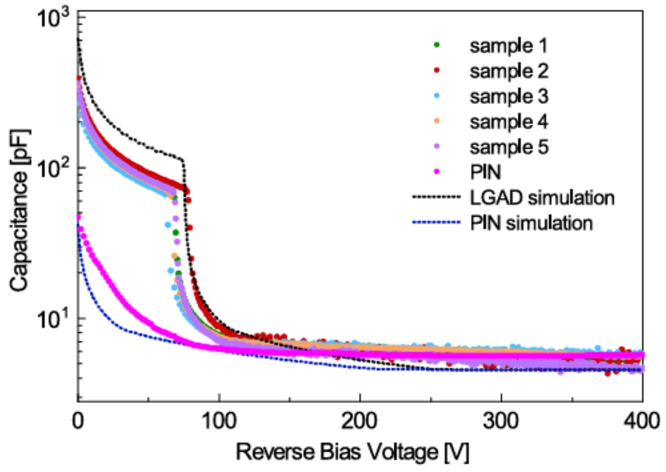
- **The feasibility of SiC for beam monitoring has been demonstrated through irradiation experiment.**
- **RASER to calibrate SiC for long-term use, with the relationshop between carrier trapping time and irradiation dose.**

Research foundation

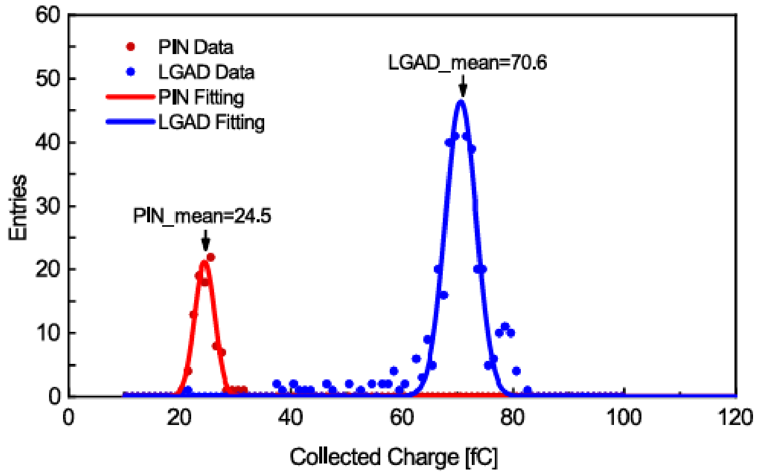
SiC LGAD development



Cross-sectional schematic of the 4H-SiC LGAD detector



CV characteristics of 4H-SiC PIN and LGAD



Charge collection distribution of 4H-SiC PIN and LGAD

- **SiC LGAD is fabricated and CV curve shows an obvious gain structure.**
- **The gain factor of SiC LGAD is ~3 at 350V in α detection.**

Summary

WG4 research goals <2027	
	Description
RG 4.1	Flexible CMOS simulation adaptable to different technology nodes and development of connections between tools for device-level simulation and electronic circuit design/validation
RG 4.2	Implementation of newly measured semiconductor properties into TCAD and MC simulations tools
RG 4.3	Definition of benchmark for validating the radiation damage models with measurements and different benchmark models.
RG 4.4	Developing of bulk and surface model for $10^{16}\text{cm}^{-2} < \Phi_{eq} < 10^{17}\ \text{cm}^{-2}$
RG 4.5	Collate solutions from different MC tools and develop an algorithm to include adaptive electric and weighting fields

WG4 research goals in the period 2024 - 2026 from DRD3 Proposal

- **Our proposal meets WG4 research goals.**
- **Sincerely invite cooperations!**
- **Contact: suyu.xiao@iat.cn**

Thank you!