Mechanisms of proton irradiation-induced defects on the electrical performance of 4H-SiC PIN detectors

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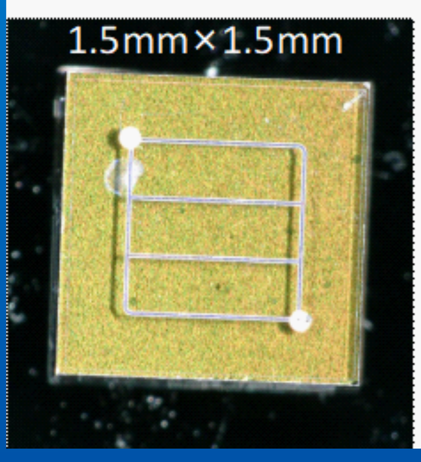
Motivation

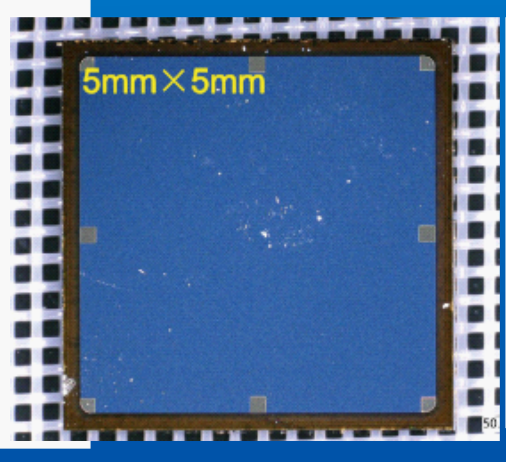
Silicon Carbide is advantagous for radiation detection with fast timing in harsh environments.

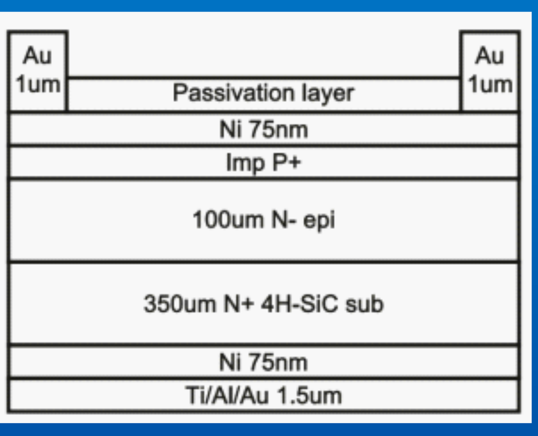
It is critical to understand the radiation effects to further develop radiation-hard detectors.

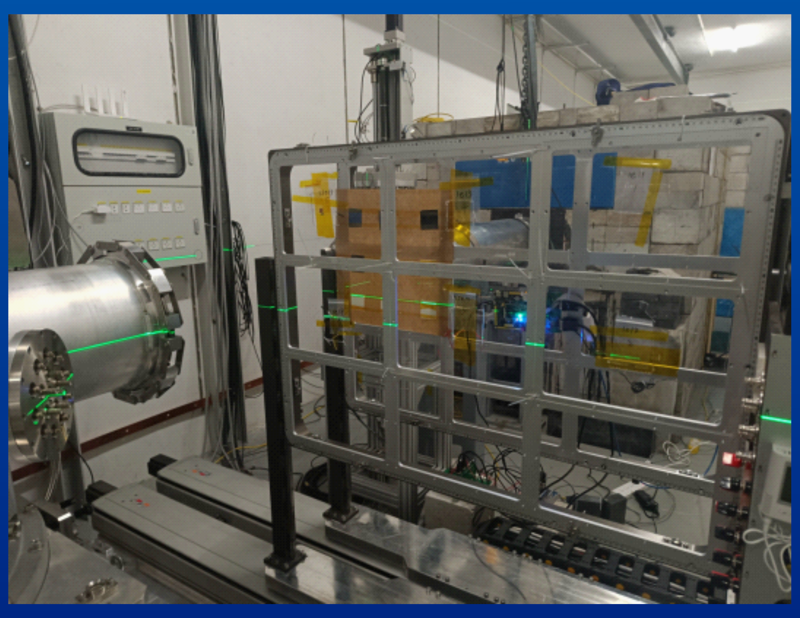
	Si	4H-SiC
Energy gap [eV]	1.12	3.23
e − h pair creation energy [eV]	3.6	7.6–8.4
Displacement Energy [eV]	13–15	30–40
Breakdown electric field [V/cm]	$3 \cdot 10^5$	$3–4 \cdot 10^6$
Saturated electron drift velocity [cm/s]	$0.8 \cdot 10^7$	$2 \cdot 10^7$
Thermal conductivity [W/Kcm]	1.5	4.9

Samples





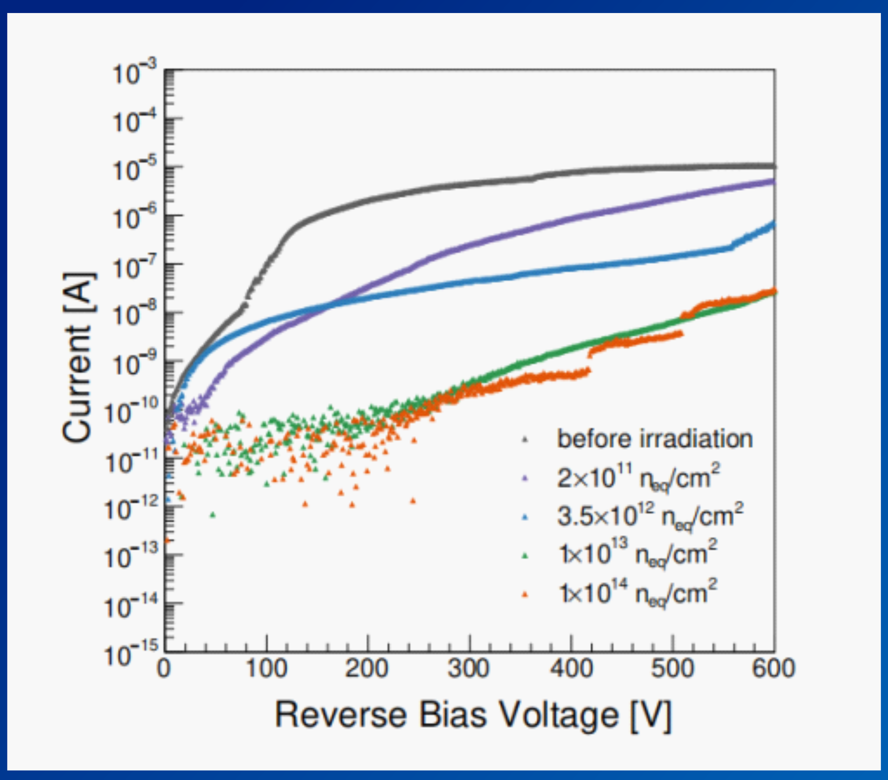




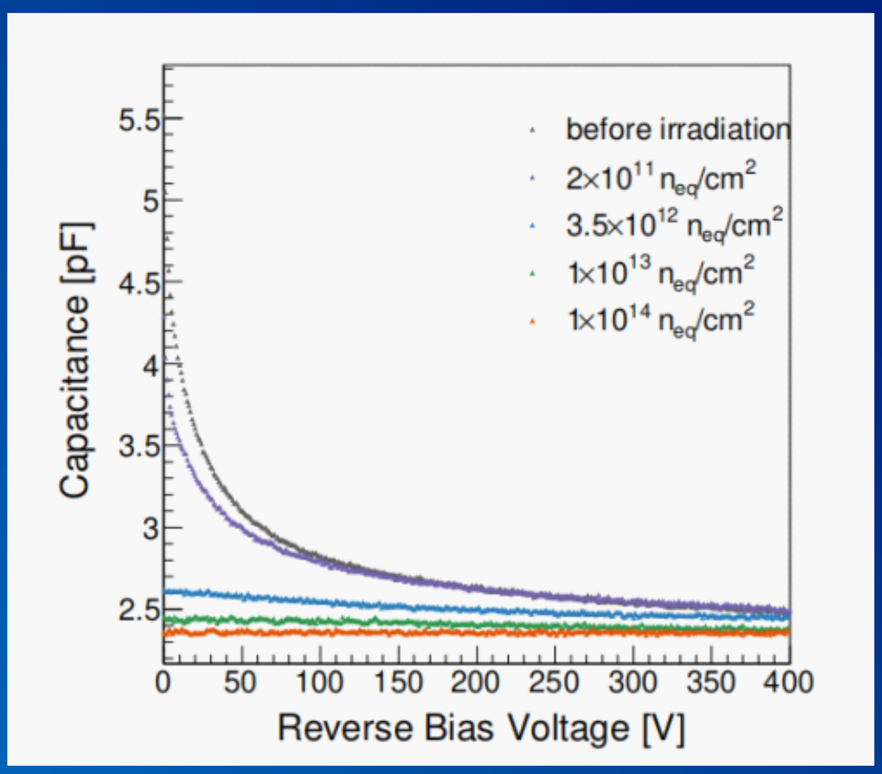
4H-SiC PINs were irradiated by 80-MeV protons with fluences below 10^{15} n_{eq}/cm^2 at China Spallation Neutron Source (CSNS).

label	size (mm^2)	irradiation fluence (n_{eq}/cm^2)
NJU-PIN-1	1.5×1.5	0
NJU-PIN-2	1.5×1.5	2×10^{11}
NJU-PIN-3	1.5×1.5	3.5×10^{12}
NJU-PIN-4	1.5×1.5	1×10^{13}
NJU-PIN-5	1.5×1.5	1×10^{14}
NJU-PIN-6	5×5	0
NJU-PIN-7	5×5	3.9×10^{13}
NJU-PIN-8	5×5	2.3×10^{14}
NJU-PIN-9	5×5	7.8×10^{14}

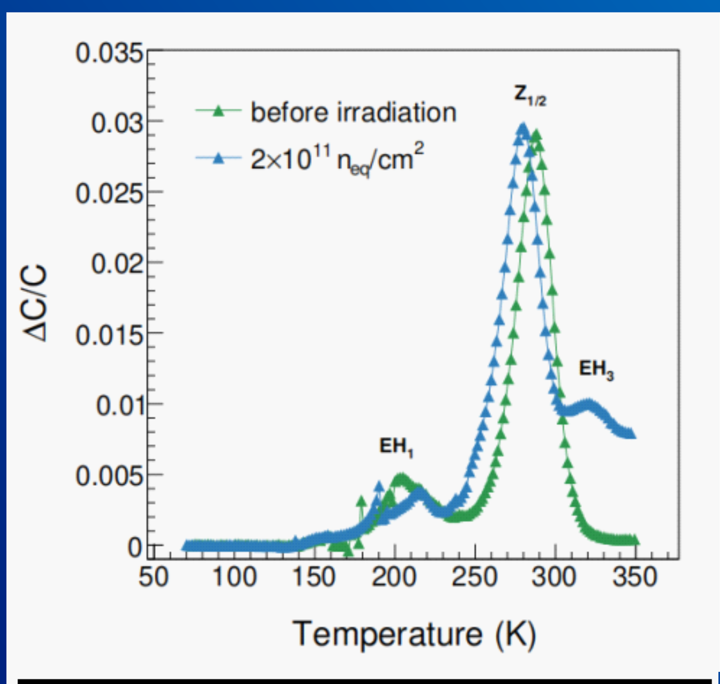
Defect Characterization



Defect characterization was conducted on the 1.5×1.5 mm^2 devices. The leakage current decreases after irradiation.

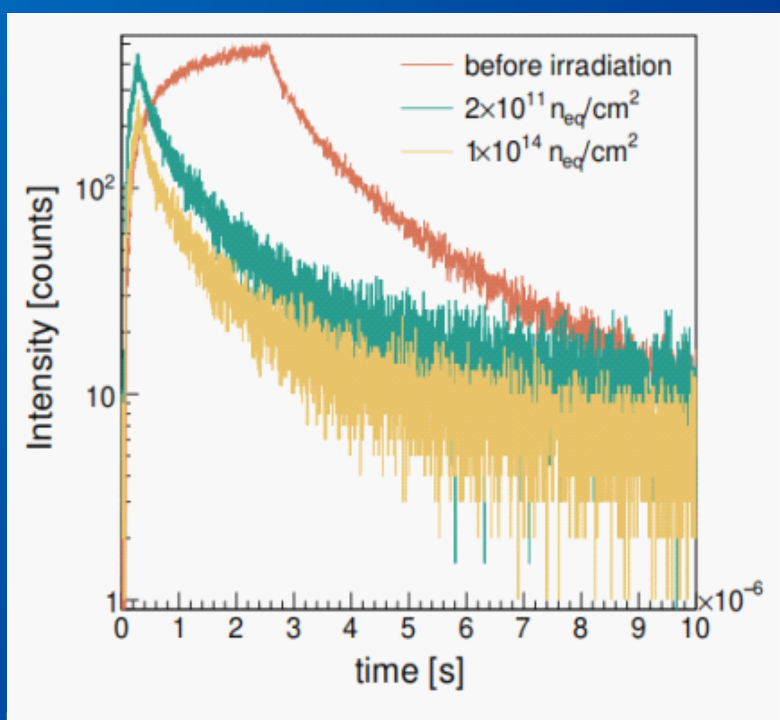


The irradiated devices gradually lose typical C-V characteristics of a pn-junction, which is attributed to compensation effect.



label	$E_C - E_T(eV)$	$N_{initial}(cm^{-3})$	$N_{irradiated}(cm^{-3})$	assignment
EH_1	0.44	1.40×10^{11}	1.11×10^{11}	V_{Si}
$Z_{1/2}$	0.63	8.52×10^{11}	8.66×10^{11}	V_C
EH_3	0.685	-	2.95×10^{11}	V_{Si}

Deep-level Transient Spectroscopy (DLTS): The EH_3 defect is uniquely observed in the irradiated sample.



$\Phi(n_{eq}/cm^2)$	0	2×10^{11}	1×10^{14}
τ(ns)	484	398	376

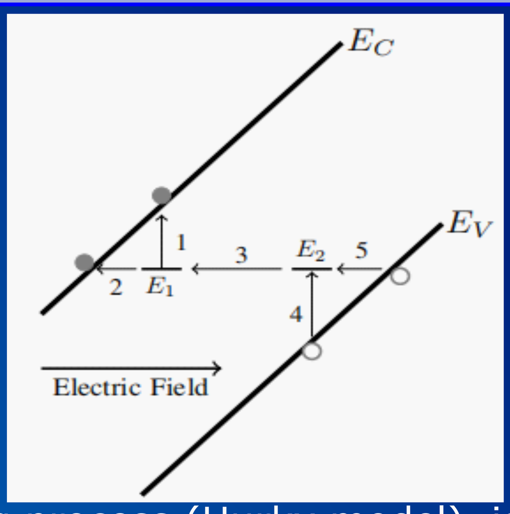
Time-resolved Photoluminescence (TRPL): Measured hole lifetime decreases after irradiation.

Simulation Model

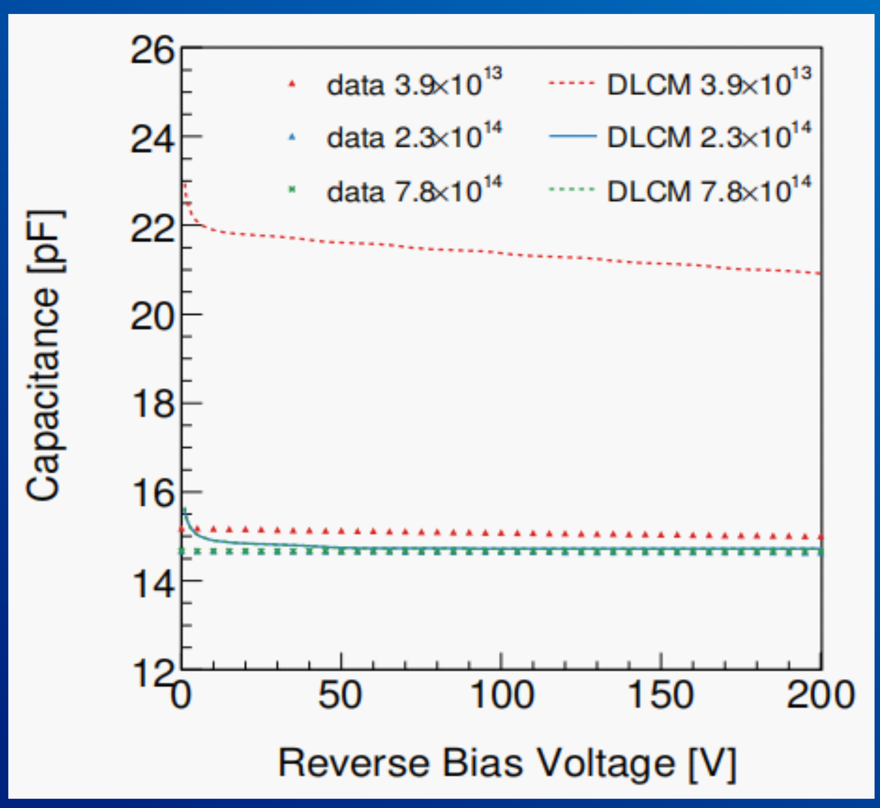
$$\Delta N_{eff} = \Delta D = g\Phi_{n_{eq}}$$

$$g \approx 1.48cm^{-1}$$

Only EH_3 is considered in this model; linear relationship is utilized as the change of effective doping (N_{eff}).

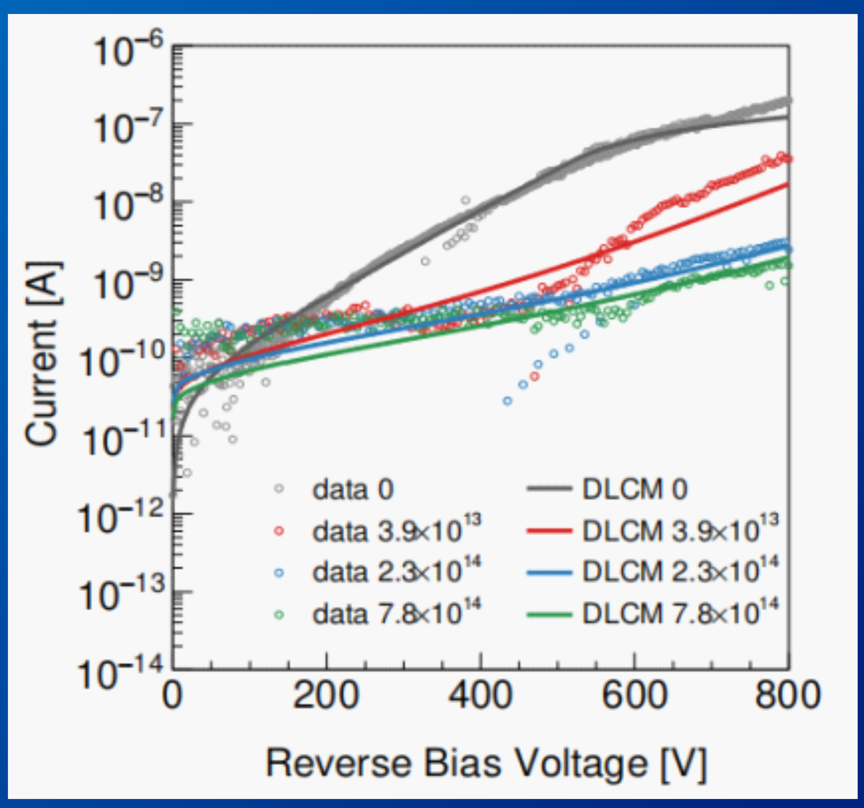


Electron tunneling process (Hurkx model) is considered in the generation-recombination (G-R) model under high electric field.



Structural parameters are extracted from C-V before irradiation.
Simulated C-V agrees with 5×5 mm^2 devices' data.
Simulation software: https://raser.team/

$$G - R = \alpha \cdot \frac{n_i^{eff}}{\tau(F)}$$



Parameters are recalibrated in the G-R term.
Simulated I-V agrees with 5×5 mm^2 devices' data.

Conclusion

The change of electric field distribution inside the diodes is the main cause of the changes in I-V and C-V characteristics.

The Deep Level Compensation model (DLCM) proposed in this work can be utilized to design radiation-hardened 4H-SiC devices.

Full paper link: https://arxiv.org/abs/2503.09016