Istituto per la Microelettronica e Microsistemi

Consiglio Nazionale delle Ricerche

Advanced 4H-SiC Solid-State Detectors: Electric Field Mapping and High-Temperature Neutron Irradiation Studies

Enrico Sangregorio[1]

Alfio Samuele Mancuso[1,2], Annamaria Muoio[1], Saverio De Luca[1], Angela Garofalo[1,3], and Francesco La Via[1]

1. National Research Council of Italy - Institute for Microelectronics and Microsystems (CNR-IMM), 95121 Catania, Italy;
2. Department of Physics and Astronomy, University of Catania, 95123 Catania, Italy;
3. Department of Physics, University of Milano-Bicocca, 20126 Milano, Italy.

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Presentation Outline

Introduction and Motivations

4H-SiC Detector Design

Edge Termination Characterization

Neutron Detection

Electrical Characterization

Conclusions and Considerations

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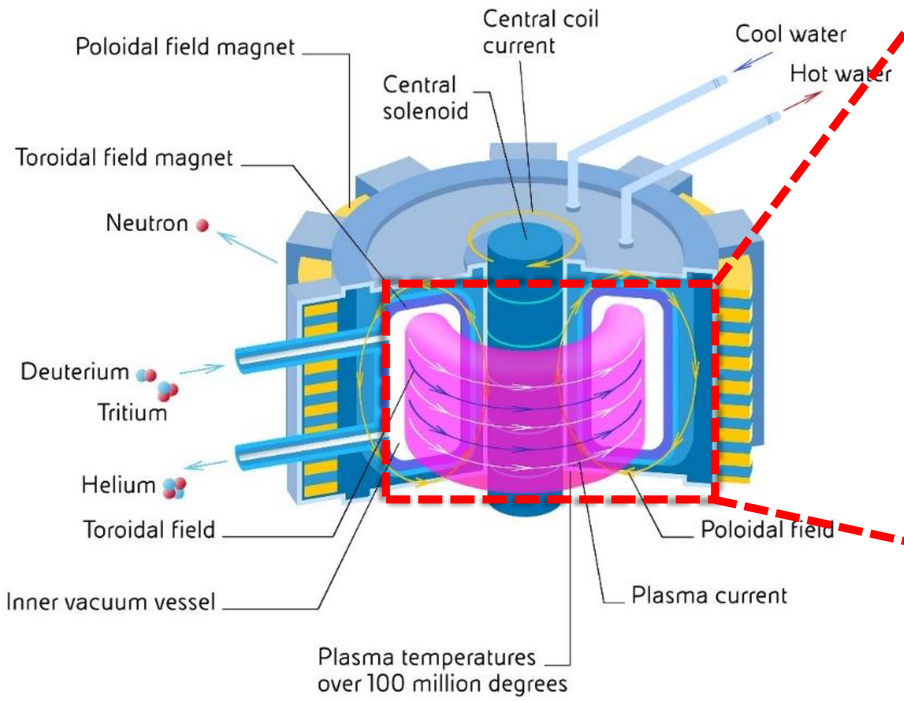
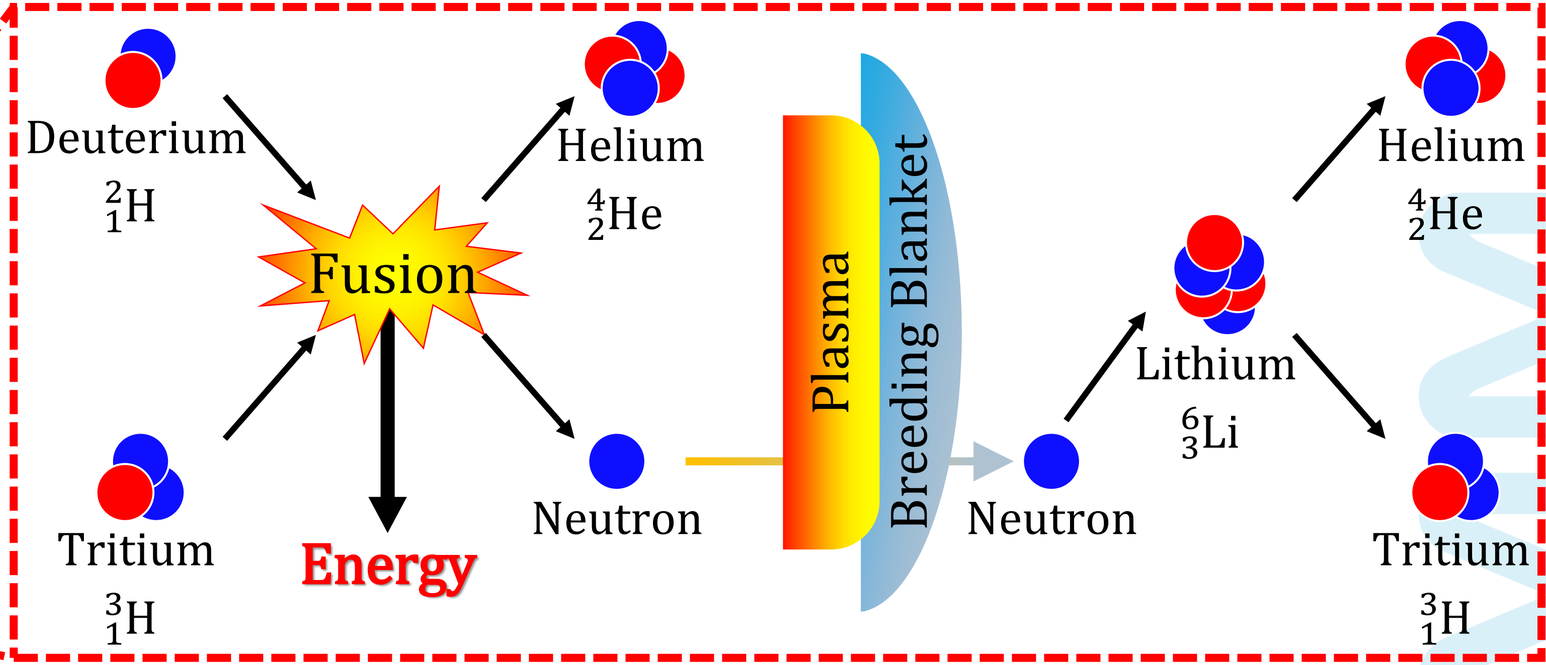
Silicon Carbide Detectors for Fusion Reactors

Simplified Tokamak Scheme





- Monitoring the fusion reaction requires a radiation-hard and temperature-stable neutron detector inside the reaction chamber

Silicon Carbide

- Chemical Stability
- Mechanical Hardness
- High Temperature Resistance
- High Thermal Conductivity
- Switching Velocity
- Radiation Hardness
- High Breakdown Electric Field

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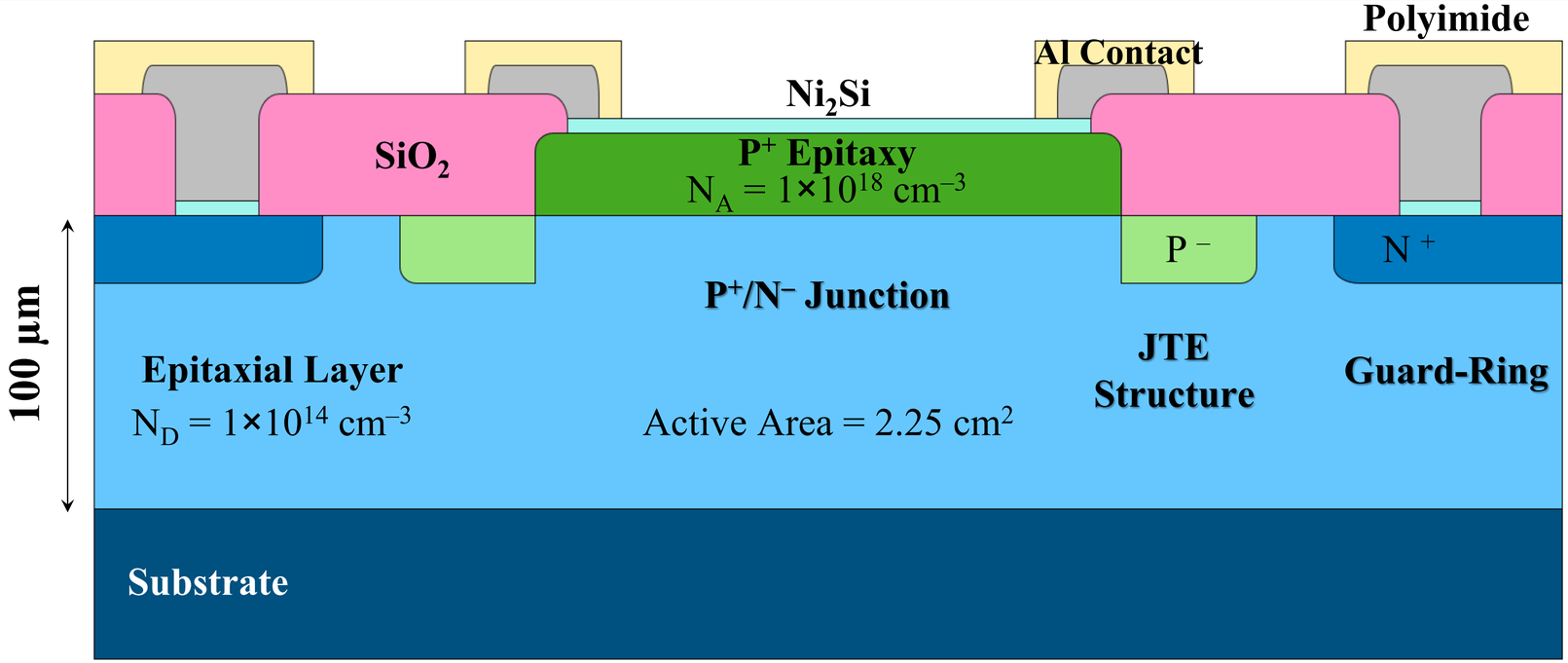
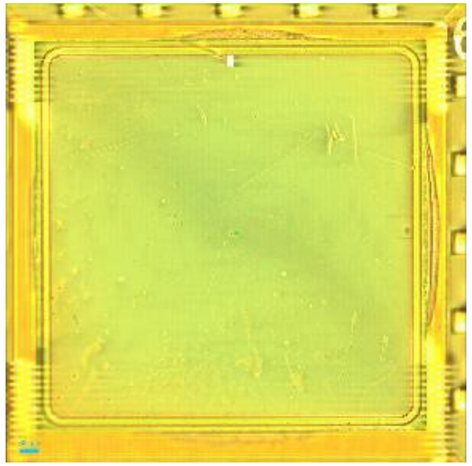
Design of a 10 kV Silicon Carbide p–n Diode



IMM Istituto per la Microelettronica e Microsistemi

INFN LNS Istituto Nazionale di Fisica Nucleare Laboratori Nazionali del Sud



ASM

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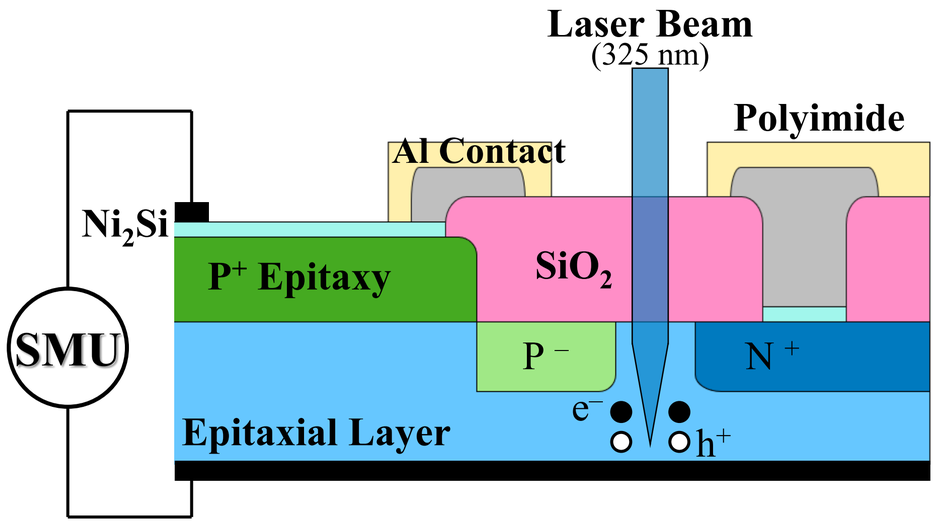
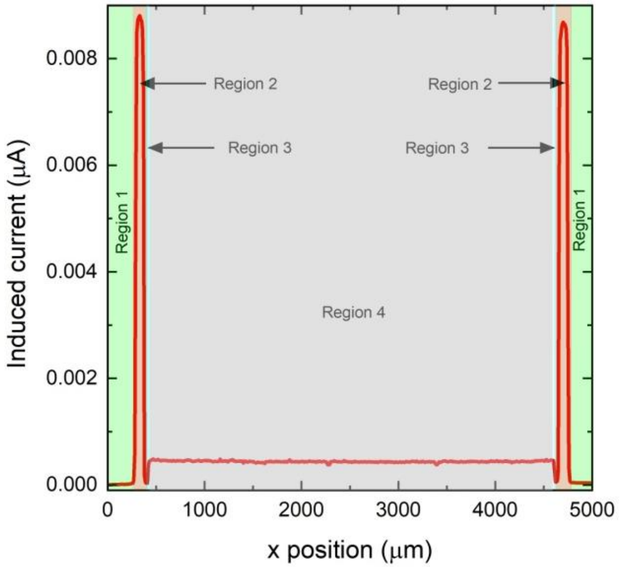
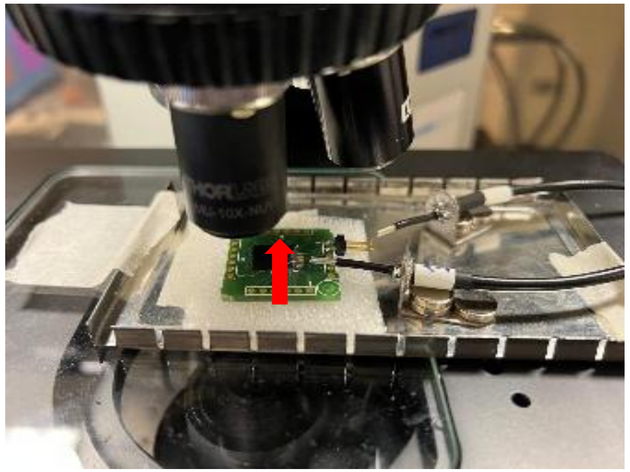
Optical Beam Induced Current (OBIC) Technique



OBIC Signal





He – Cd UV laser 325 nm
spot diameter size ~ 5 - 10 μm
40x and 10x

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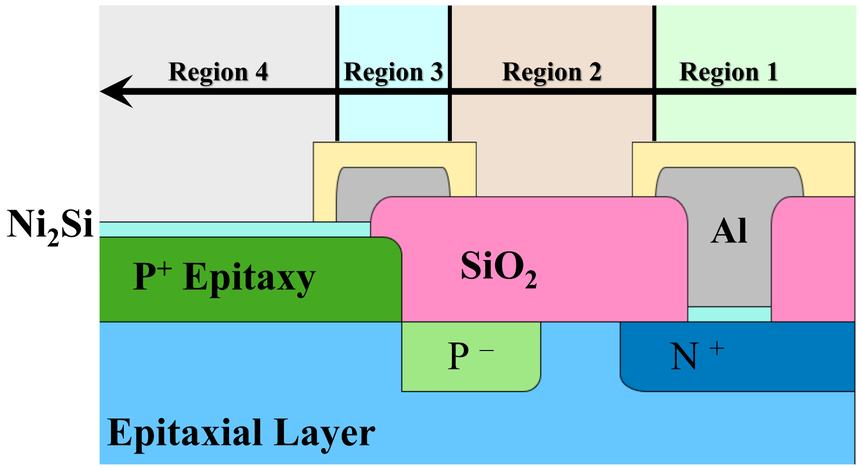
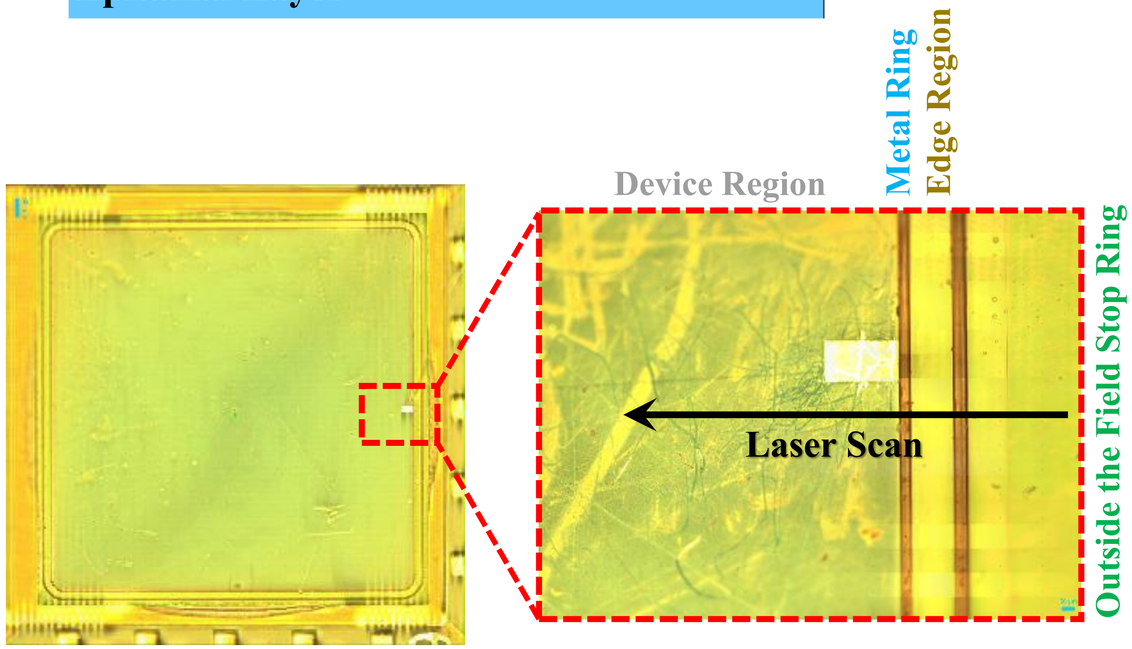
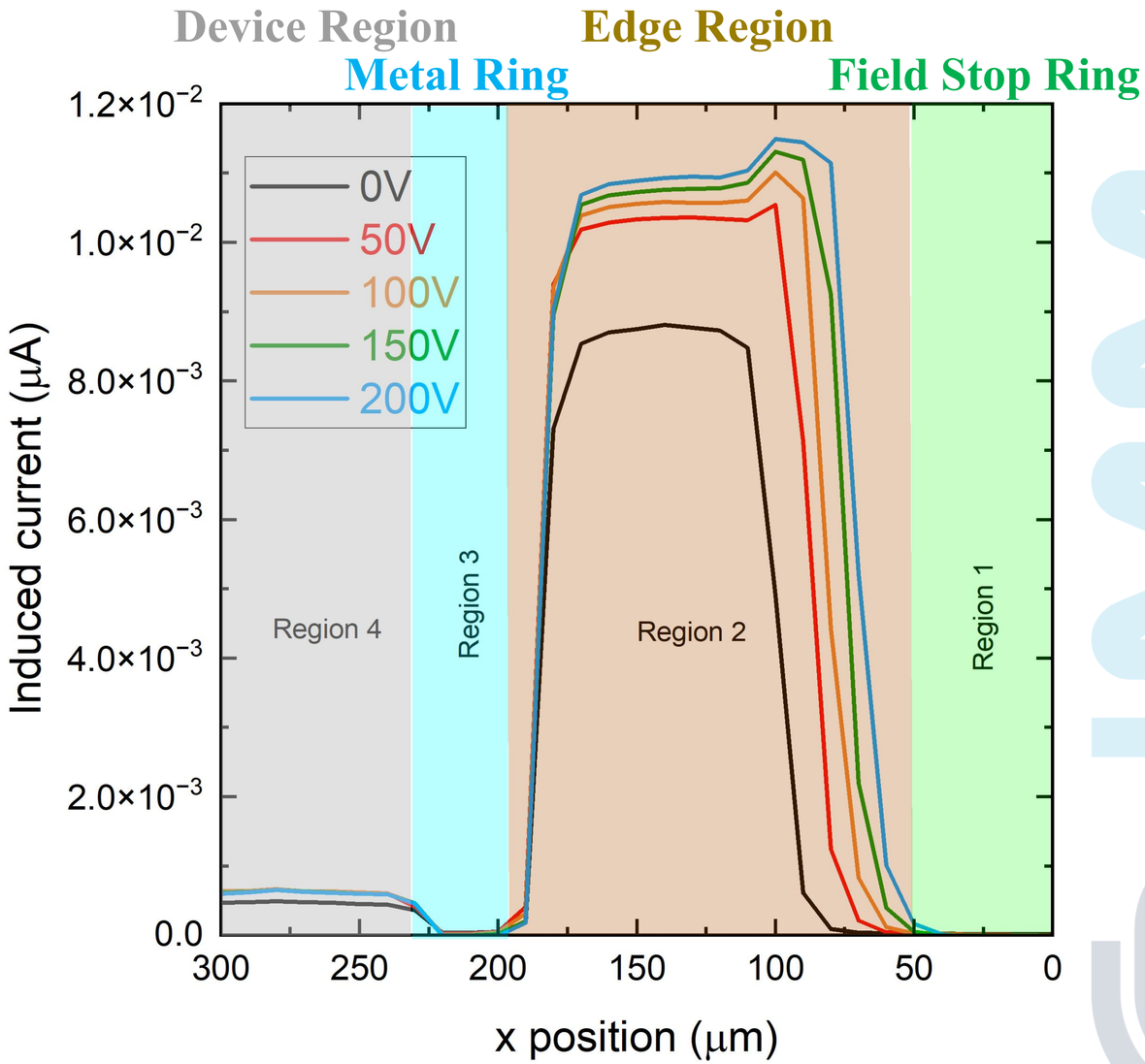
Characterization of the 100 μm SiC device







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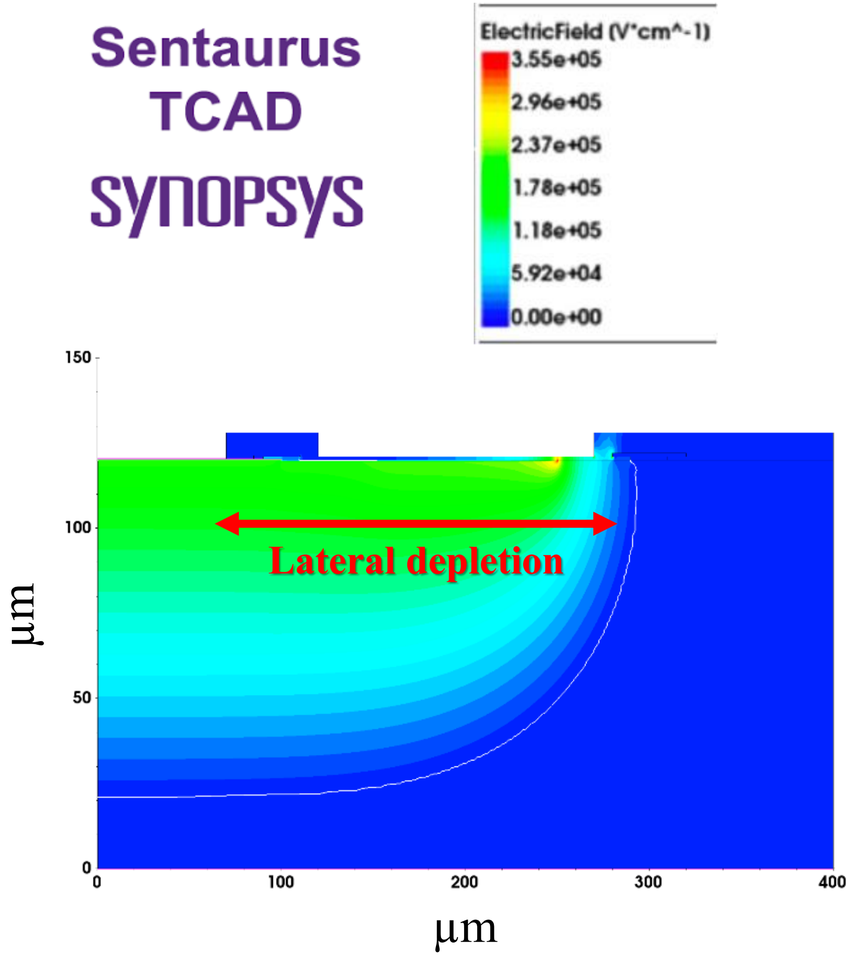
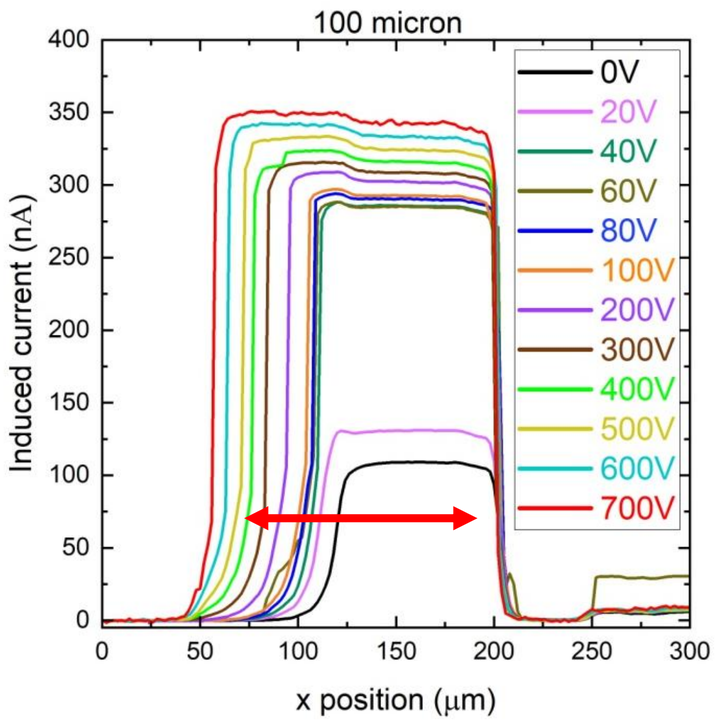
Lateral Depletion: Experimental and Simulations Validation

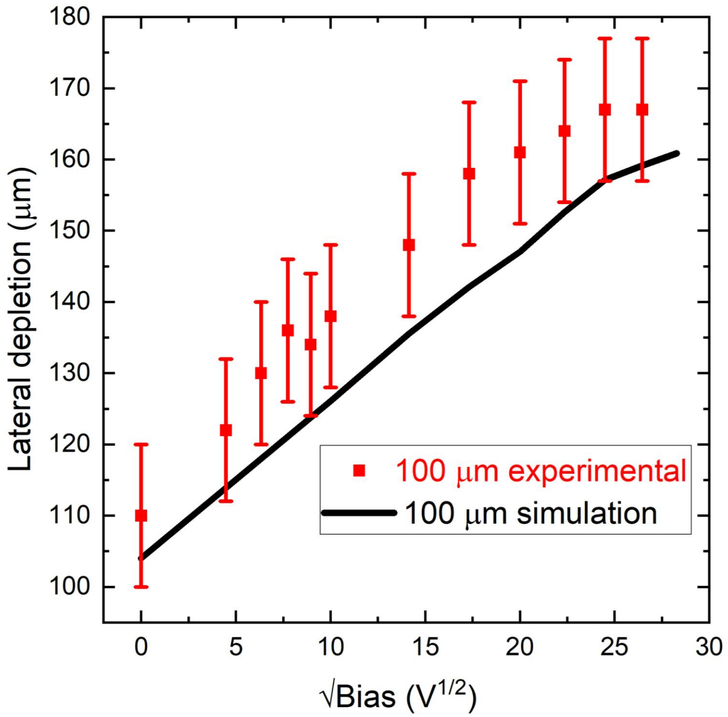
Sentaurus TCAD SYNOPSYS



OBIC Signal
Reverse Bias: 0 – 700 V



$$W = \sqrt{\frac{2\varepsilon(V_{b-i} + V_R)}{qN_D\left(1 + \frac{N_D}{N_A}\right)}}$$



Maximum Lateral Depletion = 170 µm

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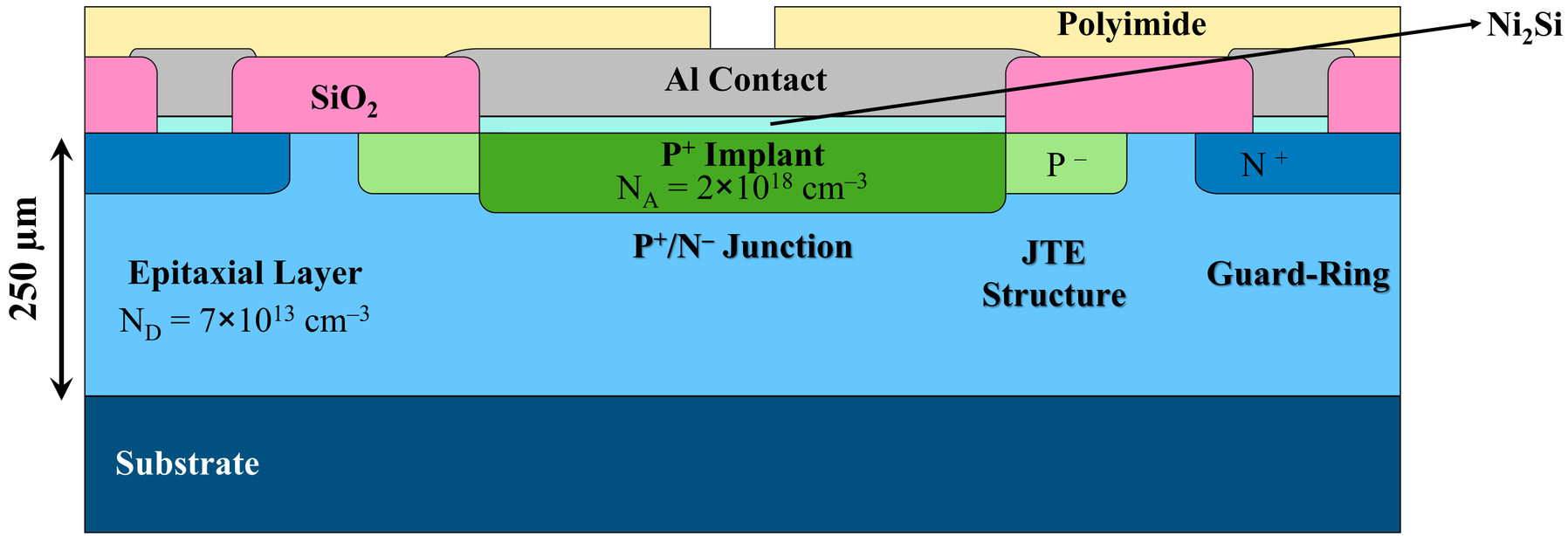
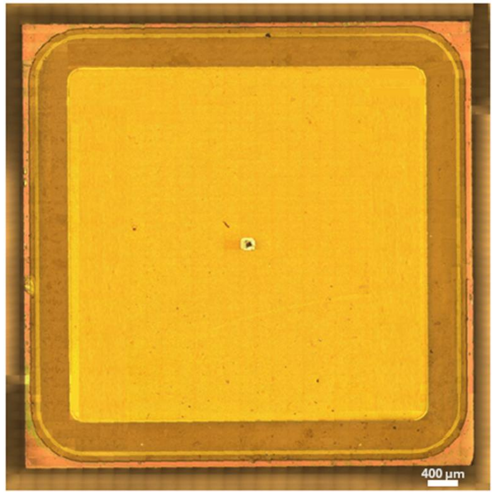
4H-SiC Neutron Detector Design





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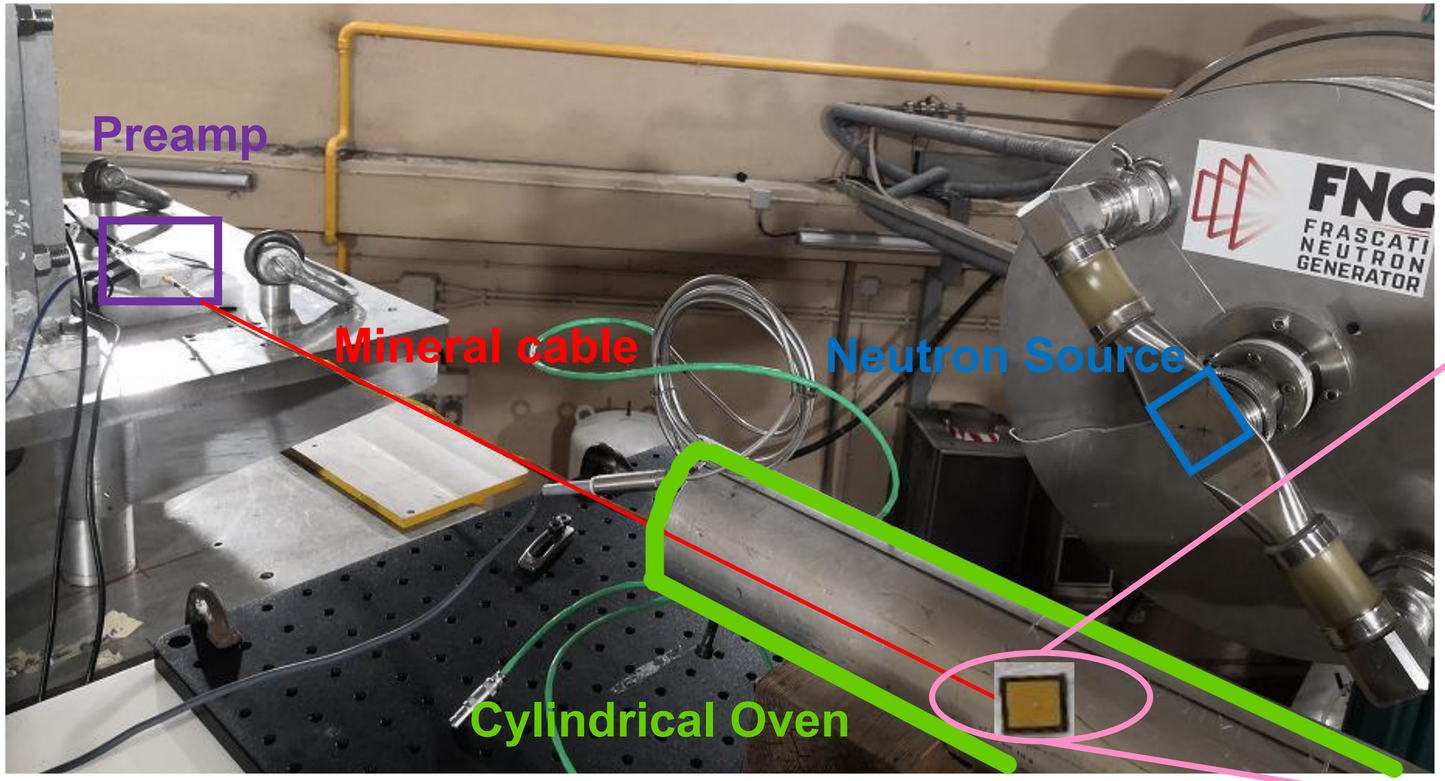
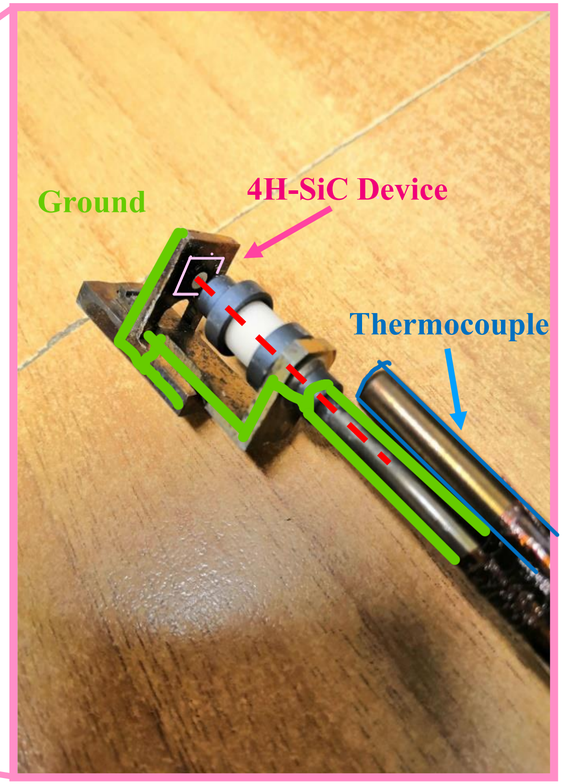
Neutron-Irradiation Experimental Setup



4H-SiC Device



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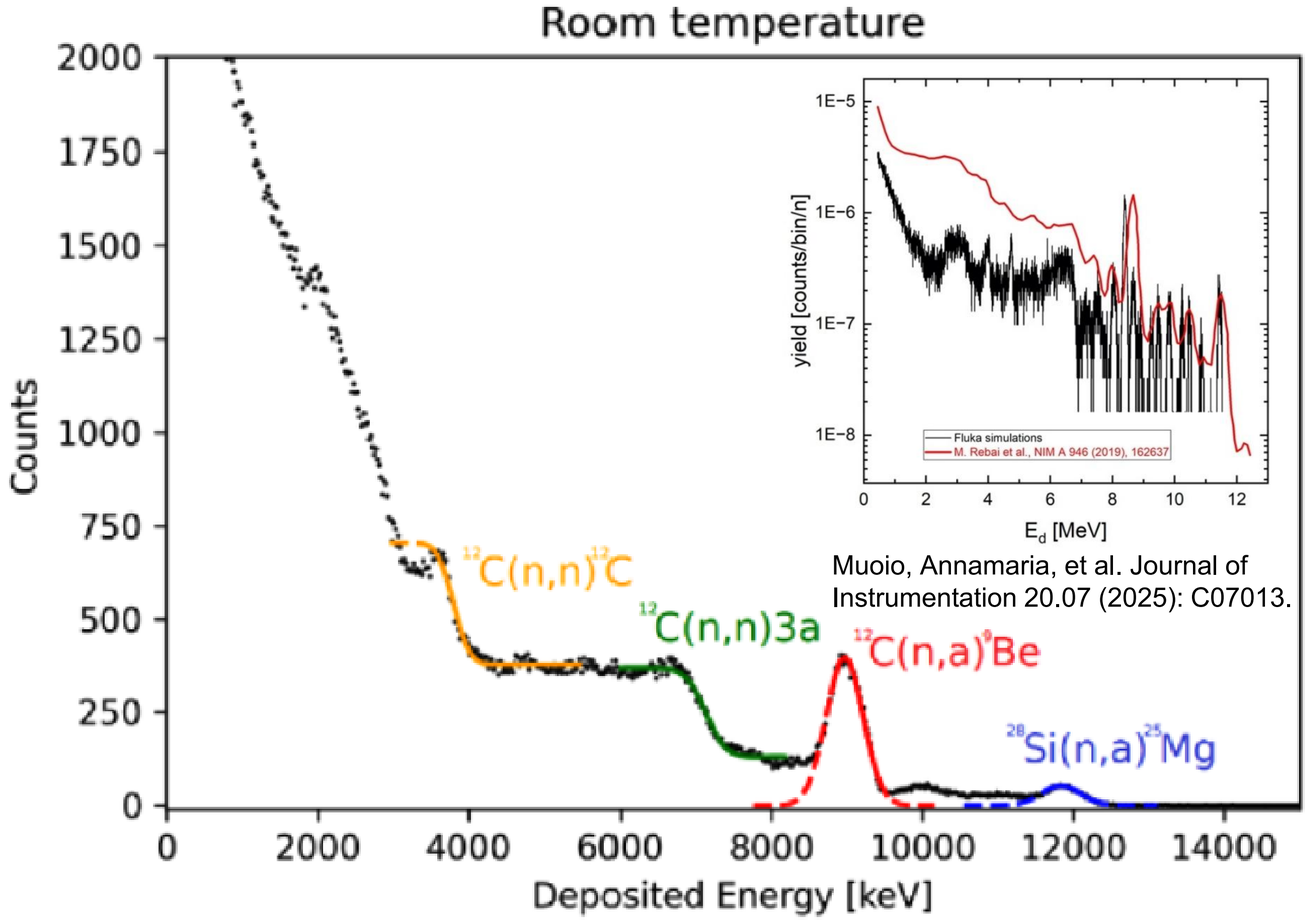
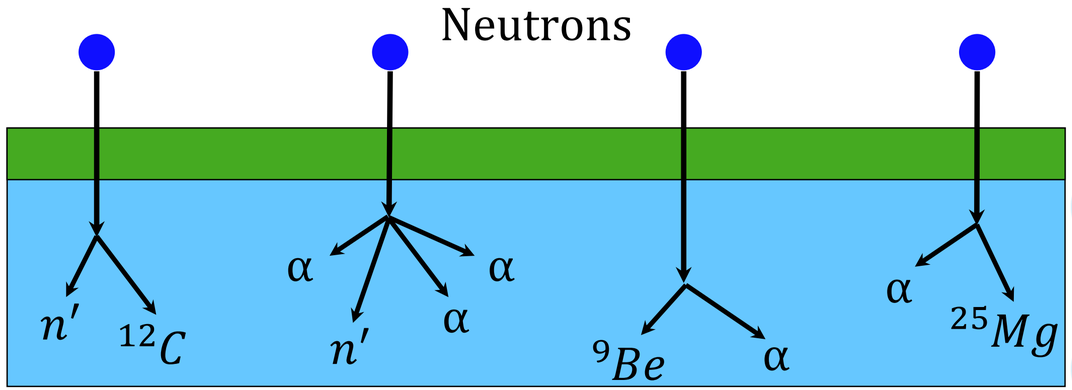
Experimental and Simulated Neutron Response

Neutron Fluence: $5 \times 10^{12}\ n/cm^2$
Neutron Energy: $14.1\ MeV$



Muoio, Annamaria, et al. Journal of Instrumentation 20.07 (2025): C07013.

Kushoro, Matteo Hakeem, et al. "Operation of a 250μm-thick SiC detector with DT neutrons at high temperatures." *Fusion Engineering and Design* 204 (2024): 114486.



	Reaction	Q-value [keV]	Cross Section @14MeV [Barn]
Carbon	Elastic Scattering		0.95
	Inelastic Scattering		0.50
	$^{12}C(n,\gamma)^{13}C$	-4946.0	$< 10^{-3}$
	$^{12}C(n,\alpha)^{9}Be$	5702.0	0.08
	$^{12}C(n,n)3\alpha$	7274.7	0.18
	$^{12}C(n,n+\alpha)^{8}Be$	7366.6	$< 10^{-3}$
	$^{12}C(n,2\alpha)^{5}He$	8010.0	$< 10^{-3}$
	$^{12}C(n,p)^{12}B$	12587.1	$< 10^{-3}$
Silicon	Elastic Scattering		0.68
	Inelastic Scattering		1.08
	$^{28}Si(n,\gamma)^{29}Si$	-8473.6	$< 10^{-3}$
	$^{28}Si(n,\alpha)^{25}Mg$	2653.6	0.18
	$^{28}Si(n,p)^{28}Al$	3859.7	0.30
	$^{28}Si(n,D)^{27}Al$	9360.3	0.02
	$^{28}Si(n,n+\alpha)^{24}Mg$	9984.1	0.02
	$^{28}Si(n,n+p)^{27}Al$	11584.9	0.07
	$^{28}Si(n,3He)^{26}Mg$	12138.2	$< 10^{-3}$
	$^{28}Si(n,2\alpha)^{21}Ne$	12539.5	$< 10^{-3}$
	$^{28}Si(n,2p)^{27}Mg$	13412.8	$< 10^{-3}$

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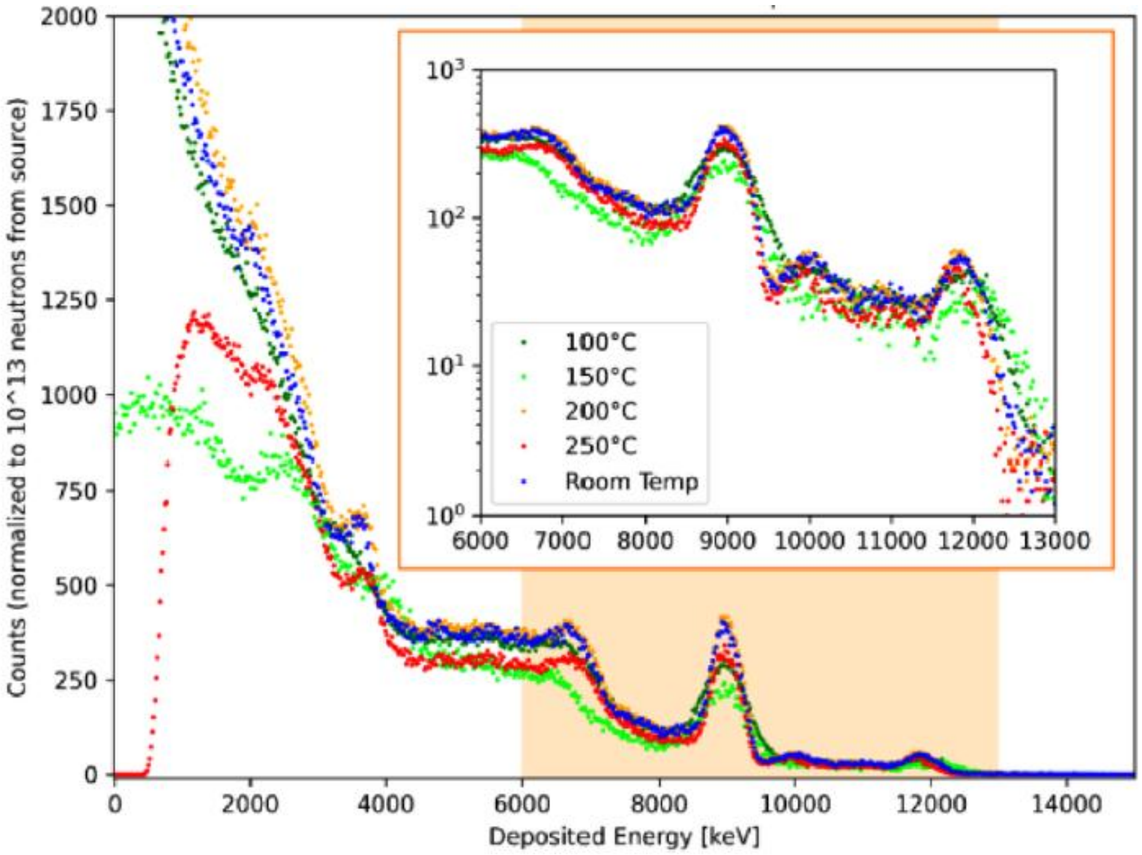
High Temperature Neutron Response

Neutron Total Fluence: $5 \times 10^{12}\ n/cm^2$
Neutron Energy: $14.1\ MeV$



4H-SiC detector response to neutrons does not change significantly within the studied temperature range

Kushoro, Matteo Hakeem, et al. "Operation of a 250μm-thick SiC detector with DT neutrons at high temperatures." *Fusion Engineering and Design* 204 (2024): 114486.

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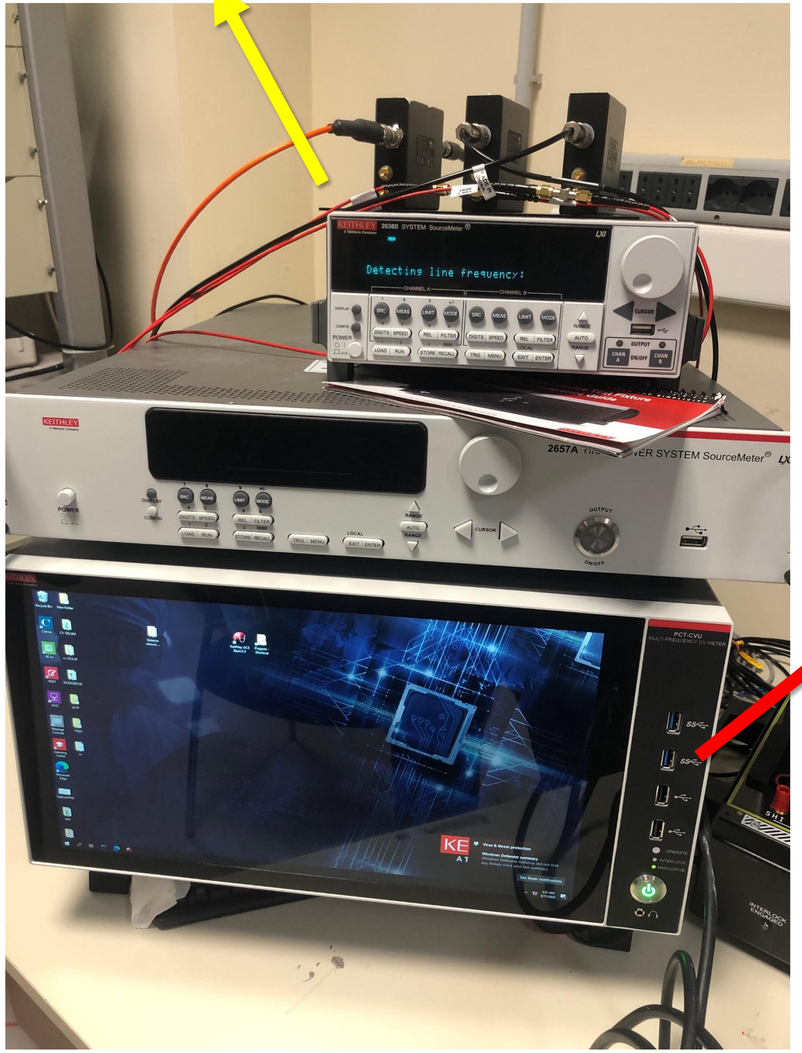
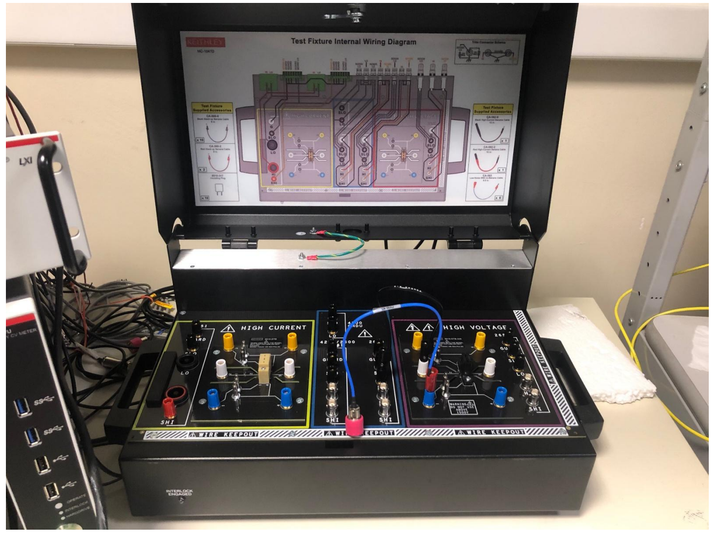
Experimental Setup for Electrical Characterization

Keithley 2612 SMU

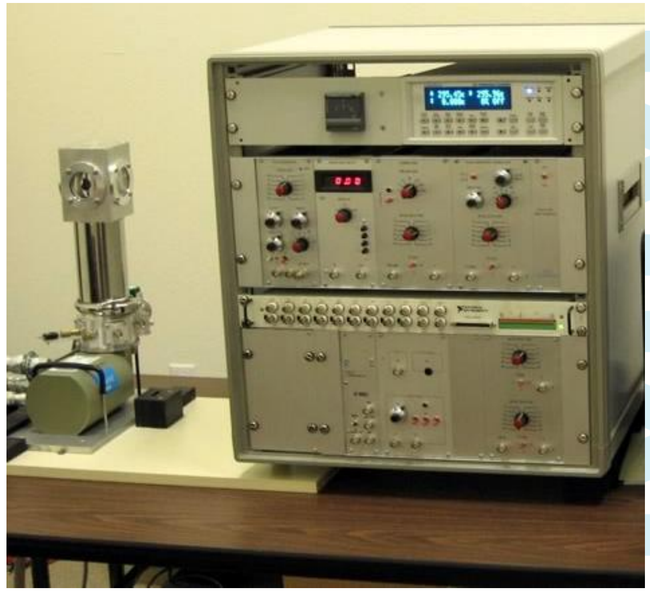


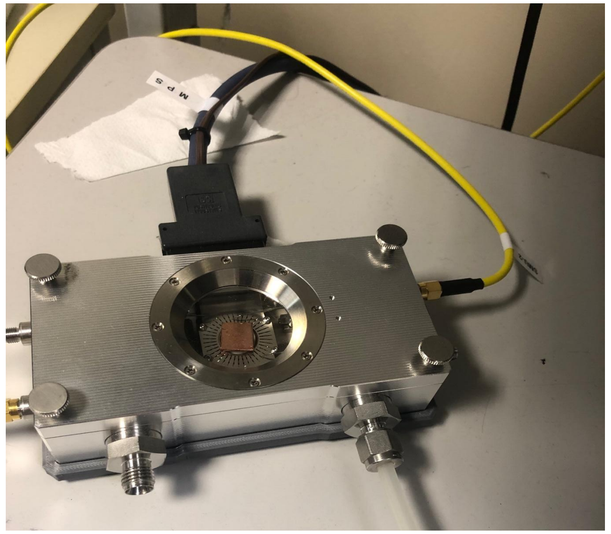
4200-SCS

Probe Station



Sula Technologies DLTS





Micro-Probe System Nextron

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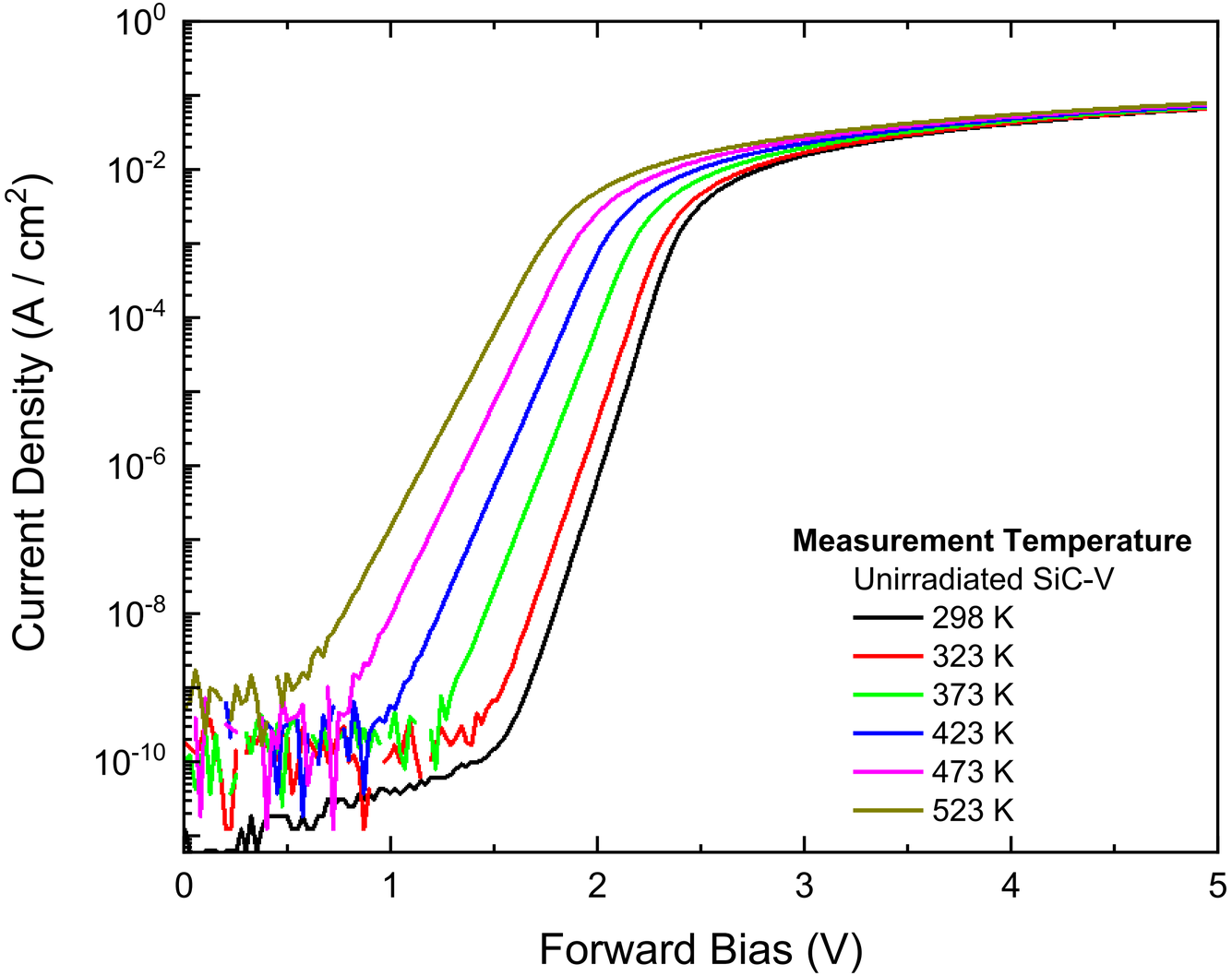
Current – Voltage Characterization

Forward J–V Characteristics of Unirradiated SiC-V Detector at Different Temperatures



- High and Temperature Independent Series Resistance

$$R_s = 35\ k\Omega$$

- Temperature Dependence of the Linear Region

$$J_{tot} = J_0\, e^{\frac{qV_F}{nkT}}$$

$$J_0 \propto T^3 e^{\left(\frac{-E_g}{2k_BT}\right)}$$

$n = 1.5\ at\ 298\ K$ $\quad$ $n = 1.1\ at\ 523\ K$

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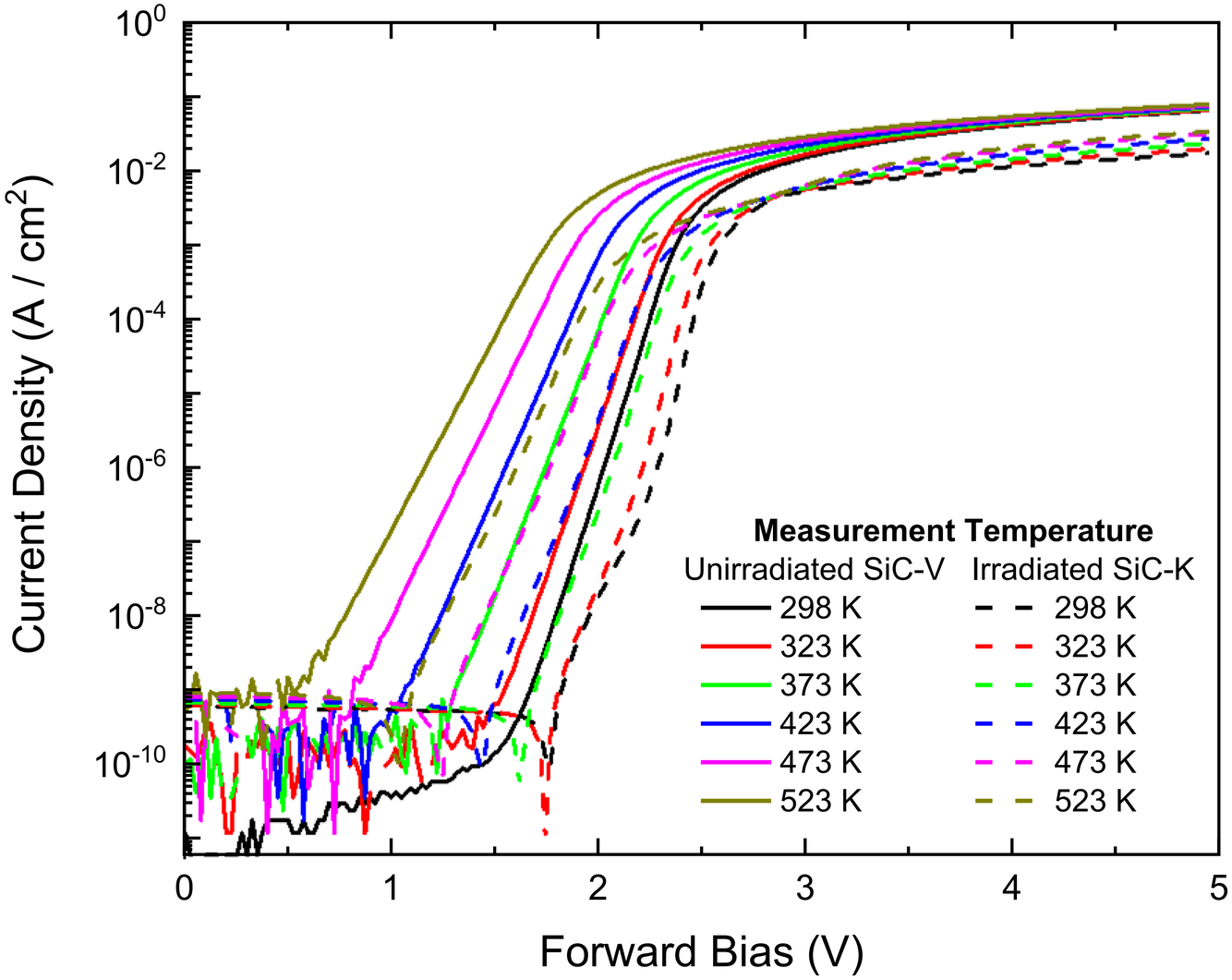
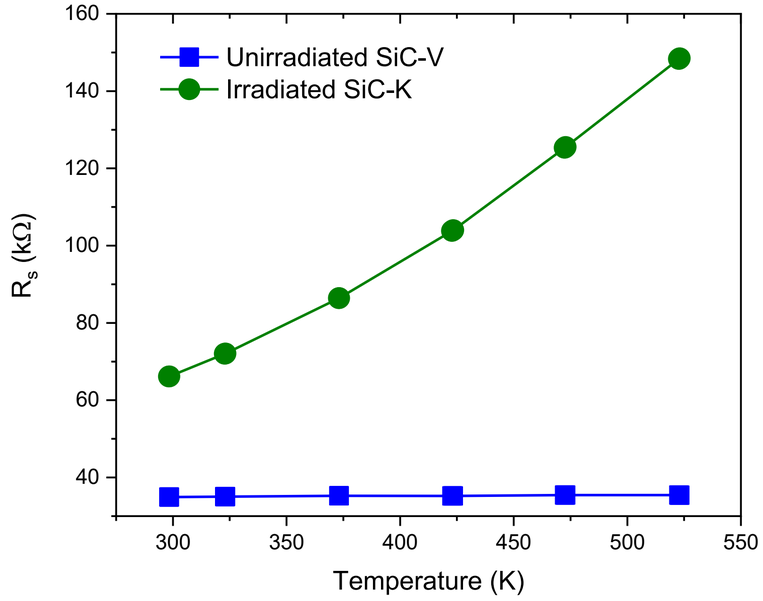
Current – Voltage Characterization

J-V Characteristics Comparison between Unirradiated SiC-V and Irradiated SiC-K Detectors



- Higher and Temperature Dependence of the Series Resistance



- Shift of the J-V Characteristics at Higher Voltages

$n = 2.4\ at\ 298\ K$ followed by a decrease at higher temperatures

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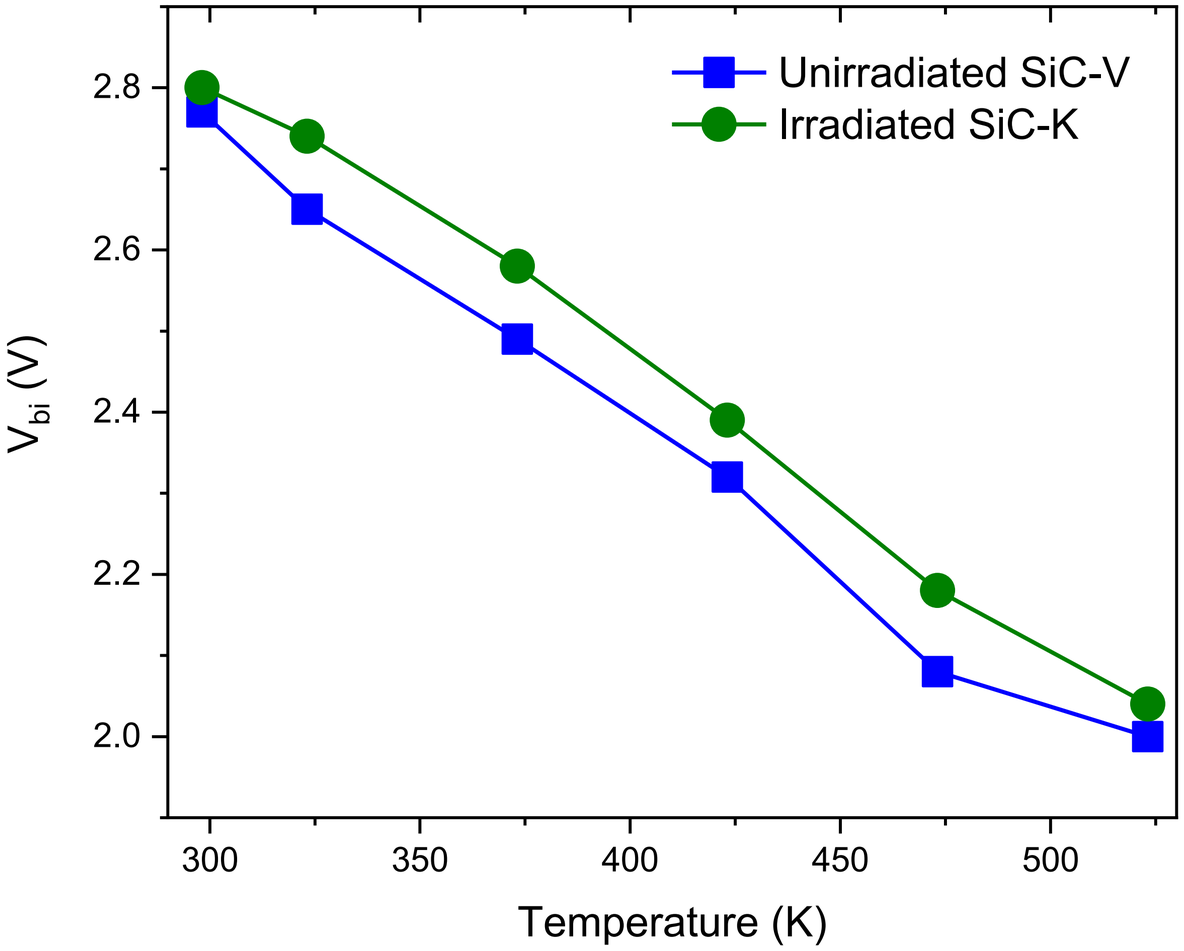
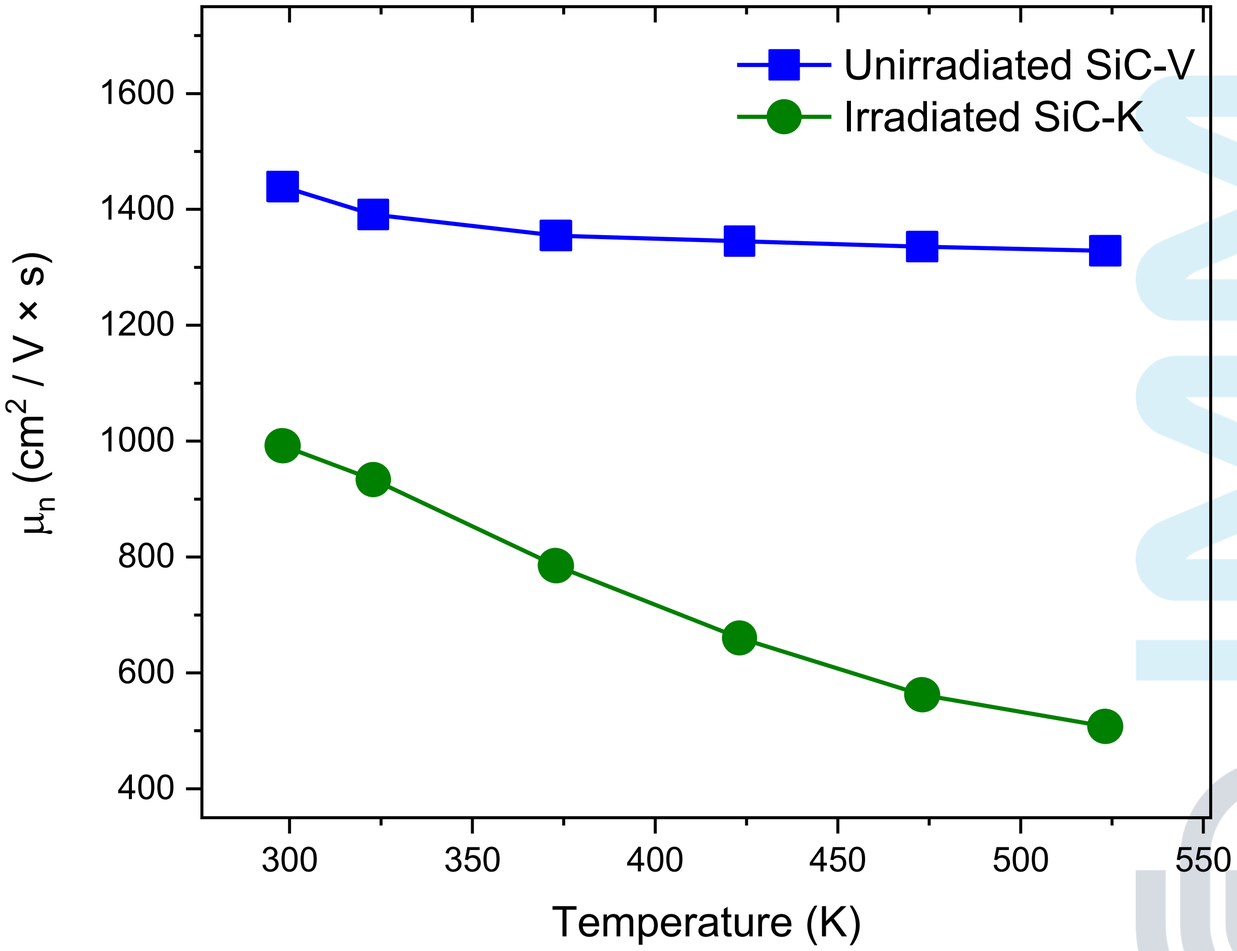
Built-in Potential and Carrier Mobility





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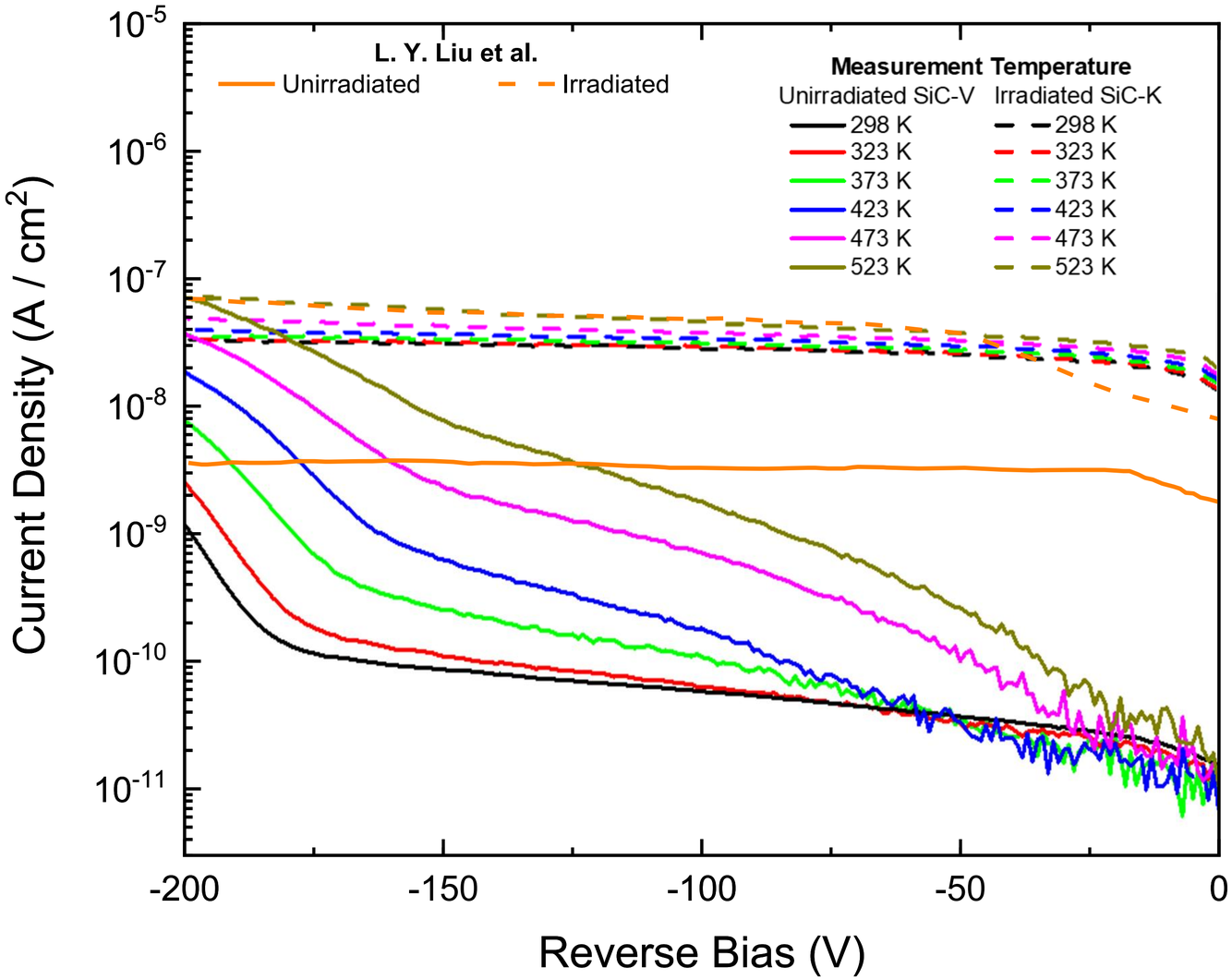
Current – Voltage Characterization

Reverse J-V Characteristics of Unirradiated SiC-V and Irradiated SiC-K Detectors



- Before Irradiation, SiC-V shows a low Leakage Current
- After Neutron Irradiation, a higher Leakage Current is detected
- In both cases, the Leakage Current Value is in good agreement with reported data

Liu, L. Y., et al. Ni/4H-SiC Schottky diode neutron detector under high fluence irradiation. Diamond Relat. Mater. 88 (2018): 256–261.

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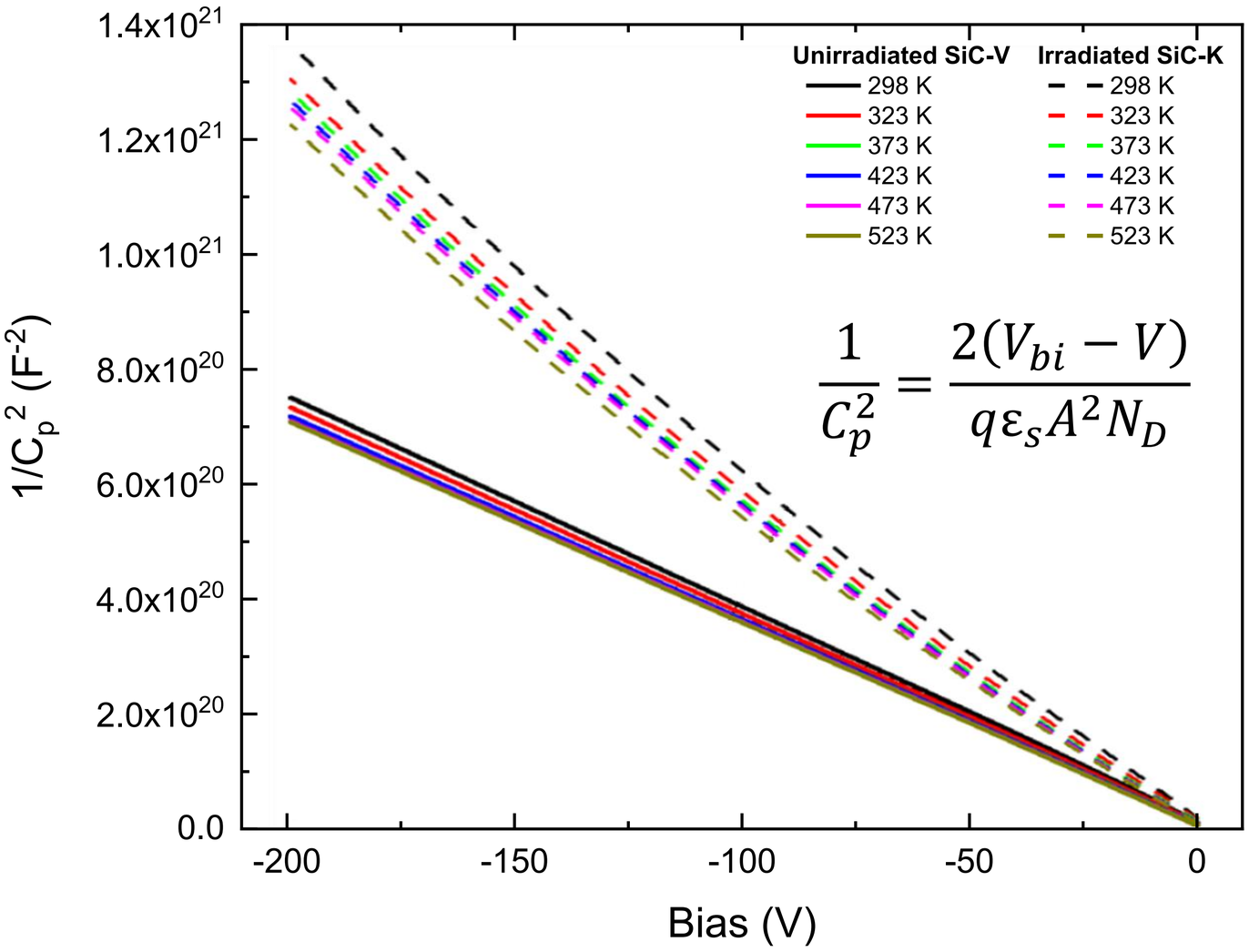
Capacitance – Voltage Characterization



$$\frac{1}{C_p^2} = \frac{2(V_{bi} - V)}{q\varepsilon_s A^2 N_D}$$

Neutron Irradiation-Induced Effects

- Change in the Slope after Irradiation
- Stronger temperature dependence
- Change of the V-axis Intercept
- Linearity differences between SiC-V and SiC-K

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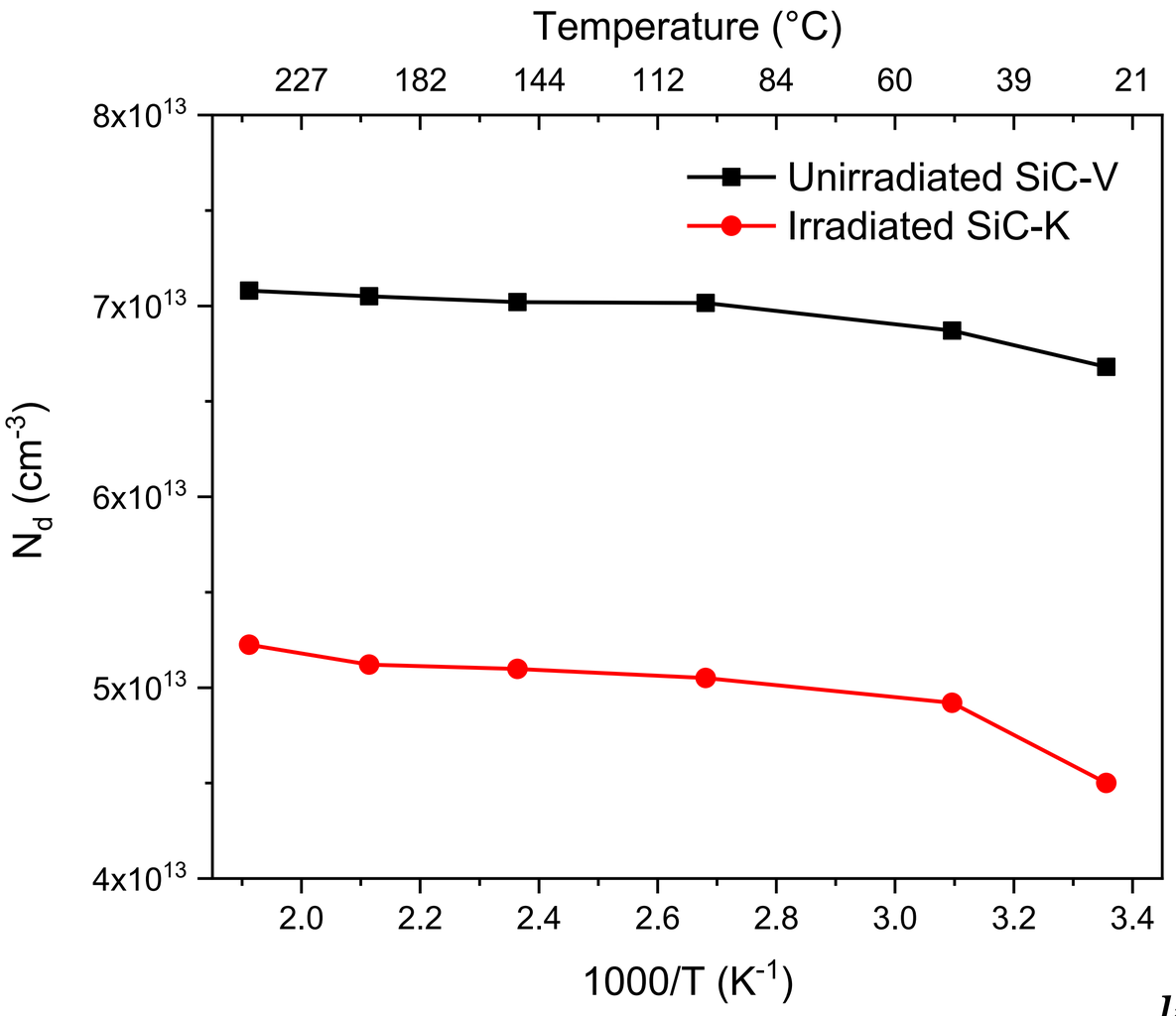
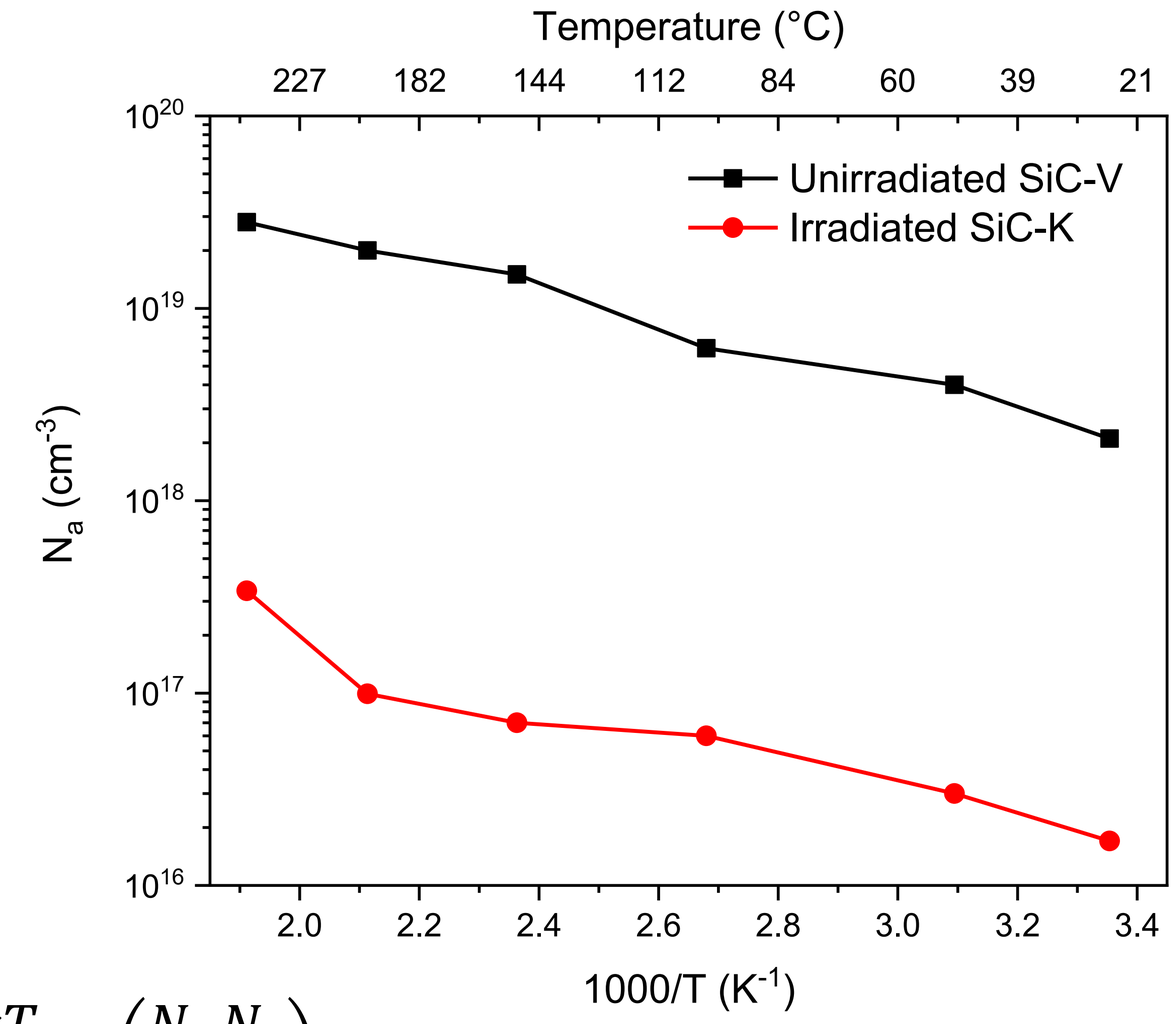
Doping Concentration Evolution





$$V_{bi} = \frac{kT}{q} ln\left(\frac{N_D N_A}{n_i^2}\right)$$

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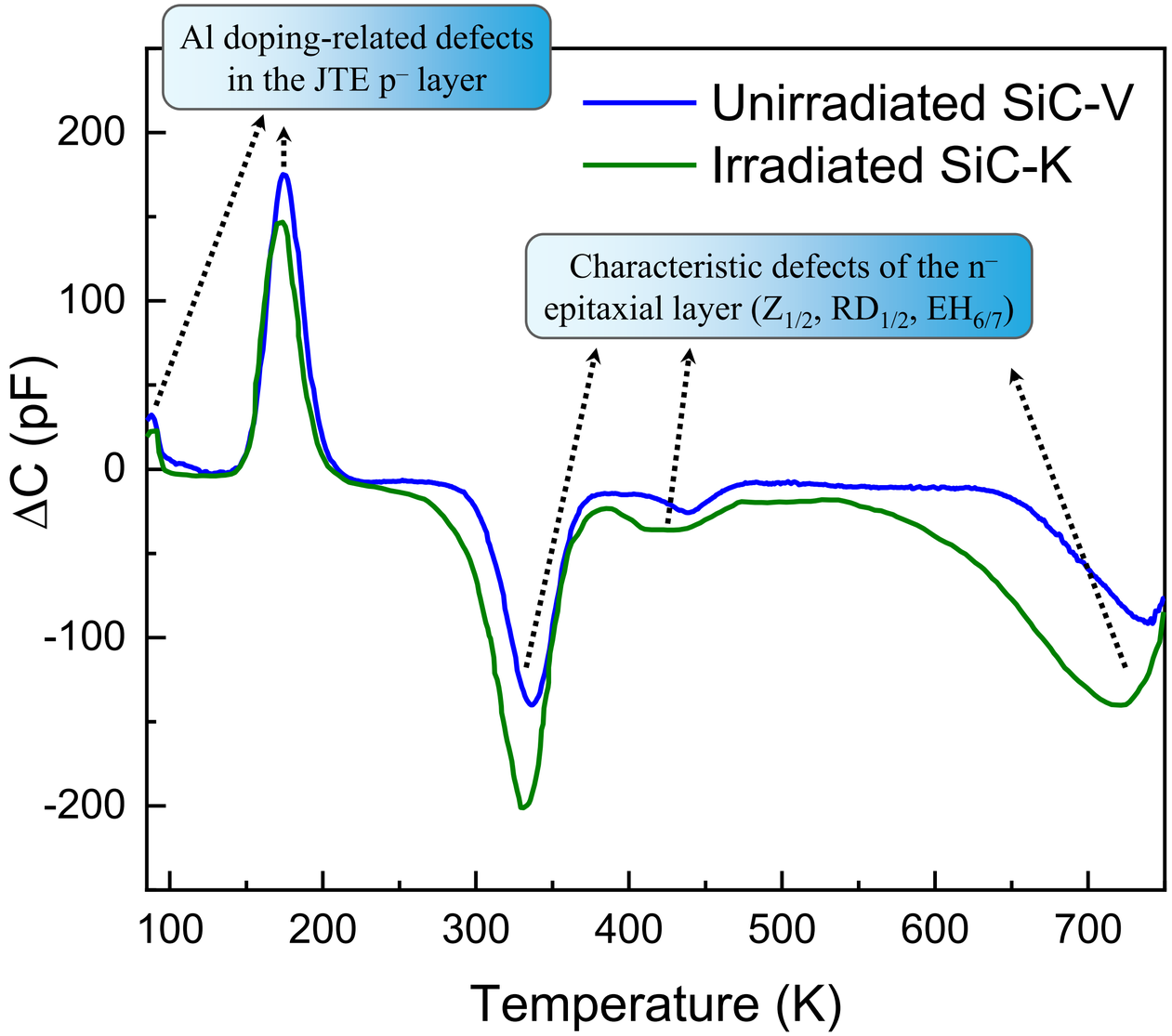
Deep Level Transient Spectroscopy



Neutron Irradiation-Induced Effects

- Shift of the Trap Energy

	SiC-V	SiC-K
	$E_C - E_T$ (eV)	$E_C - E_T$ (eV)
$Z_{1/2}$	0.56 ± 0.02	0.67 ± 0.01
$RD_{1/2}$	0.93 ± 0.03	0.84 ± 0.09
$EH_{6/7}$	1.69 ± 0.23	1.52 ± 0.19

- Increase of the Trap Concentrations

	SiC-V	SiC-K
	N_T (cm^{-3})	N_T (cm^{-3})
$Z_{1/2}$	8.03×10^{13}	1.34×10^{14}
$RD_{1/2}$	1.54×10^{13}	2.39×10^{13}
$EH_{6/7}$	5.22×10^{13}	9.23×10^{13}

Enrico.Sangregorio@imm.cnr.it

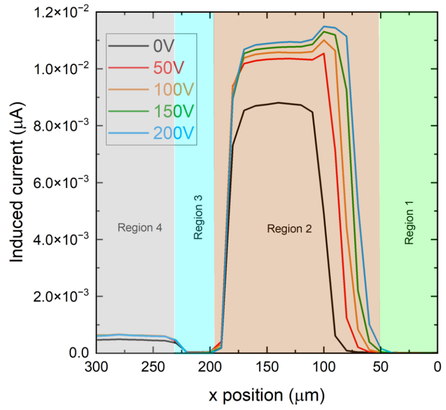
Summary and Conclusions

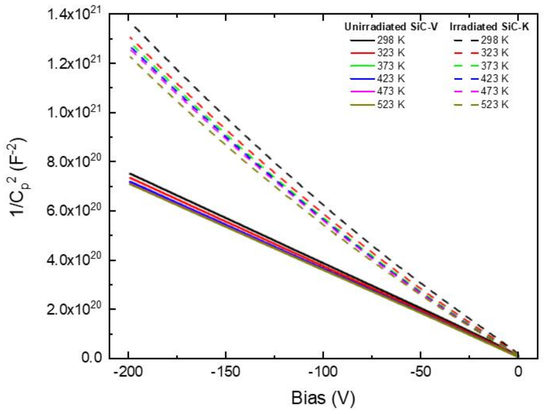
- The HR-**OBIC** technique proved to be an effective method for characterizing the edge structure of SiC devices.

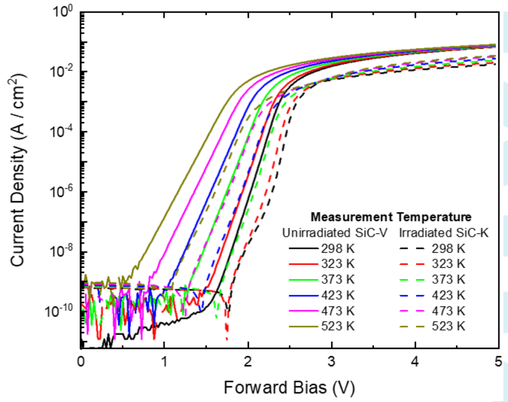
- J–V measurements showed an increase in **Rs** and **n**, influencing $\mathbf{V_{bi}}$ and $\boldsymbol{\mu_n}$, and an enhanced $\mathbf{J_{Leak}}$ after neutron irradiation.

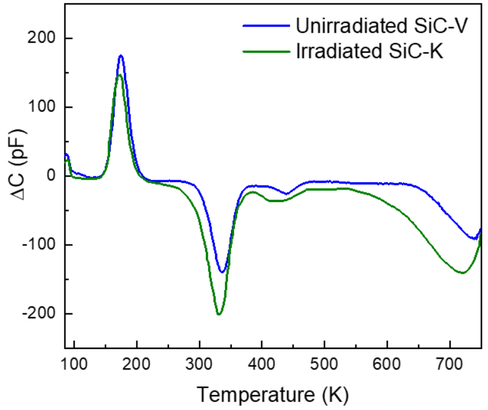
- C-V analysis highlighted **Dopant Deactivation** through defect-induced carrier compensation.

- DLTS identified the characteristic SiC traps, with irradiation shifting their **Energy Levels** and increasing their **Concentration**.









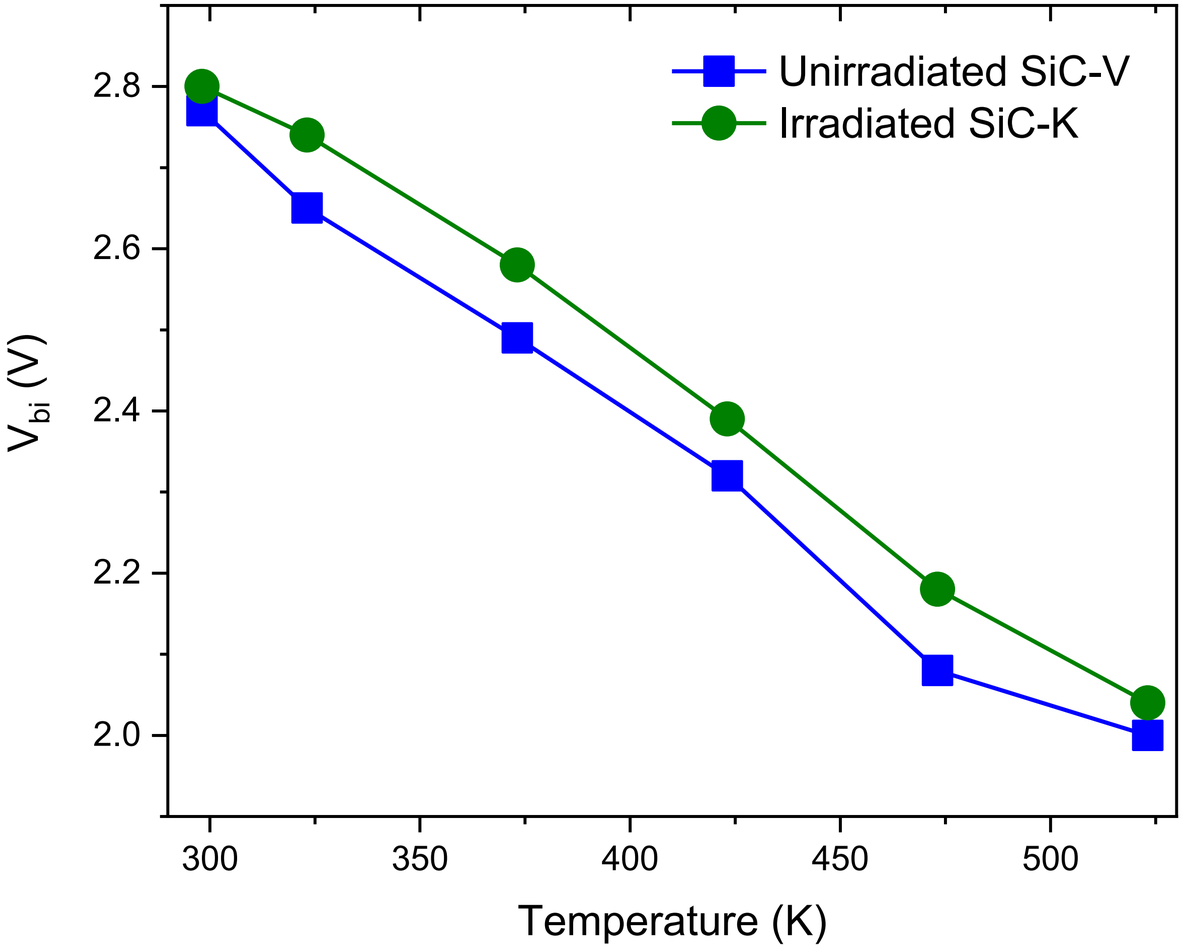
Despite neutron-induced electrical degradation, the tested 250 μm 4H-SiC device exhibited promising radiation hardness and thermal stability, supporting its use for neutron detection in fusion reactors.

Enrico.Sangregorio@imm.cnr.it

Thank you for your Attention

IMM INFN ASM WBG Wide Band Gap future power electronics

Built-in Potential with J-V



$$V_{bi} = \frac{kT}{q} ln\left(\frac{N_D N_A}{n_i^2}\right)$$

$$n_i = \sqrt{N_c\left(\frac{T}{300}\right)^{3/2} N_v\left(\frac{T}{300}\right)^{3/2}} exp\left(\frac{-E_g}{2k_B T}\right)$$