Thermal Annealing of Electron, Neutron and Proton Irradiation Effects on SiC Radiation Detectors

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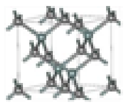
Conclusions

Introduction and **motivation**

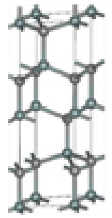
4H-SiC properties

Property	SiC advantage		
E_g (eV) - band gap	x3	Si	1.1
		SiC	3.3
v_{sn} (cm/s) – electron saturation velocity	x2	Si	1×10^7
		SiC	2×10^7
μ_n (cm^2/Vs) – electron mobility	~	Si	1350
		SiC	950
e_r - dielectric constant	~	Si	11.8
		SiC	9.7
E_c (V/cm) - critical electric field	x15	Si	2×10^5
		SiC	3×10^6
k (W/cm K) - thermal conductivity	x3	Si	1.5
		SiC	5

Si
Cubic



SiC
Hexagonal



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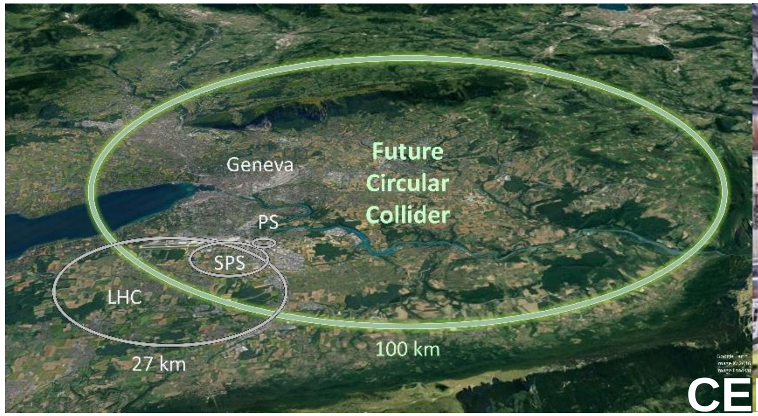
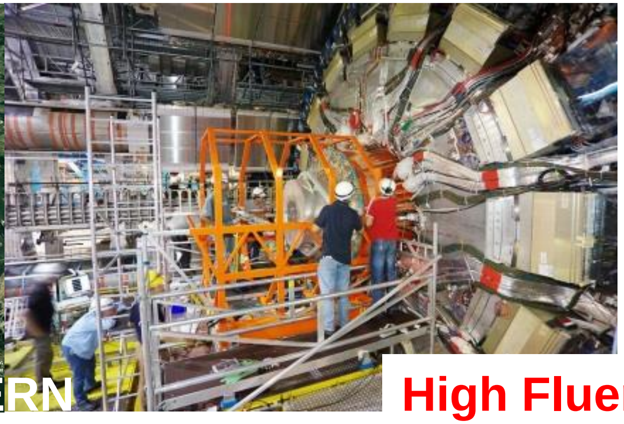
- **Wide bandgap energy** (less affected by **high T**)
- **Low leakage current** (even **after irradiation** and **room T**)
- **High transparency** (not affected by **visible light**)
- **High breakdown voltage** (power devices and detectors)
- **High thermal conductivity** (power devices)
- **High saturation velocity** (potential for **timing** applications)
- **High atomic displacement threshold energy** (potential **radhard**)
- **Potential NEMS structures** & **3D detectors** (**micromechanization**)
- **High quality SiC substrates available** (up to 6 or 8 inches) (driven by commercial applications)

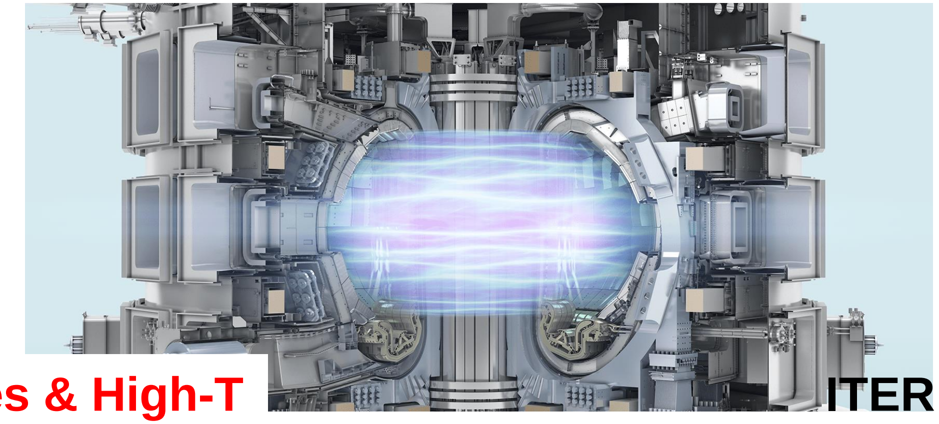
SiC radiation detectors applications

High Energy Physics Experiments





Nuclear fusion plasma diagnostics

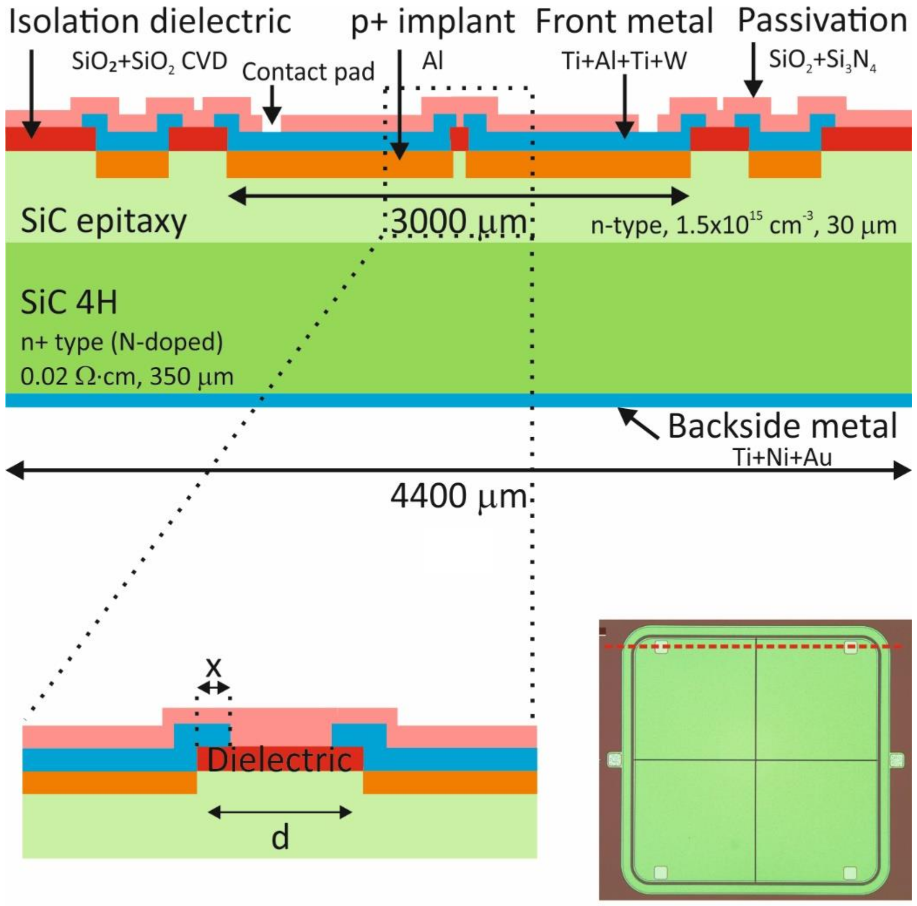


High Fluences & High-T

- **Renewed interest** in **SiC** for **radiation detector applications** and **radiation effects** (**HEP**, **fusion, synchrotron**, space, medical (real time monitoring and dosimetry), ion beams (IBIC)…)
- Significant number of **existing results**: more primitive **substrates**, different **polytypes**, different **irradiation sources,** mostly **Schottky** diode structures but also **p-n junction** diodes
- Scattered **pioneering works** already described most of the radiation-induced observed effects
- **Present work re-visits** the **potential** of **state-of-the-art SiC material** for **radiation detectors**

Experimental

Fabricated devices



- **IMB-CNM cleanroom**
- **Single diodes + 4-quadrant diodes**
- **n$^-$ epi 4H-SiC** (no suitable high-resistivity bulk SiC)
- **p-on-n process**
- (+2 other substrates: HR FZ Bulk & 10 μm Si)
- **MOS capacitors** (interquadrant isolation)

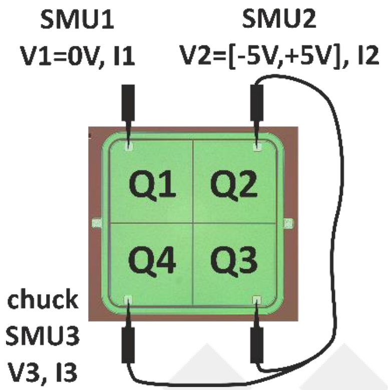
J.M. Rafí, et al., Journal of Instrumentation, 2018, v. 13, C01045, DOI: 10.1088/1748-0221/13/01/C01045
J.M. Rafí, et al., IEEE Transactions on Nuclear Science, 2020, v. 67, nº 12, pp. 2481-2489, DOI: 10.1109/TNS.2020.3029730
J.M. Rafí, et al., IEEE Transactions on Nuclear Science, 2023, v. 70, nº 10, pp. 2285-2296, DOI: 10.1109/TNS.2023.3307932

Unbiased irradiations (terminals left floating)

- **2 MeV e-** @Takasaki-QST, Takasaki, Japan
  $\Phi = 1\text{x}10^{14}, 1\text{x}10^{15}, 1\text{x}10^{16}$ e/cm^2
  NIEL hardness factor (Si-1MeV n) ~ 0.0249

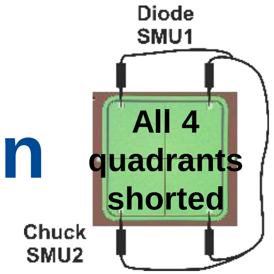
- **Neutron** @JSI TRIGA, Ljubljana, Slovenia
  $\Phi = 5\text{x}10^{13}, 1\text{x}10^{14}, 5\text{x}10^{14}, 1\text{x}10^{15}, 2\text{x}10^{15}, 1\text{x}10^{17}!, 3\text{x}10^{17}!$ n/cm^2
  NIEL hardness factor (Si-1MeV n) ~ 0.9

- **24 GeV/c p+** @PS-IRRAD CERN, Geneva, Switzerland
  $\Phi = 8.6\text{x}10^{13}, 1.5\text{x}10^{14}, 1.0\text{x}10^{15}, 1.7\text{x}10^{15}, 2.5\text{x}10^{15}$ p/cm^2
  NIEL hardness factor (Si-1MeV n) ~ 0.56



$$R_{interquadrant} \equiv \frac{1}{\frac{dI_1}{dV_2}}$$

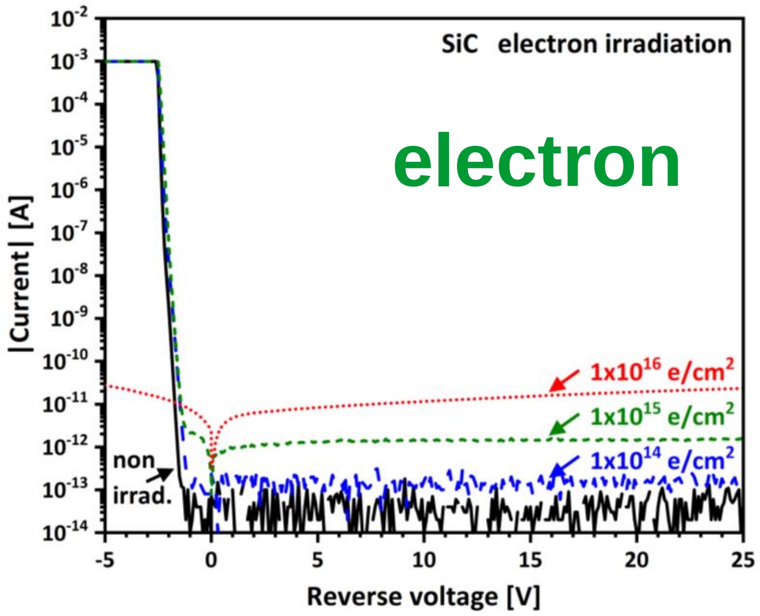
Electrical characterization

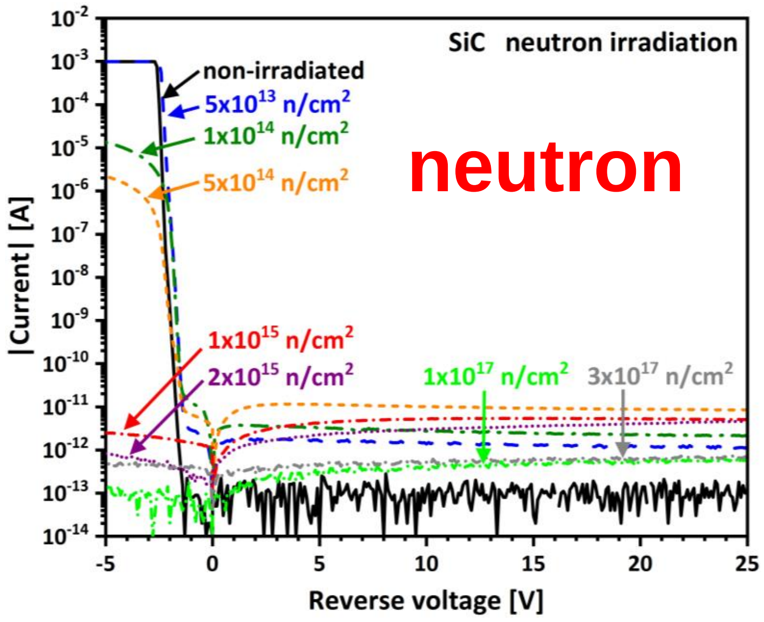


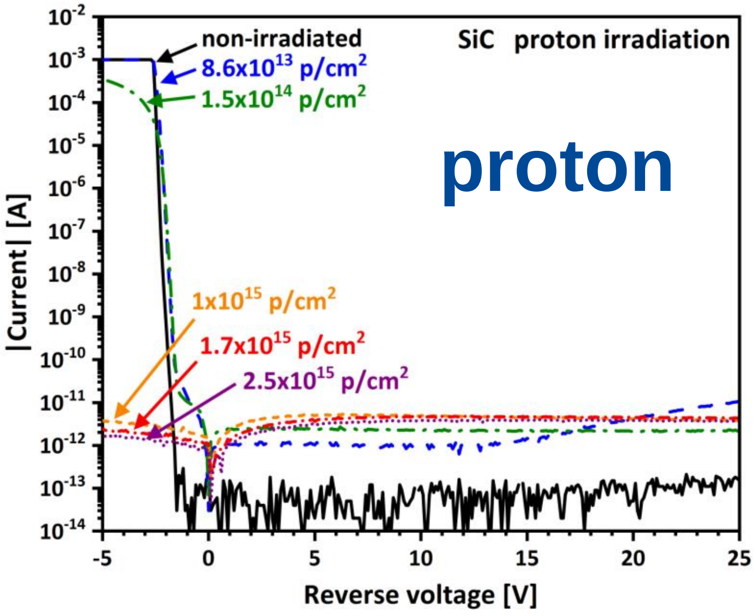
(except interquadrant resistance)

Radiation effects
and
thermal annealing

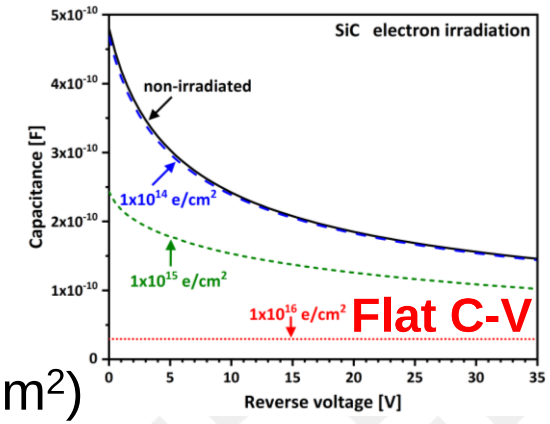
Radiation effects: I-V and C-V @Room T



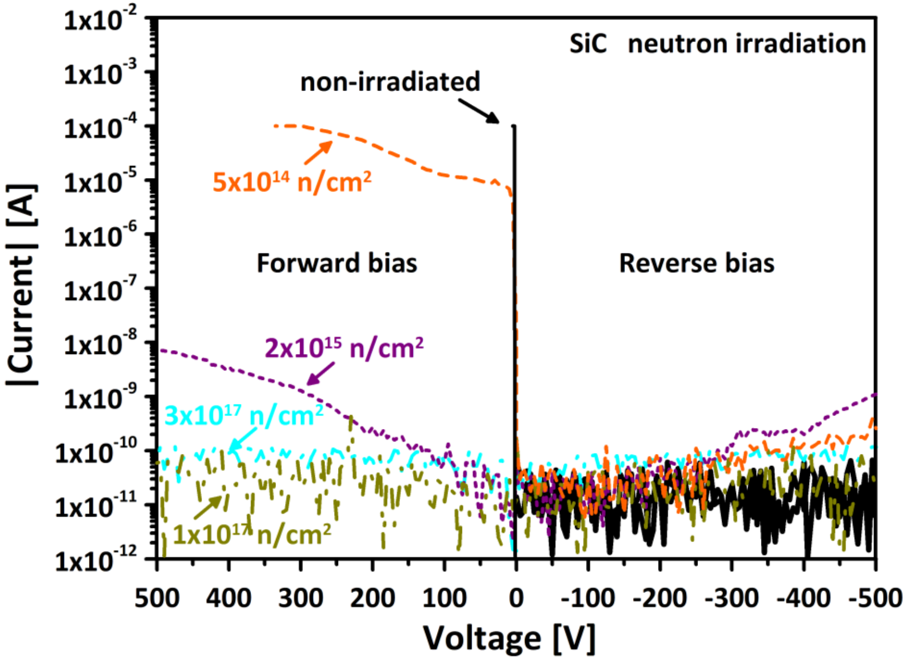


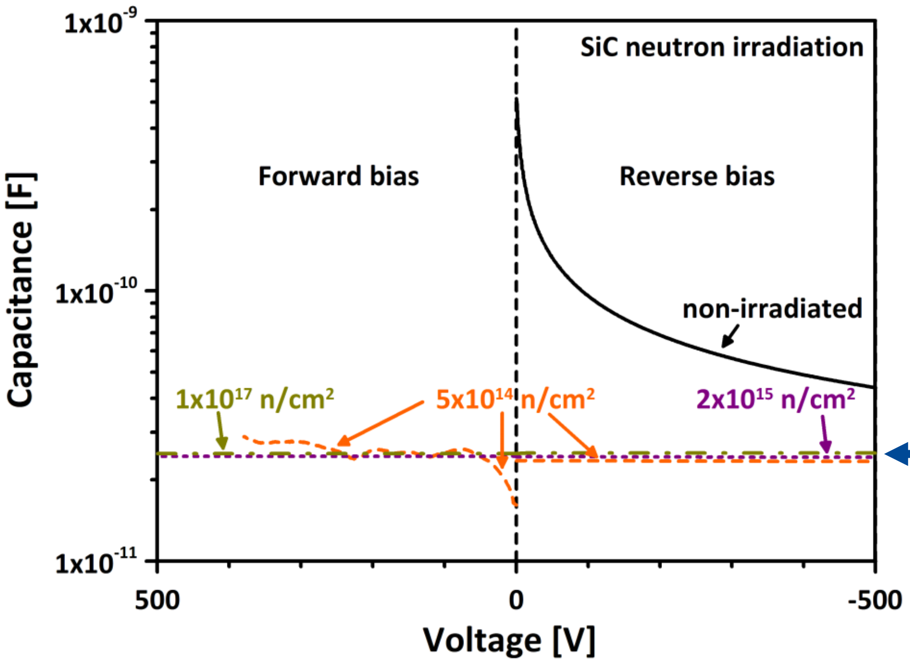


- **Low $I_{reverse}$ @room T** for **all irradiations** (**different to Si**: $I_{vol\_Si} = \alpha \cdot \Phi$)
- **Radiation-induced decrease** in $I_{forward}$
  Defects (V_C,V_{Si},V_C+V_{si}…) ➔ **conduction resistance↑**
  carrier removal/doping compensation ➔ R_{series}↑ (unipolar Schottky)
  $\tau_{recombination}$↓ ➔ conduction modulation drift layer↓ (bipolar p-n)
- **Electrical rectification lost** for **highest fluences** (1x10^{16} e/cm^2 & >1x10^{15} n-p/cm^2)



Radiation effects: I-V and C-V @Room T - High V





Geometrical capacitance

$$C = \frac{\varepsilon_{SiC} \cdot Area}{Epi\ thickness} \sim 25.7\ pF$$

Electrical rectification character is **lost** for the **highest fluences:**

➡ **Low currents** (reverse + direct)

➡ **Flat C-V characteristics** (reverse + direct)

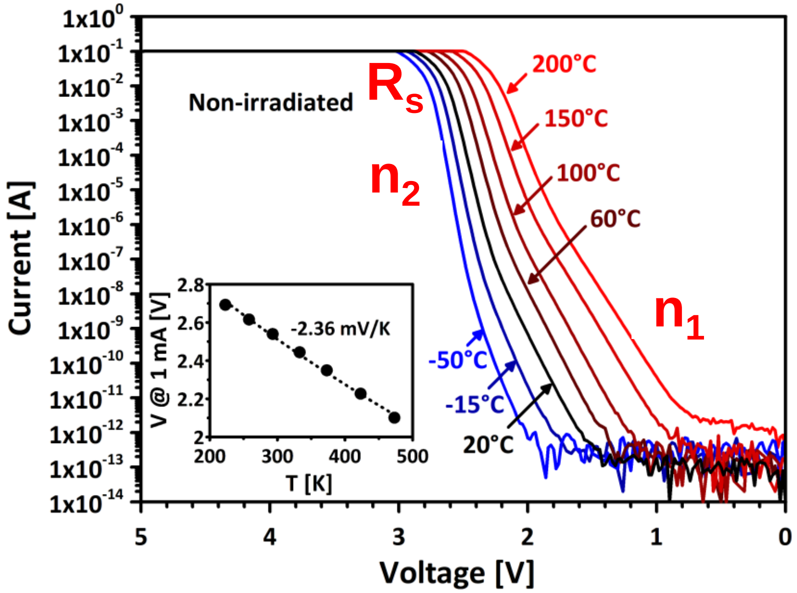
Lightly doped epilayer **becoming intrinsic**

"Like a stone"

I-V direct: impact of measuring T [-50ºC to 200ºC]

$$I = I_0 \cdot \left(e^{\frac{q(V - I \cdot R_S)}{nKT}} - 1 \right)$$

Non-irradiated



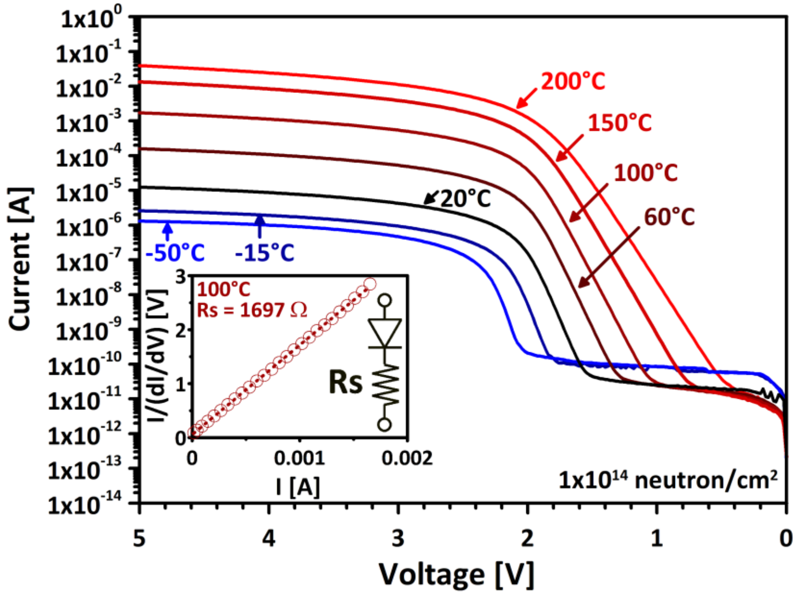
T-constant low R_s

n_2~[1.12-1.15] (quasi neutral region)

n_1~[1.8-2.4] (space charge region)

Medium fluences

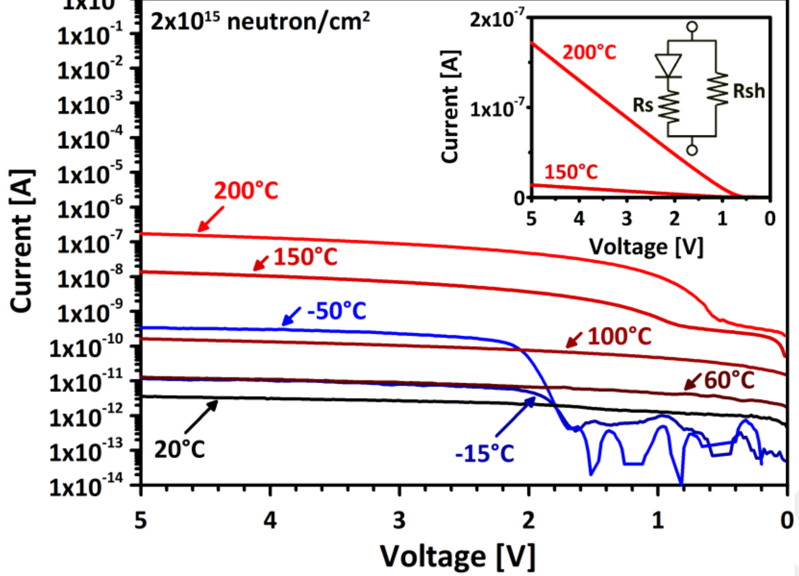
~1x10^{14} n/cm^2 or ~1.5x10^{14} p/cm^2



T-dependent R_s

High fluences

~2x10^{15} n/cm^2 or ~1.7x10^{15} p/cm^2



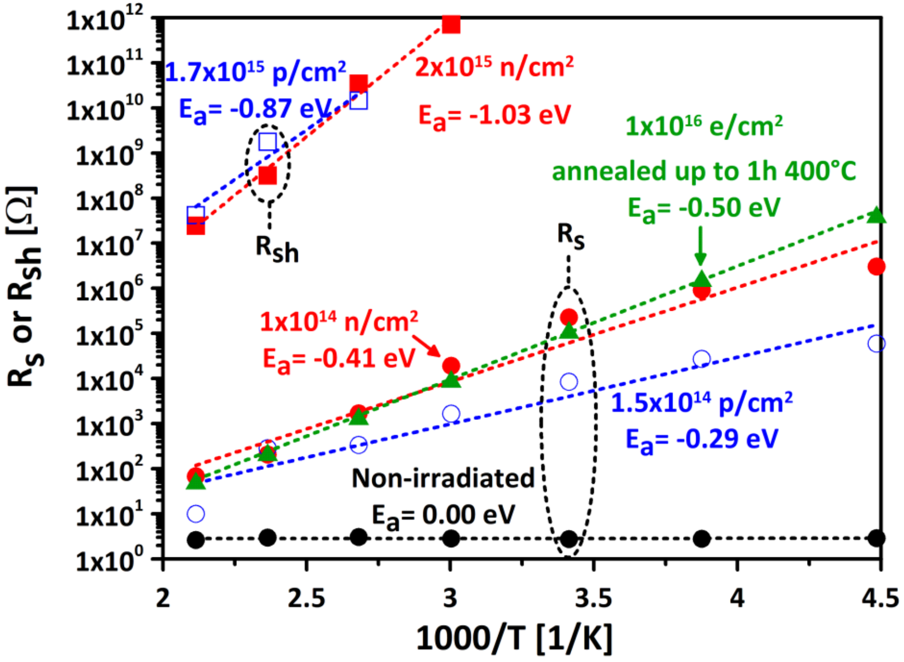
T-dependent higher R_s

T<-15°C defect freeze-out

I-V: impact of measuring T [-50ºC to 200ºC]

T-dependence R_s

(base/epitaxy ρ)



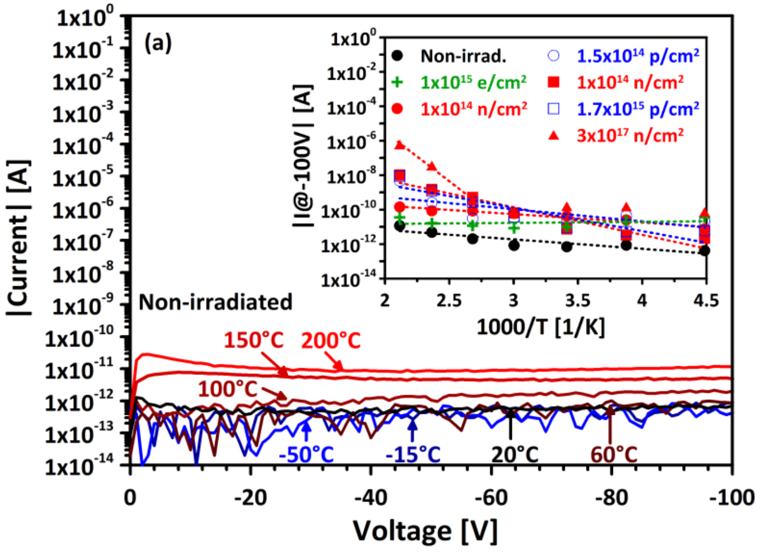
$E_{activation}$ [0.3-1] eV

Fluence ↑ ⇒ deeper E_{act} ↑

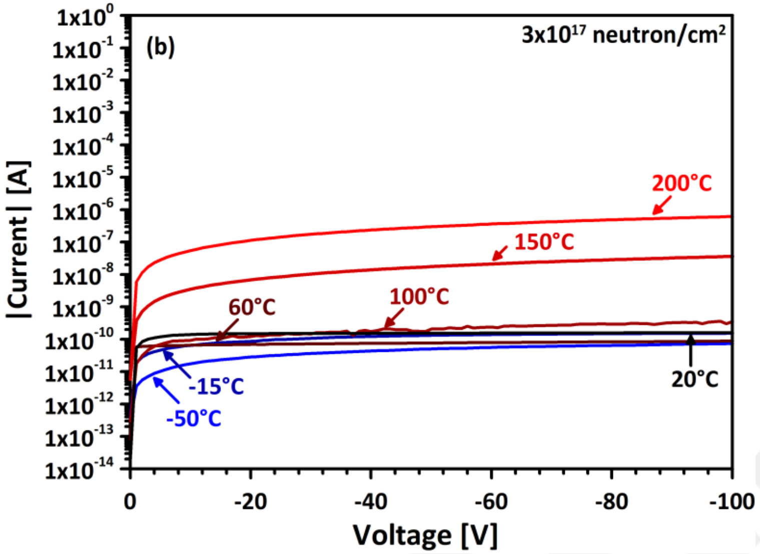
($Z_{1/2}$ level 0.5<E_a<0.69 eV ?)

I-V reverse

Non-irradiated



3x10^17!! neutron/cm²



Highest irradiation fluences

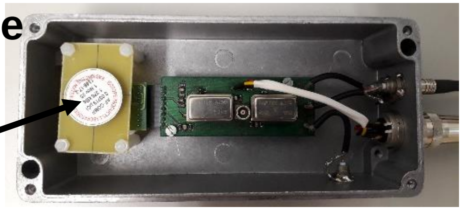
T-dependent reverse current↑ (>100°C)

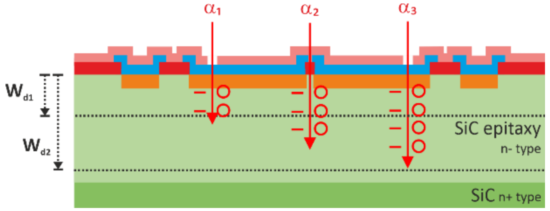
$E_{activation}$↑

α particle detection

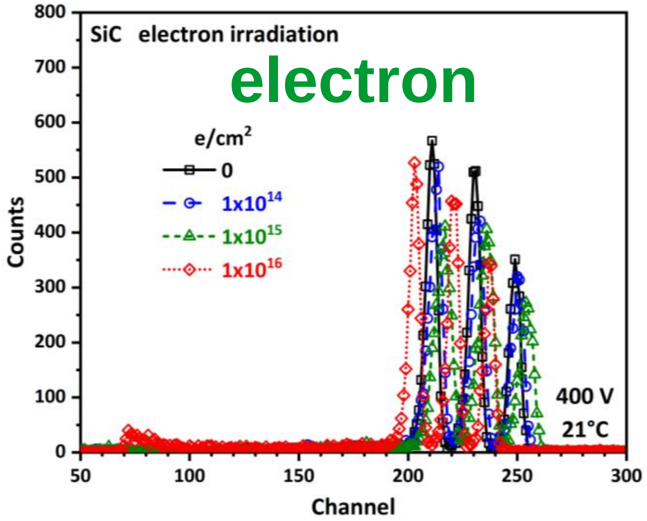
Tri-α source

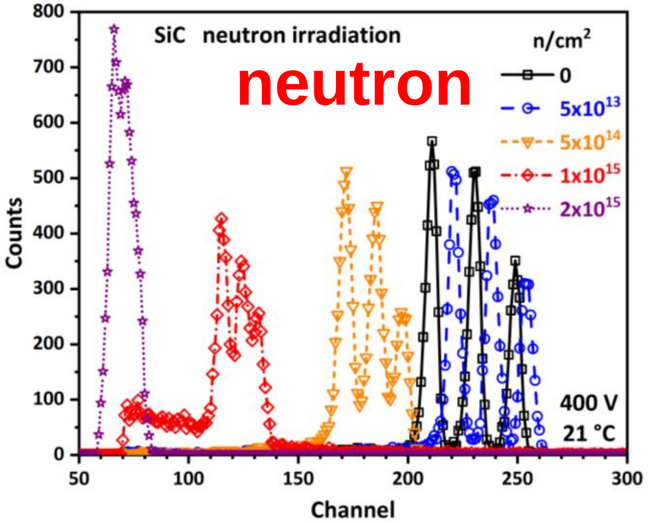
^{239}Pu
^{241}Am
^{244}Cm

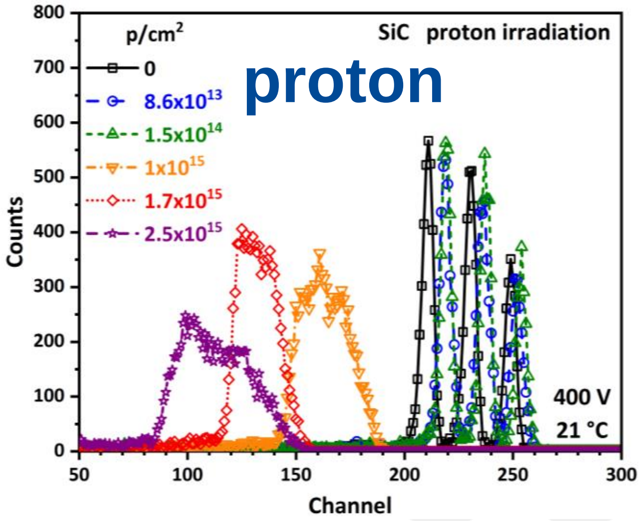




SRIM => α **range**
~ 12-15 μm < epi-SiC



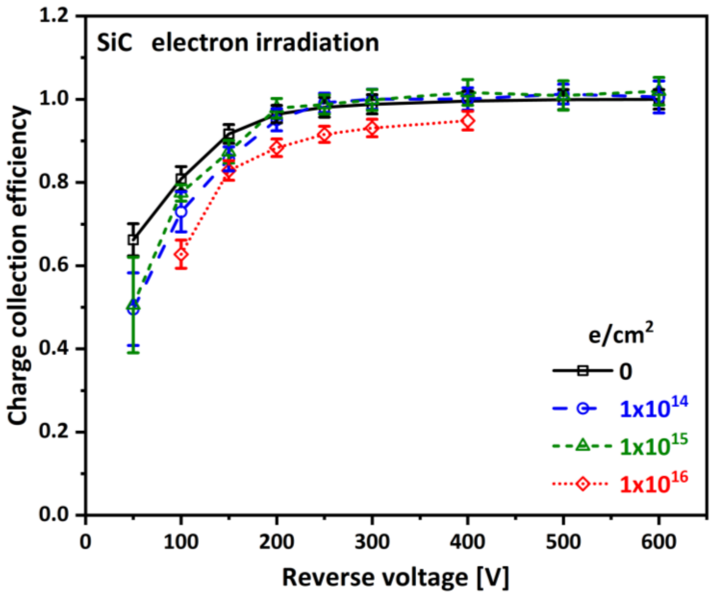




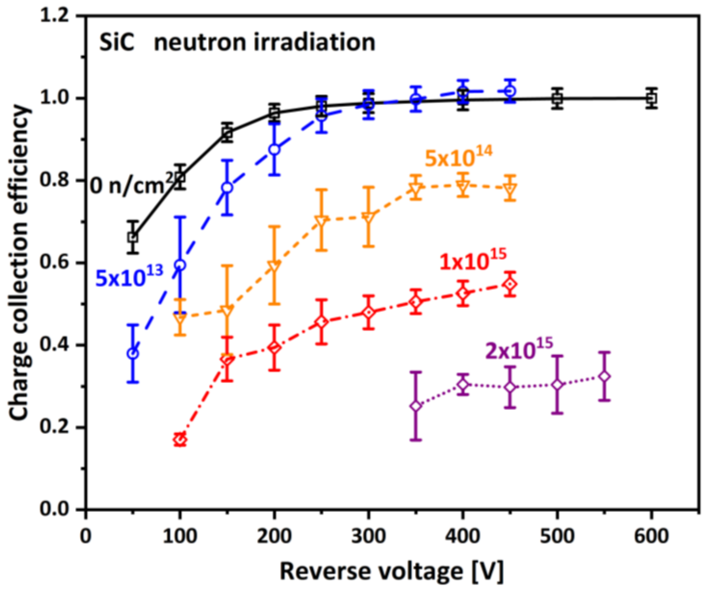
- ➡ **Non-irradiated: 3 peaks** with centroids around channels 210, 230, 250
- ➡ **SiC spectra acquisition @ room T** ($I_{reverse\ SiC}$ << $I_{reverse\ Si}$ Si noise)
- ➡ **α detection still observed** for **high irradiation fluences** where no electrical rectification is observed
- ➡ Peaks **shift + broaden** for **highest** neutron and proton **fluences**
  (defects ➔ recombination/charge traps ➔ collected charge↓, straggling↑)

α particle detection

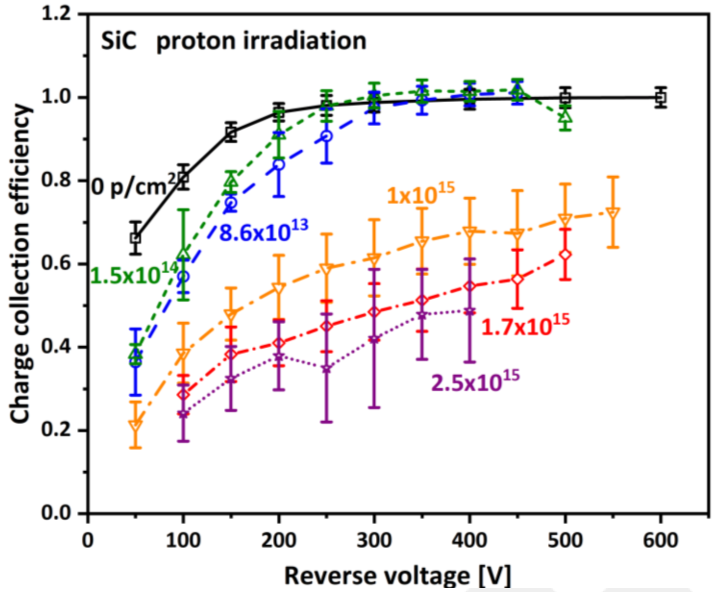
electron



neutron



proton

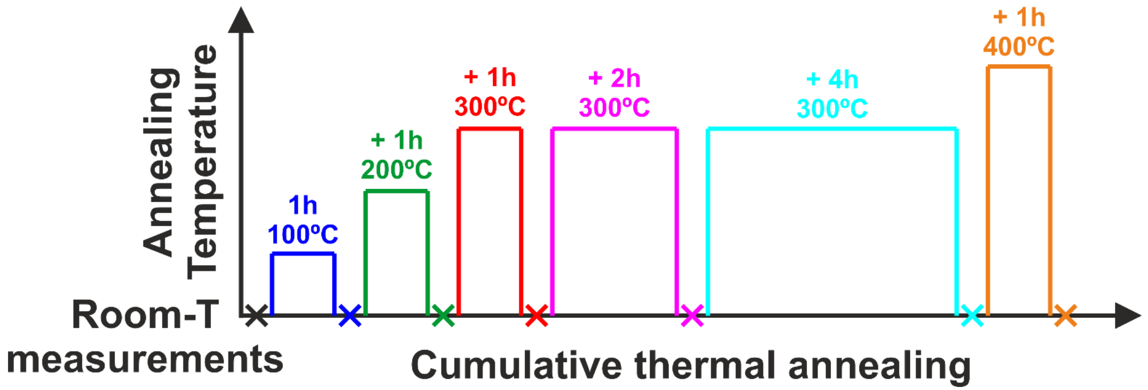


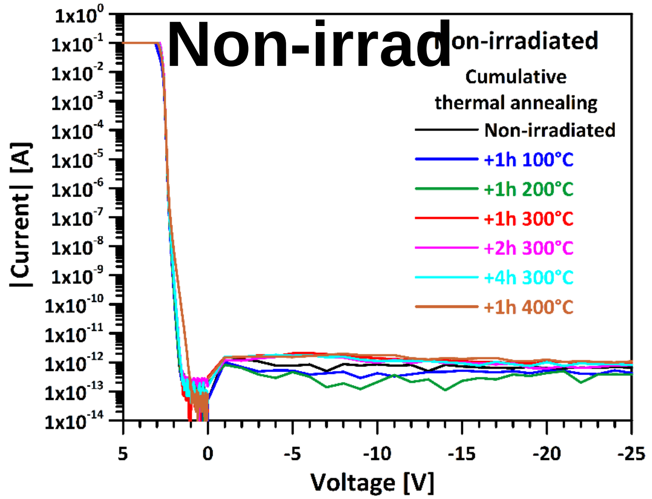
➡ **Non-irradiated efficiency saturation @~250 V** (W_{dep}~12.5 μm)

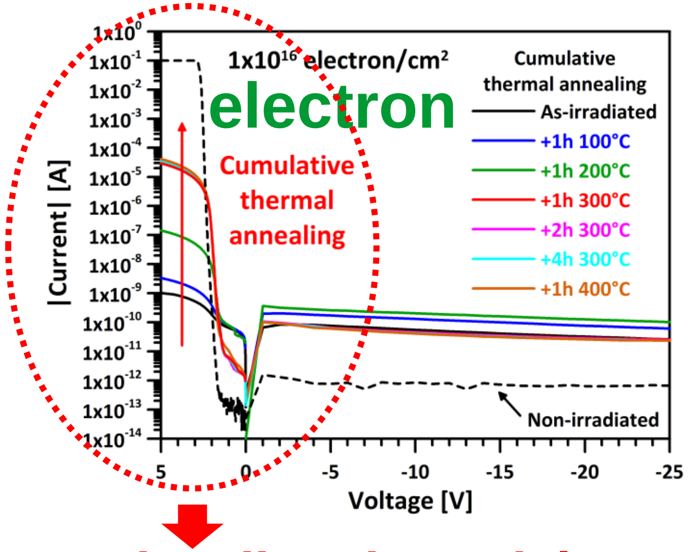
➡ **Capability** for **α detection** is **still observed** for **high irradiation fluences** where no electrical rectification character is observed

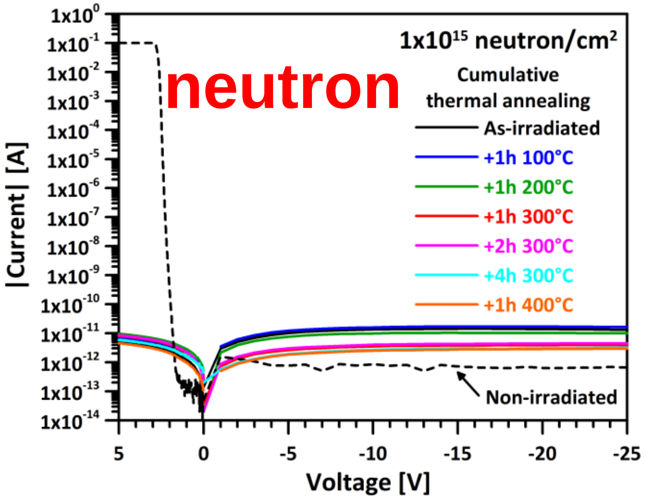
For example: ΔCCE @400V: ~-10% @$1x10^{16}$e/cm^2, ~-50% @$1x10^{15}$ n/cm^2, ~-33% @$1x10^{15}$ p/cm^2

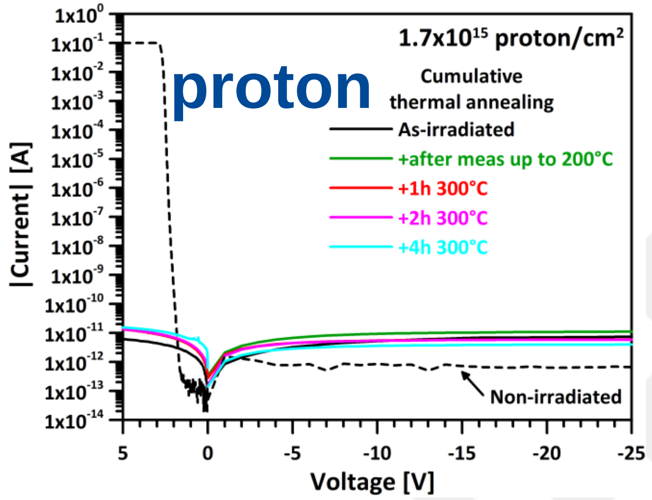
Cumulative thermal annealing experiments









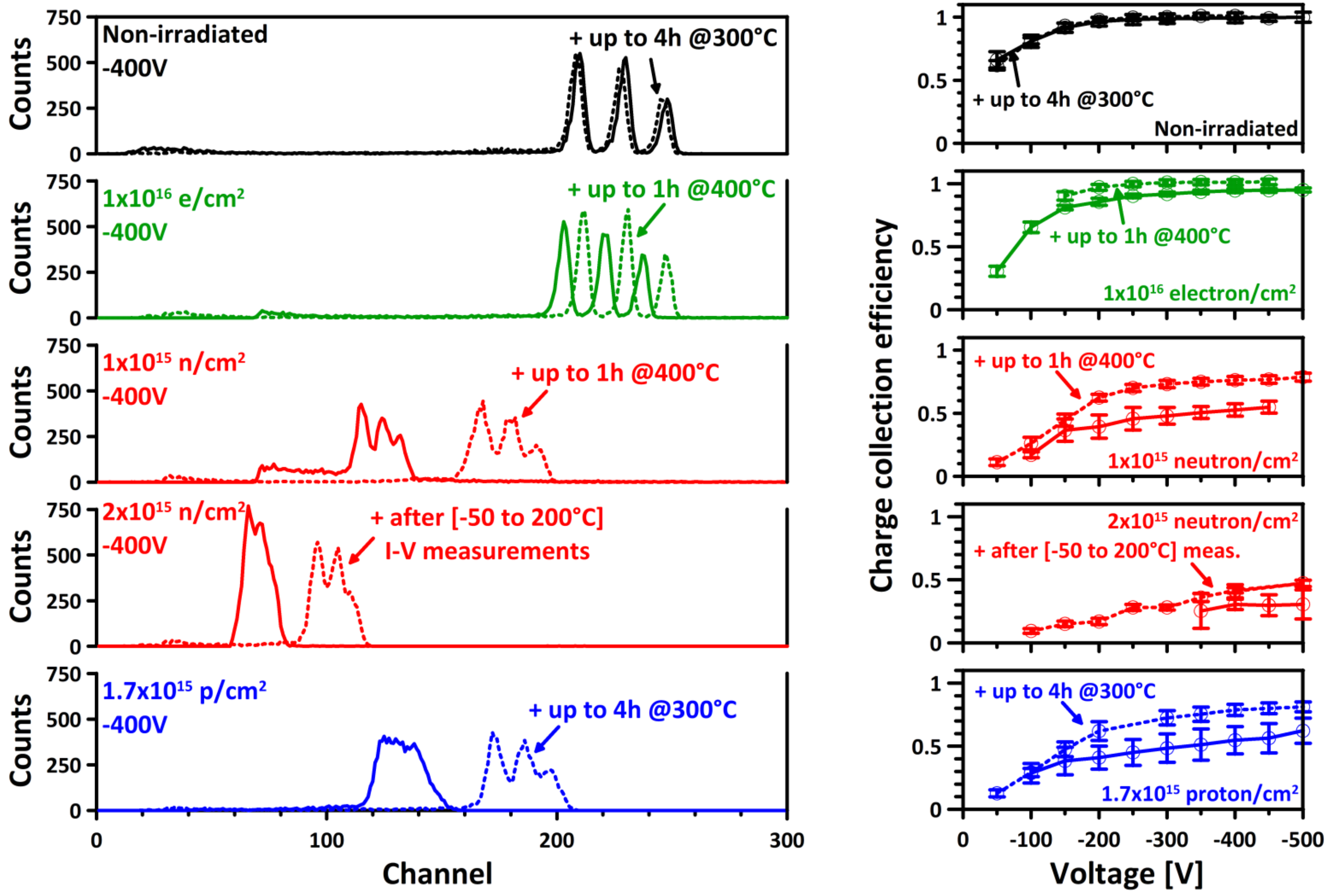


e- irradiated: partial recovery of direct conduction (diode functionality) + **C-V diode-like**

(low-T anneal: annihilation of close pairs of Si and C vacancies & interstitials, R. Karsthof, Phys. Rev. B, 184111, 2020)

T-dependent R_s ($E_{activation}$~ 0.50 eV $\Rightarrow$ **$Z_{1/2}$ level** (0.5<E_a<0.69 eV)) (**No significant changes** in **$I_{reverse}$ & $R_{interquadrant}$**)

Thermal annealing on α particle detection



Some **improvement** in

charge collection efficiency

after **thermal annealing**

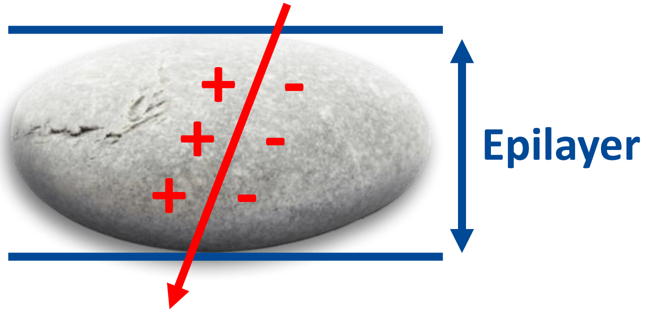
⬇

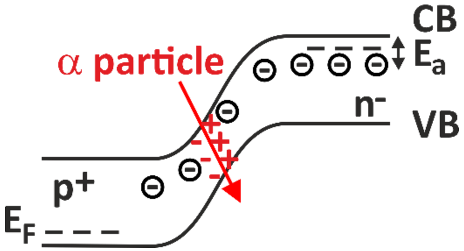
Pointing to

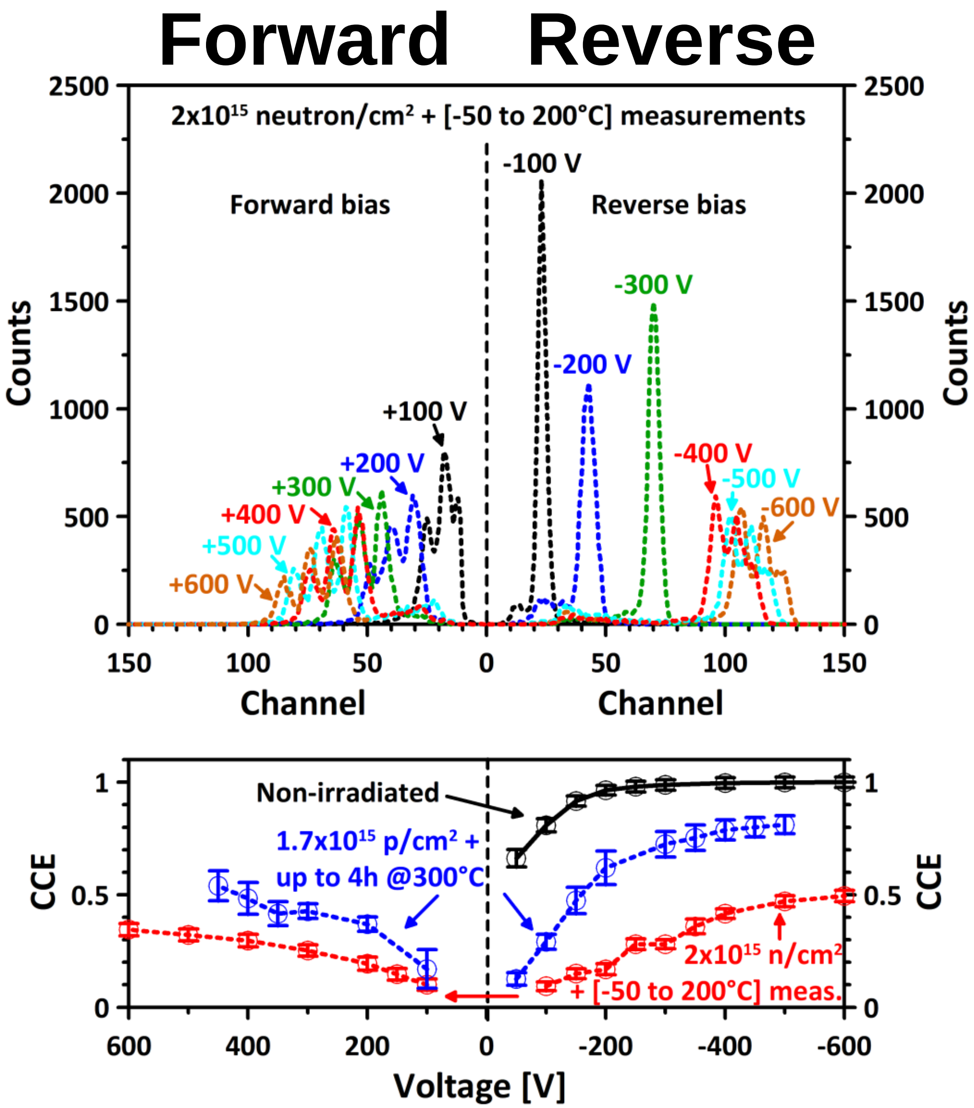
radiation harder under

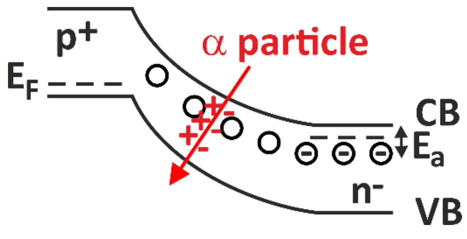
high-T operation

α particle detection also in forward operation









Some **smaller charge collection efficiency** in **forward**, but **better energy resolution**, even at low |V|

Filled radiation-induced acceptors under **forward bias** may **decrease charge trapping**

Conclusions

Conclusions

- **p-n junction diodes** fabricated on **epitaxied SiC**

- Effects of **2 MeV e-**, **neutron** & **24 GeV/c p+** irradiation on electrical characteristics (I-V, C-V, $R_{interquadrant}$)
  - **Low $I_{reverse}$ @room T**, with **loss** of **electrical rectification** character (I-V and C-V) for highest fluences

- Impact of **measuring temperature** [-50ºC-200ºC]
  - **Radiation-induced T-dependent R_s** in **direct** (Fluence ↑ ⇒ $E_{activation}$ ↑)
  - Highest irradiation fluences ⇒ T-dependent **reverse current**↑ (>100°C), $E_{activation}$↑

- **Cumulative thermal annealing experiments** [100ºC-400ºC]
  - **e-irradiated: partial recovery** of **diode functionality** (I-V and C-V) (annihilation of close defects, V_s and I_s)
  - **T-dependent R_s** in **direct** ($E_{activation}$~ 0.5 eV, in agreement with $Z_{1/2}$ level)
  - Some **improvement** in **charge collection efficiency** after thermal annealing

- α **particle detection** also in **forward operation**

- **Studies/collaboration** would be needed to get a better picture of the involved phenomena (defect characterization, annealing, simulation…)

- Some **superior properties** of **SiC devices** for **radiation detectors applications: high-T** applications and **simplify current experiments** implemented with **Si** (**no cooling needed** & **visible light proof**)

Thank you for your attention

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