Electron, neutron and proton irradiation effects on four-quadrant SiC radiation detectors

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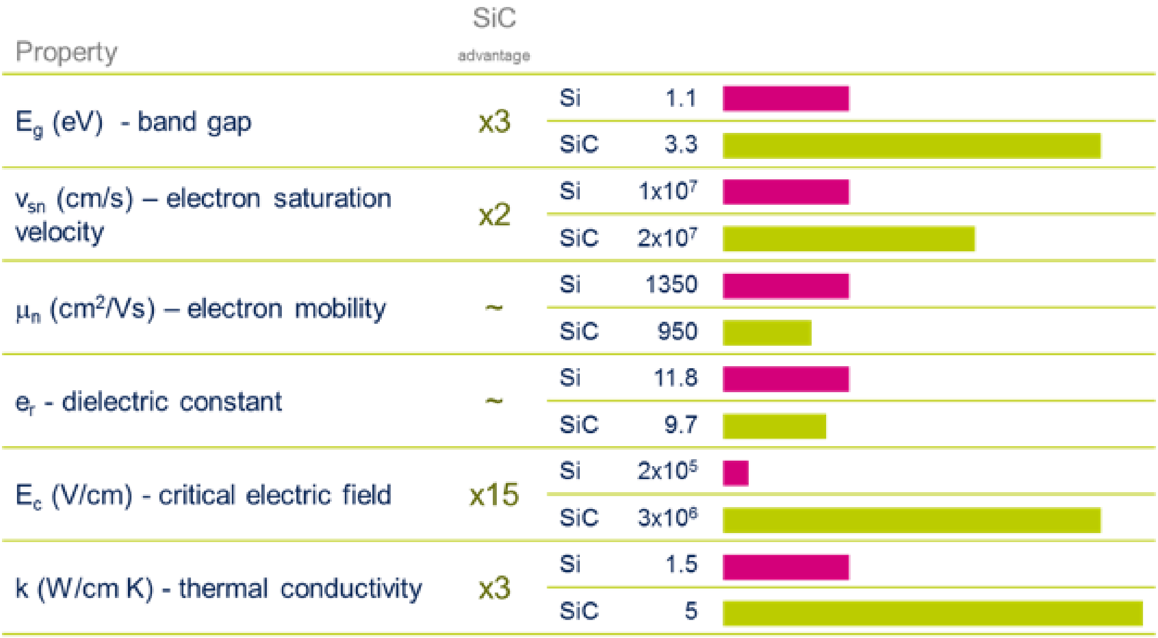
18th November 2020

4H-Silicon carbide (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	$1x10^7$
		SiC	$2x10^7$
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	$2x10^5$
		SiC	$3x10^6$
k (W/cm K) - thermal conductivity	x3	Si	1.5
		SiC	5

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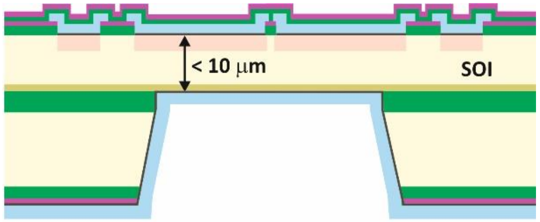
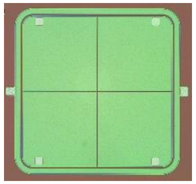
- **Wide bandgap energy** (less affected by high T)
- **Low leakage current** (even after irradiation and room T)
- **High transparency** (not affected by visible light)
- **High saturation velocity** (potential for timing applications)
- **High breakdown voltage, high termal conductivity** (power devices)
- **High atomic displacement threshold energy** (potential radiation hardness)
- **Potential** for **fabrication** of **3D detectors** and other **NEMS structures**
- **High quality SiC substrates available** (up to 6-inch) (commercial applications)

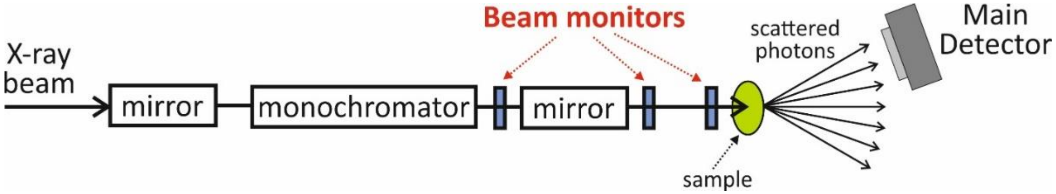
4-quadrant diodes

- **Space applications** (solar tracking systems (bulk Si))

- **X-ray beam monitors** (Synchrotron)







Transmissive mode

<10µm Si => >90% transmission (10 keV XR)

WBG

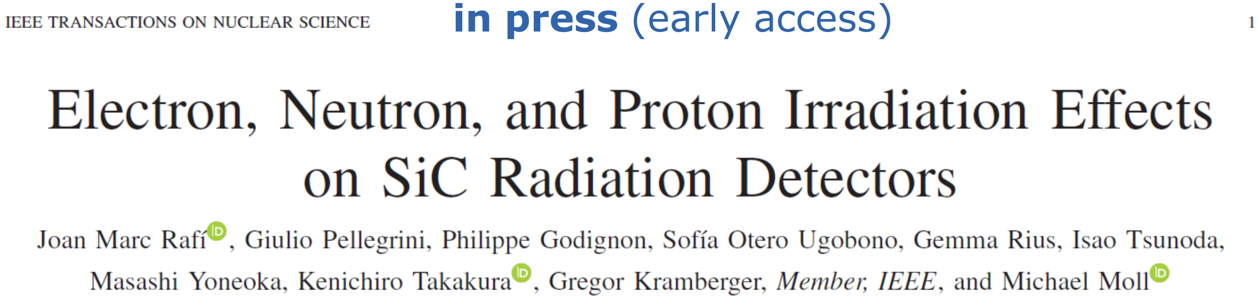
- **Dark current** ↓ ("T-proof")
- **Transparency** ↑ (visible "light-proof")
- **Superior radiation hardness?**

Diamond
(cost↑ area↓ process☹)

SiC

Radiation effects on **SiC** for **detectors**

- **Renewed interest** in **radiation effects** on **SiC technologies** for the **envisaged applications** (fusion, HEP, space, synchrotron, medical…)
- Significant number of **existing results**, some from more primitive **substrates**, different **polytypes**, different **irradiation sources,** mostly **Schottky** diode structures but also **p-n junction** diodes
- Important **pioneering results** from **RD50 collaboration** already described most of the radiation-induced observed effects
- The **present work** is an occasion to **re-visit** the **potential** of **state-of-the-art SiC material** for **radiation detectors**



IEEE TRANSACTIONS ON NUCLEAR SCIENCE **in press** (early access) 1

Electron, Neutron, and Proton Irradiation Effects on SiC Radiation Detectors

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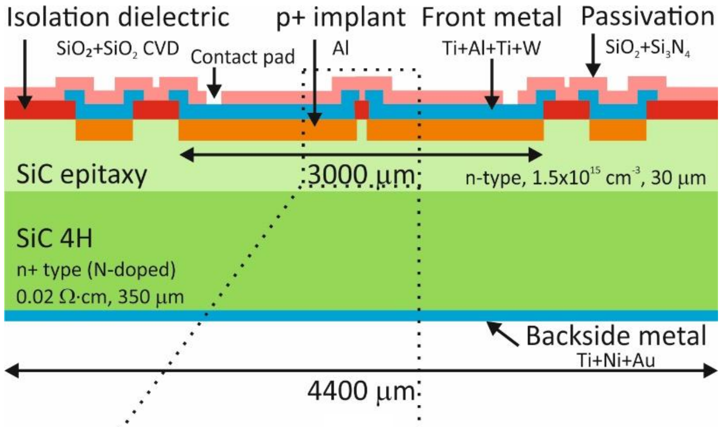
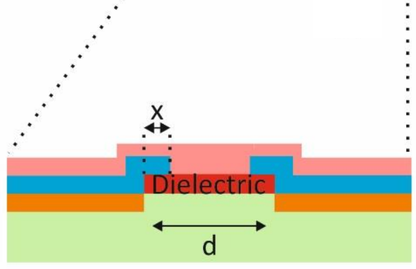
DOI: 10.1109/TNS.2020.3029730

SiC, Si bulk & Si 10 μm

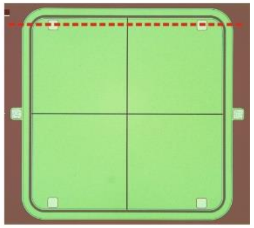
- Device fabrication at IMB-CNM cleanroom
- **3 substrates** (same photolithographic mask set), **p-on-n process**
- Single + **4Q diodes** + **MOS capacitors** (interquadrant isolation)

Epitaxied 4H-**SiC**



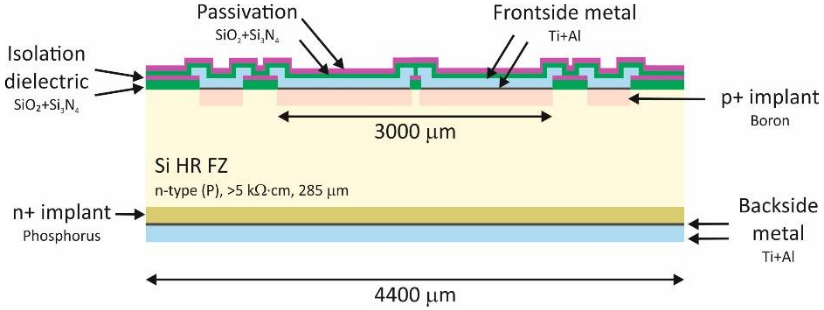


4Q diode

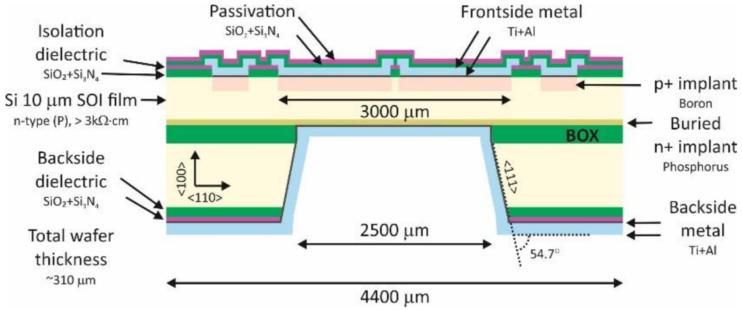


d=25 μm
area=
0.885 cm^2

HR FZ **Si Bulk** (V_{FD}~130V)



HR FZ **Si 10 μm**



J.M. Rafí, et al., J. Instrum., 2017, C01004, DOI: [10.1088/1748-0221/12/01/C01004](https://doi.org/10.1088/1748-0221/12/01/C01004)
J.M. Rafí, et al., J. Instrum., 2018, C01045, DOI: [10.1088/1748-0221/13/01/C01045](https://doi.org/10.1088/1748-0221/13/01/C01045)

Irradiations and **Experimental**

- **Unbiased irradiations** (terminals left floating)

  2 MeV e- @Takasaki-QST, Takasaki, Japan
  Φ = 1x10^{14}, 1x10^{15}, 1x10^{16} e/cm^2
  NIEL hardness factor (Si-1MeV n) ~ 0.0249

  Neutron @JSI TRIGA, Ljubljana, Slovenia
  Φ = 5x10^{13}, 1x10^{14}, 5x10^{14}, 1x10^{15}, 2x10^{15}, 1x10^{17}, 3x10^{17} n/cm^2
  NIEL hardness factor (Si-1MeV n) ~ 0.9

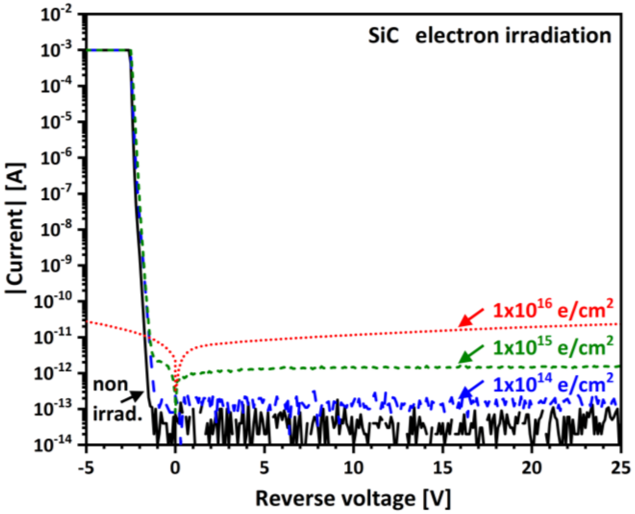
  24 GeV/c p+ @PS-IRRAD CERN, Geneva, Switzerland
  Φ = 8.6x10^{13}, 1.5x10^{14}, 1.0x10^{15}, 1.7x10^{15}, 2.5x10^{15} p/cm^2
  NIEL hardness factor (Si-1MeV n) ~ 0.56

- **Electrical characterization** (except $R_{interquadrant}$ measurements)

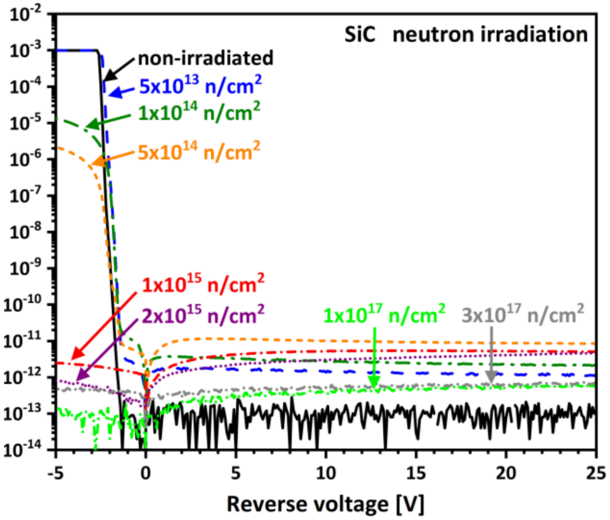
  I-V (low V): HP4155B Semiconductor Parameter Analyzer (triax)
  I-V (High V): Ke2410 SMU (**coax**) and new Ke2470 SMU (**triax**)
  C-V: Agilent 4284A Precision LCR meter (+coupling box when needed)

SiC I-V characteristics (low V)

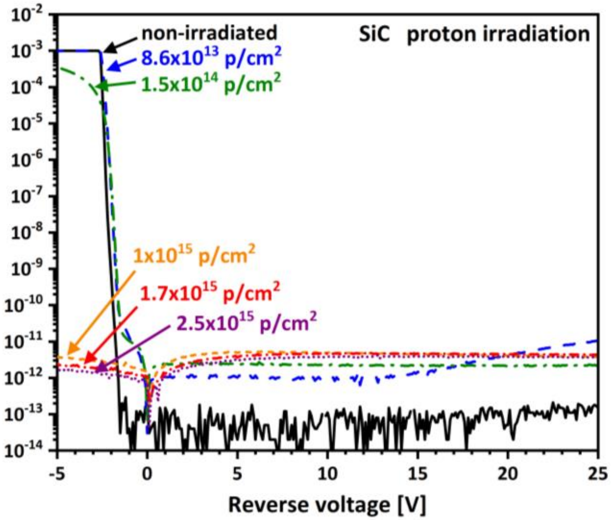
electron



neutron



proton



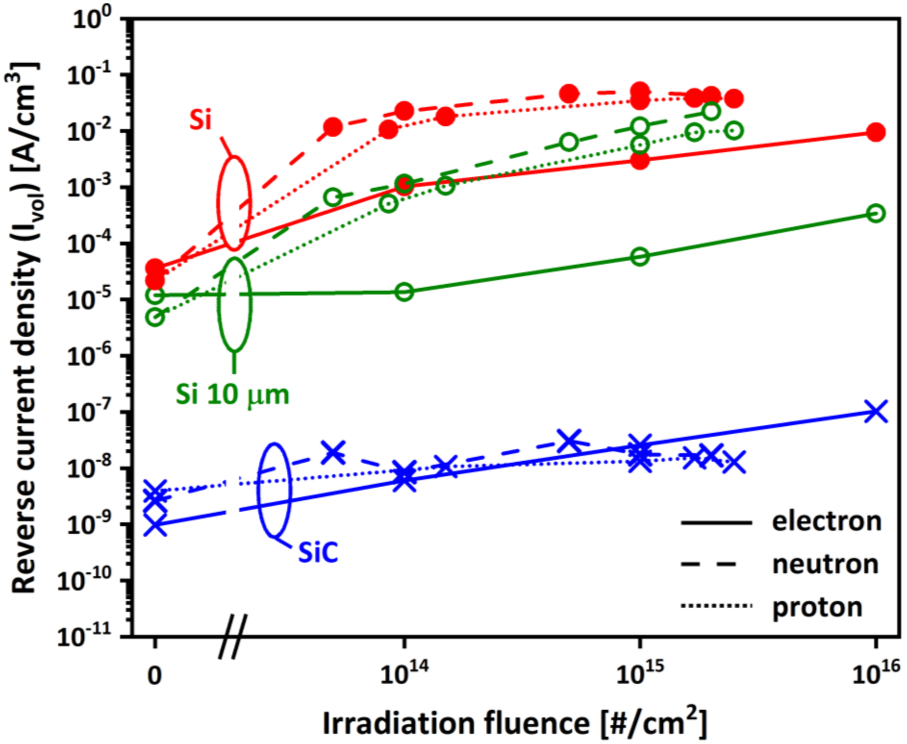
➡ **SiC: low $I_{reverse}$** for **all irradiation fluences** (@ room T)

➡ Bulk Si & 10 μm-Si: >4-6 orders magnitude higher $I_{reverse}$

➡ **Radiation-induced decrease** in **$I_{forward}$**
radiation induced 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 character** is **lost** for the **highest fluences** ($1x10^{16}$ e/cm^2 & >$1x10^{15}$ n-p/cm^2) (lightly doped epi **becoming intrinsic**)

I-V reverse characteristics (low V)



Bulk Si & **10 µm-Si:**
generation-recombination
centers ➔ $\mathbf{I_{vol}}$ ↑

$$I_{vol} \equiv \frac{I_{reverse}}{Area \cdot W_{depletion}}$$

$$\boldsymbol{I_{vol} = \alpha \cdot \Phi}$$

$$\alpha \sim 3.5x10^{-17}\ A/cm$$

(1 Mev-n eq.)

➨ **SiC: low $\mathbf{I_{reverse}}$ ➔ difficult extract α** (perhaps ~5 orders <Si for e-irr.)

Lower creation damage due to **higher atomic displacement energies**

Lower carrier generation in created defects due to **higher bandgap**

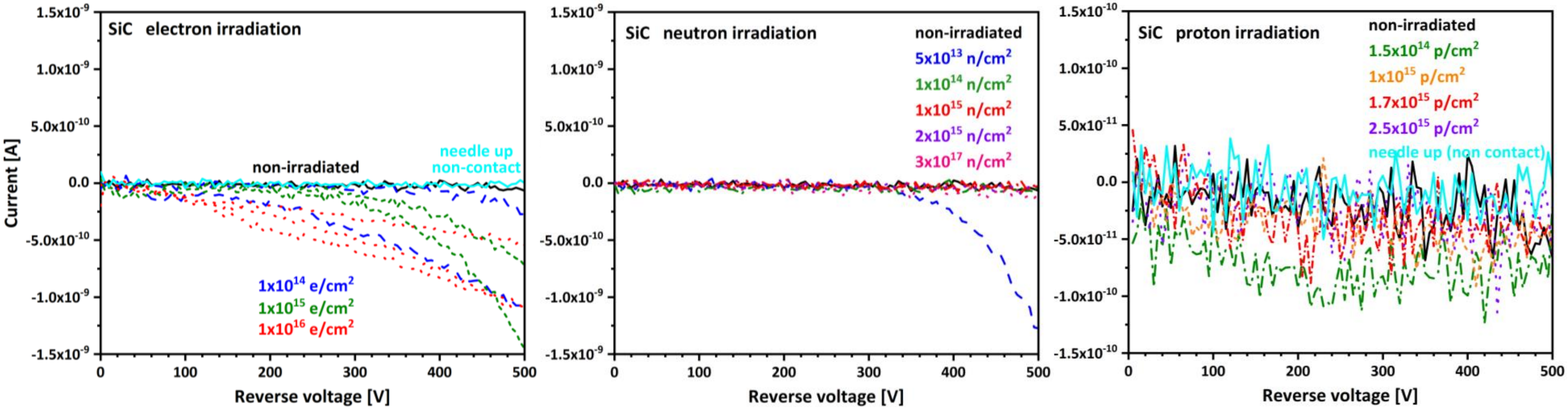
Even slight $\mathbf{I_{reverse}}$ decrease for **highest p+** and **n fluences**

(possible compensation of native defects originally responsible for $I_{reverse}$)

SiC I-V reverse characteristics (high V)

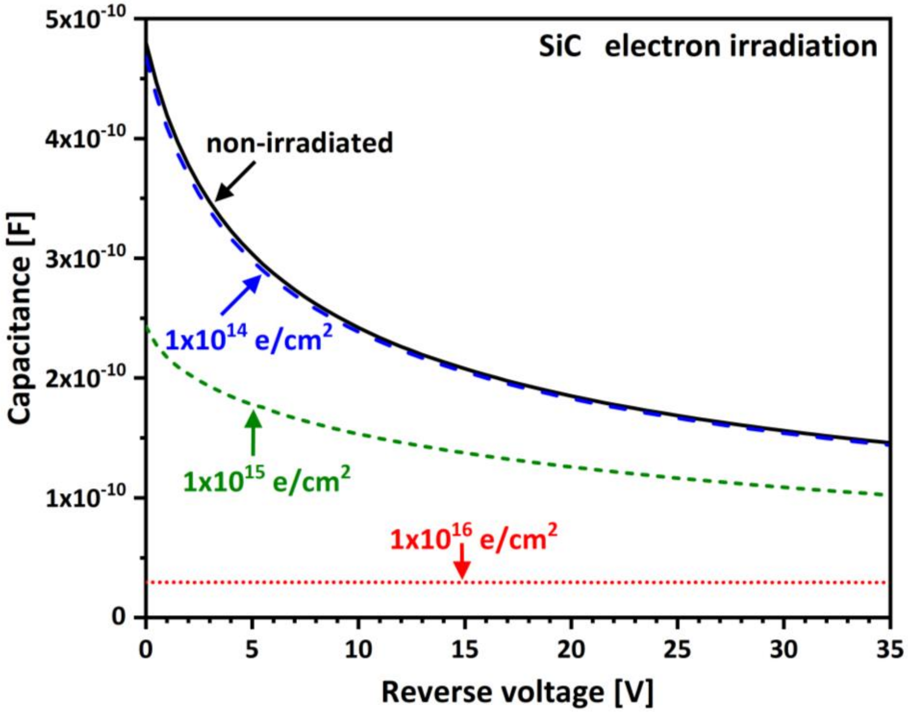
Set-up **Ke2410 SMU coaxial** => Set-up **Ke2470 SMU triaxial**
(resolution ~ 1 nA) (resolution ~ 30-50 pA)

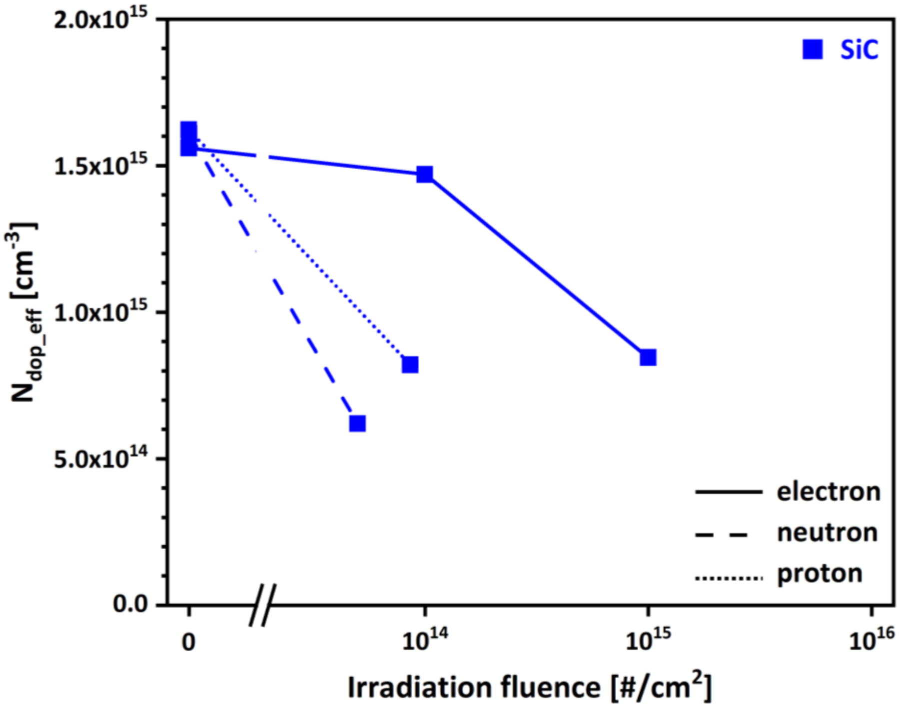
preliminary results with Ke2470 triaxial:



- **SiC:** quite **low $I_{reverse}$** up to 500 V for **all irradiation conditions**
- A bit higher for 2 MeV e-irradiated (to be studied/experimental…?)

SiC C-V characteristics

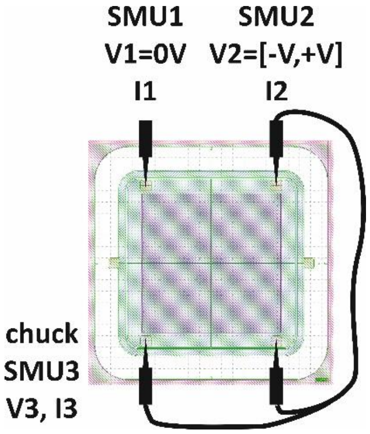


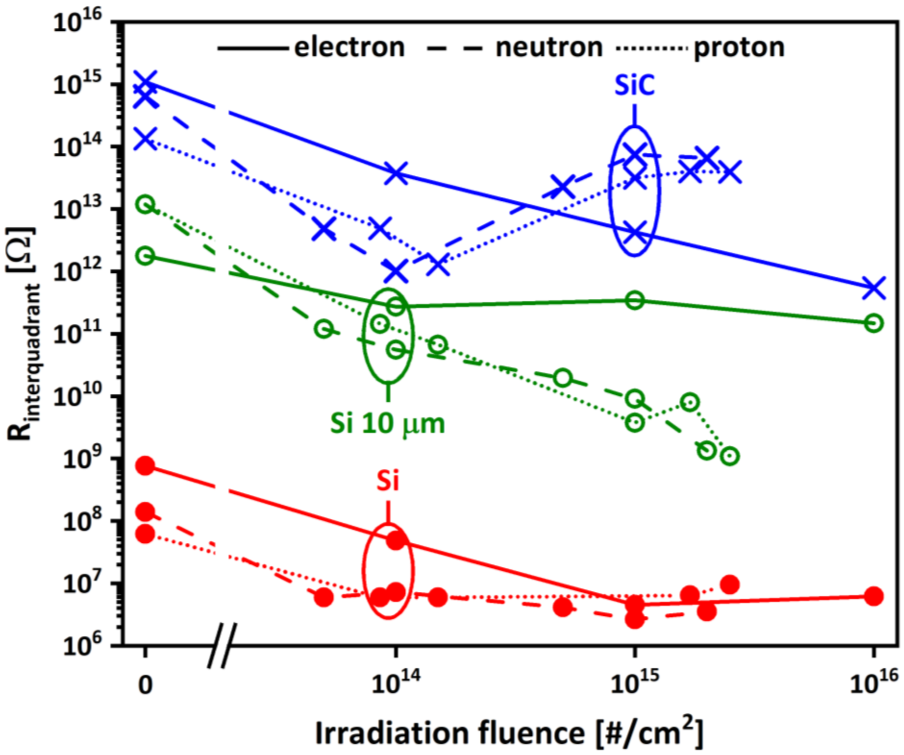


- **Diode-like C-V** only for **lowest Φ** ($\leq 1\times10^{15}$ e/cm^2, $<1\times10^{14}$ n-p/cm^2)
- **Flat C-V** for **highest Φ** (fixed C ~ 25 pF = Area$\cdot\varepsilon_{SiC}$/epilayer thickness) Indicative of **lightly doped n-epilayer becoming intrinsic** due to compensation by radiation-induced defects
- **Carrier removal rates** [cm^{-1}]: 0.72 (e-), 19.8 (n), 9.3 (p+) cm^{-1}, in the range of some previous estimations for e- and n irrad. Schottky barriers

Interquadrant resistance ($R_{interq.}$)

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



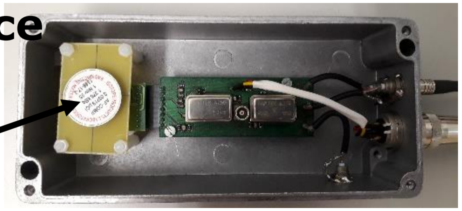


- $R_{interq.}$ SiC > $R_{interq.}$ Si 10 μm > $R_{interq.}$ Si
- **General trend: irradiation → $R_{interq.}$** ↓, except:
  SiC highest neutron & proton Φ (with rectification character lost)
  Si bulk $R_{interq.}$ saturation for highest Φ
- **Radiation-induced charge build-up** in **diode interquadrant isolation**, studied by means of **MOS test structures** (see ref. article)

SiC alpha particle detection

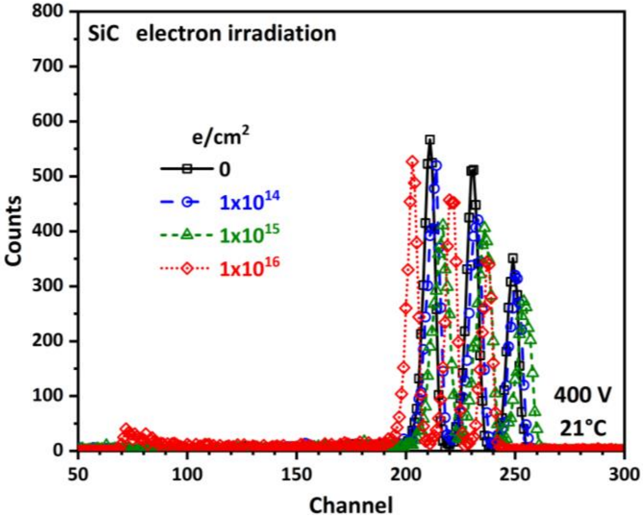
Tri-α source

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

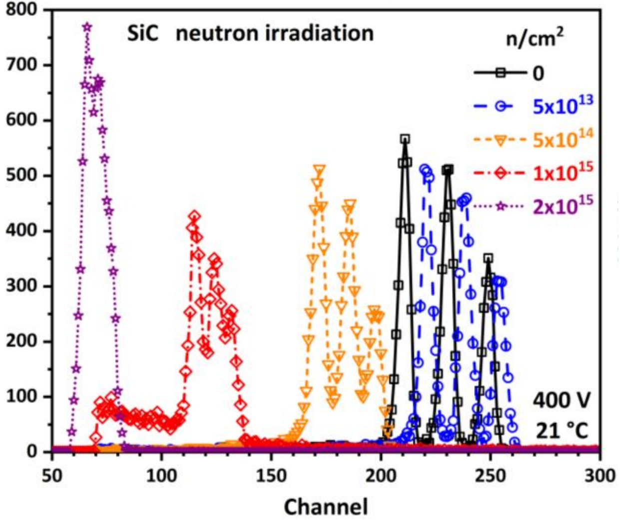


SRIM => α **range**
~ 12-15 μm < epi-SiC

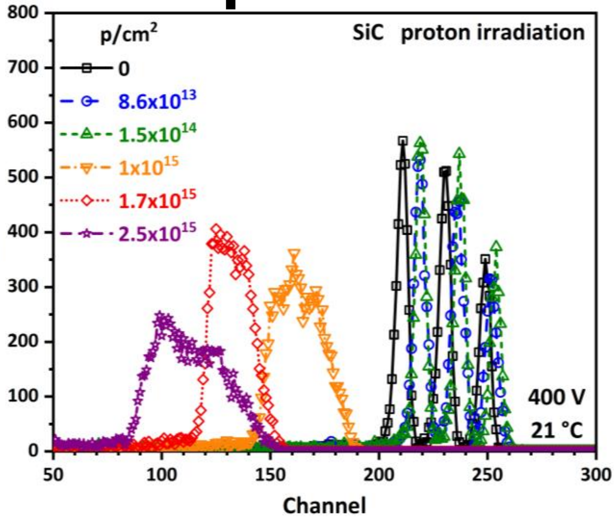
electron



neutron



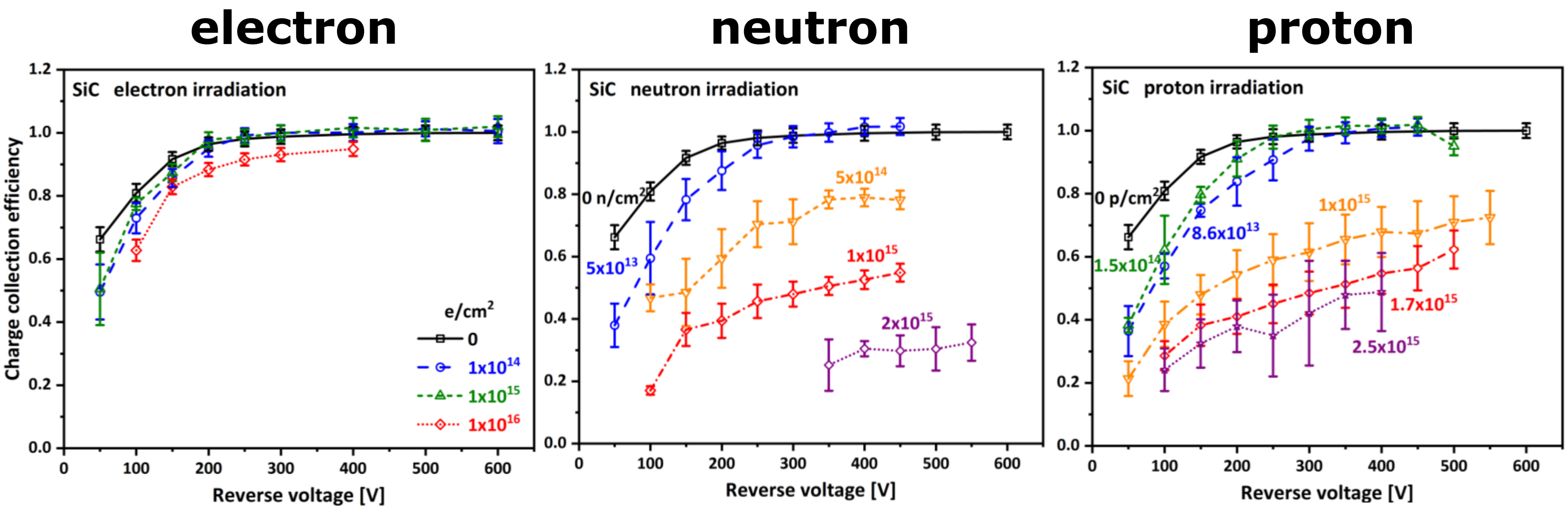
proton



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

(defects ➔ recombination/charge traps ➔ collected charge↓, straggling↑)

SiC charge collection efficiency


electron **neutron** **proton**

➡ **Non-irradiated efficiency saturation @~250 V** (W_{dep}~12.5 μm)
(in agreement with simulated active depth for α detection)

➡ **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, ~-66% @1x10^{15} n/cm^2, ~-50% @1x10^{15} p/cm^2

Summary & outlook

- **4Q p-n junction diodes** fabricated on **epitaxied SiC**, as well as on **HR FZ bulk** and **10 μm-Si**
- Effects **2 MeV e-**, **neutron** & **24 GeV/c p+** on electrical characteristics
- **Low $I_{reverse}$** for **SiC devices** subjected to all studied irradiations, with loss of electrical rectification character for highest fluences
- **Impact of irradiation** on **$R_{interquadrant}$** (and charge build-up in interquadrant isolation) have been assessed
- Tri-α source ➔ **SiC** device performance as a **radiation detector** is **preserved** at **room T**, at least up to $2x10^{15}$ n/cm^2, as well as all other reached e- and p+ fluences
- **Studies/collaboration** would be needed to get a better picture of the involved phenomena (defect characterization, annealing, simulation…)
- Some **superior properties** of **SiC devices**. In particular, advantages for α **particle detection** in plasma diagnostic systems for future **nuclear fusion reactors** is envisioned

Acknowledgements

Thank you very much for your attention

This work was supported in part by the **Spanish Ministry of Science, Innovation and Universities** through the Nuclear and Particle Physics Program under Project FIS-FPN-RTI2018-094906-B-C22 (MCIU/FEDER UE), in part by the **European Union's Horizon 2020** Research and Innovation Program under Grant 654168 (AIDA-2020), in part by a collaborative research project at Nuclear Professional School, School of Engineering, **The University of Tokyo**, under Grant 20016, in part by The **Japan Society for the Promotion of Science KAKNHI**, under Grant JP19K05337, and in part by MINECO through the use of the **Spanish ICTS Network MICRONANOFABS**. The work of Gemma Rius was supported by Spanish Ministry of Science and Innovation through **Ayudas Ramón y Cajal** 2016, under reference RYC-2016-21412.