Advanced Power Semiconductor Laboratory

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

Terrestrial neutron effects on commercial SiC power MOSFETs

Corinna Martinella

R. G. Alia, R. Stark, A. Coronetti, C. Cazzaniga, M. Kastriotou,
Y. Kadi, R. Gaillard, U. Grossner, A. Javanainen

R2E Annual Meeting – 2-3 Feb, 2021
https://indico.cern.ch/event/971222/

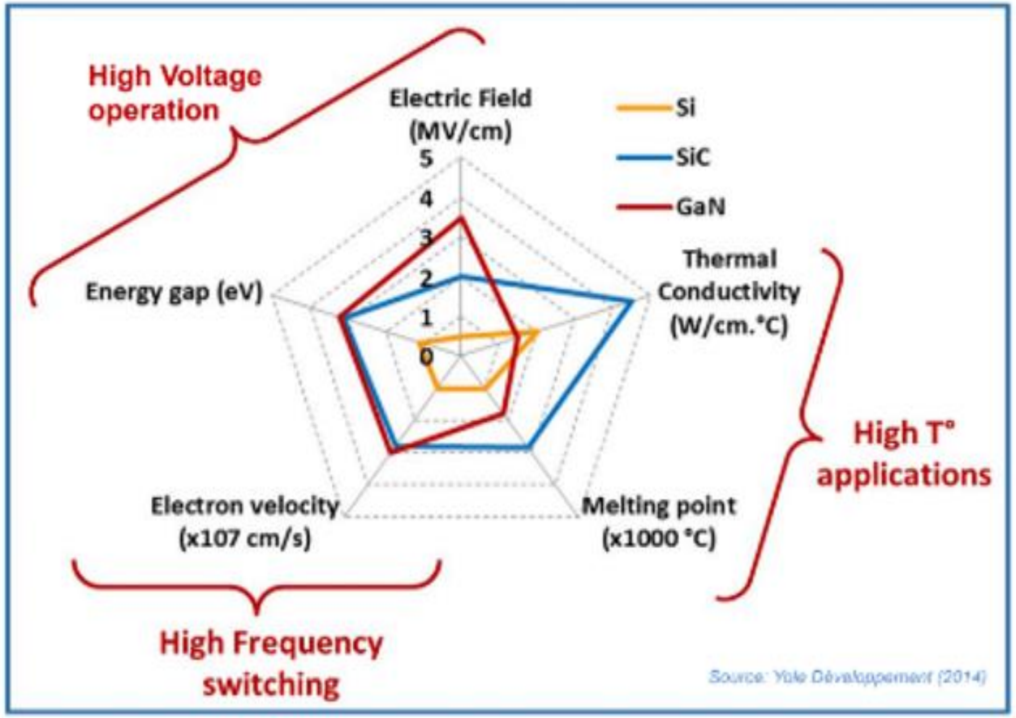
CERN SY STI R2E

Agenda

1. Introduction on SiC power MOSFETs
2. Atmospheric-like neutron experiment
3. Results
4. Conclusions

Introduction - SiC material

Silicon carbide (SiC) is a **wide bandgap material** with an energy gap of **3.23 eV** (4H-SiC at 25 ̊C), almost 3 times the bandgap of Si (1.12 eV).

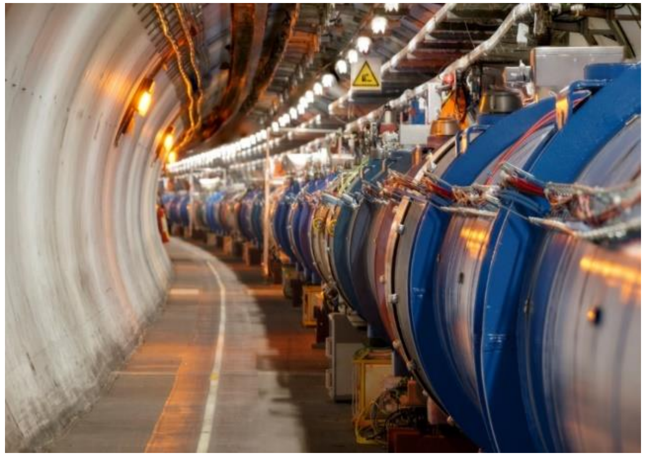


Source: Yole Développement (2014)

The physical, electrical and thermal properties of SiC are attractive for **power devices applications**:

- ❑ **high voltage** operations;
- ❑ **high temperatures** applications;
- ❑ **switching frequencies** (>100 kHz);
- ❑ **lower conduction losses** than Si.

Introduction - SiC in high-energy accelerators



Requirements from TE/ABT:

- ❑ Voltage rating >1.2 kV;
- ❑ Pulse current rating > 150 A;
- ❑ On state resistance < 100 mΩ;
- ❑ Current rise/fall time < 25 ns.

- ❑ SiC MOSFETs are a promising technology for high-energy accelerators.

- ❑ SiC MOSFETs were considered for the design of a **prototype inductive adder (IA)** based on semiconductor switches, to be used as a pulse generator for the injection kicker magnets in FCC and in PS (TE/ABT).

D. Woog *et al.*, *Journal of Physics*, Conf. Ser. 874 012096, Jul. 2017.

D. Woog *et al.*, in IPMHVC 2018, 2018, pp. 464–468, doi: 10.1109/IPMHVC.2018.8936655.

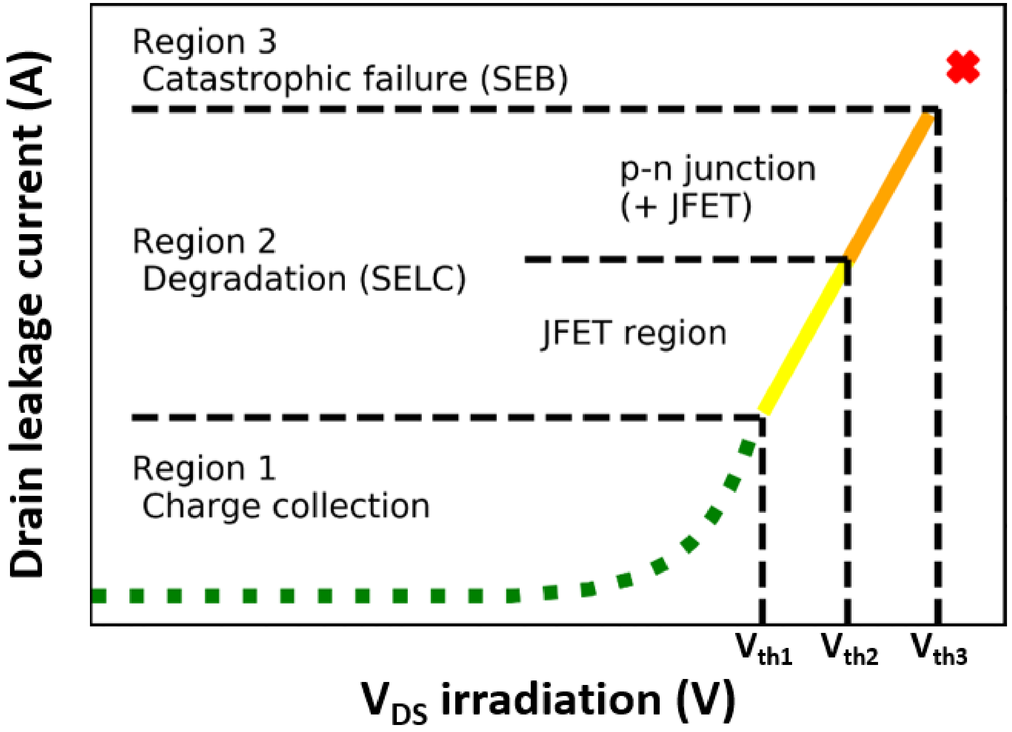
- ❑ **Marx generator** based on SiC MOSFETs for use in SPS and potentially LHC (IA technology not suitable due to longer pulses).

L. M. Redondo *et al.*, *IEEE Trans. Plasma Sci.*, vol. 46, no. 10, pp. 3334–3339, 2018.

- ❑ **Neutrons** can cause issues for electronic systems in underground areas at CERN. **Radiation tests** to assess the reliability of SiC MOSFETs.

R. García Alía *et al.*, *IEEE Transactions on Nuclear Science*, vol. 65, no. 1, pp. 448-456, Jan. 2018.

Introduction - SEE on SiC power MOSFETs

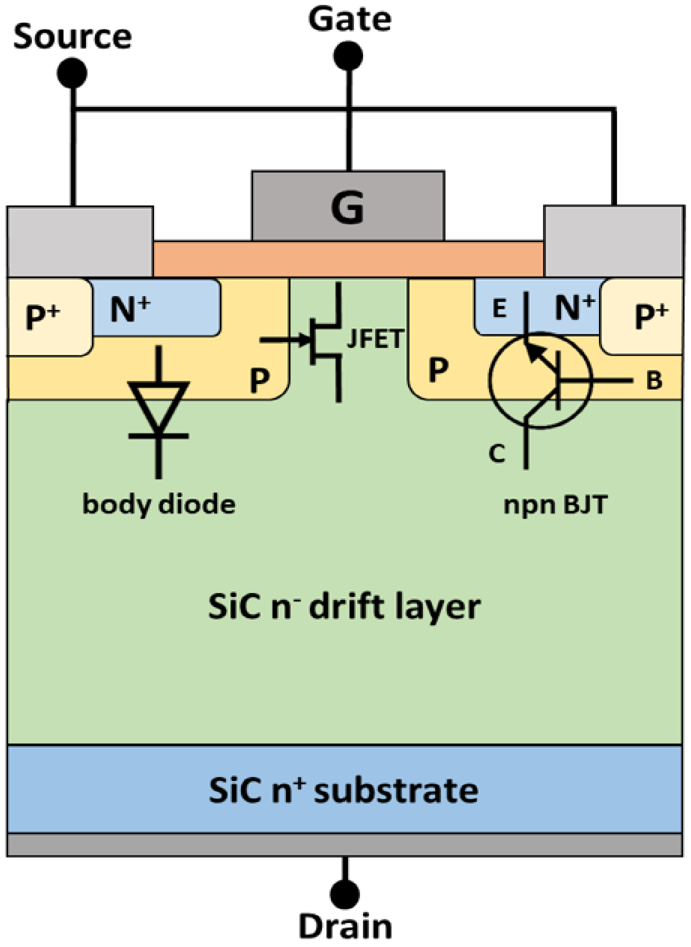


C. Martinella *et al.*, *IEEE Trans. Nucl. Sci.*, vol. 67, no. 7, pp. 1381–1388, Jun. 2020.

Regions of damage for SiC power MOSFETs:

- ❑ **Region 1:** **charge collection**, no permanent damage. Heavy ions, protons and neutrons.
- ❑ **Region 2:** **Single Event Leakage Current (SELC)**. **Permanent increase of drain and gate leakage currents. Not observed with Si power MOSFETs**. Reported only with heavy ions.
- ❑ **Region 3:** destructive **Single Event Burnout (SEB)**. Heavy ions, protons and neutrons.

Introduction - SEB on SiC power MOSFETs

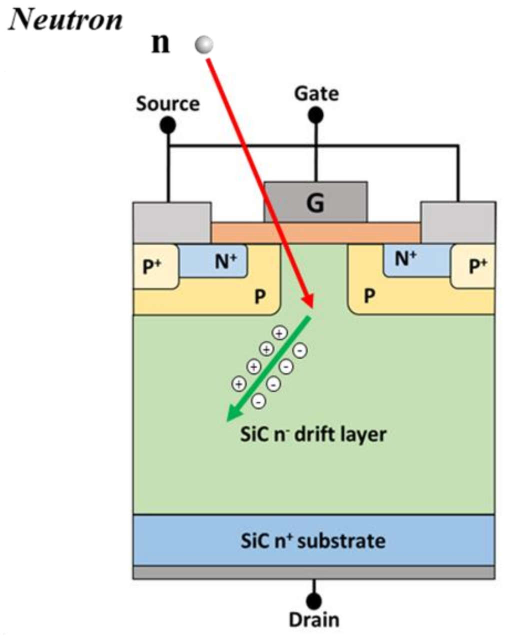


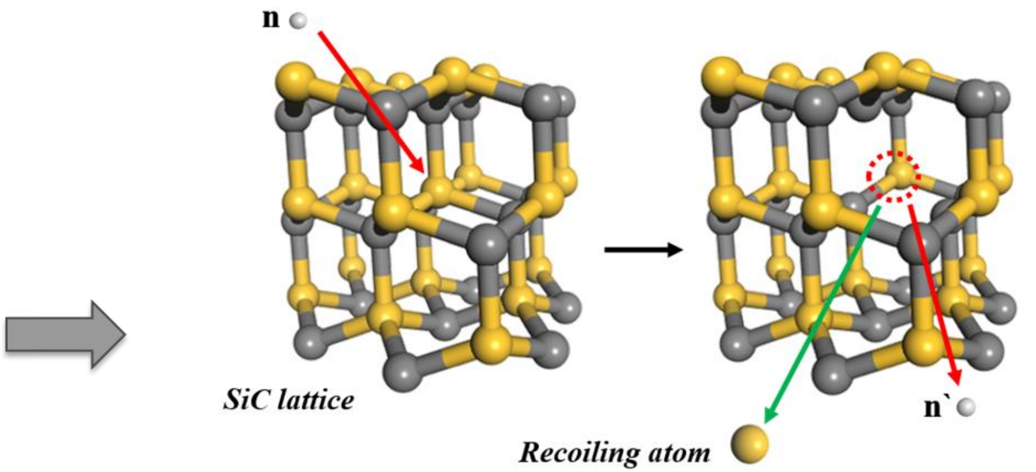
SEB mechanism in SiC power MOSFETs:

- ❑ For Si Power MOSFETs the SEB is associated with the **parasitic n-p-n BJT** and tunneling assisted avalanche multiplication mechanisms.
- ❑ Similar SEB tolerance for **SiC MOSFETs** and **SiC diodes**. No parasitic BJT in diode structure.
- ❑ The mechanisms underlying the SEB in Si MOSFETs might be **suppressed** in SiC MOSFETs where the **current gain** of the parasitic BJT is **lower**.

H. Asai *et al.*," *IEEE Trans. Nucl. Sci.*, vol. 61, no. 6, pp. 3109–3114, Dec. 2014.

Introduction - SEB with neutrons





By the elastic and inelastic scattering with the SiC lattice, the atmospheric neutrons produce recoiling atoms (i.e, α, C, Si, Mg, Al) which generate ionizing tracks inside the power MOSFET.

A. Akturk *et al.*, *IEEE Trans Nucl. Sci.*, vol. 65, no. 6, Jun 2018.

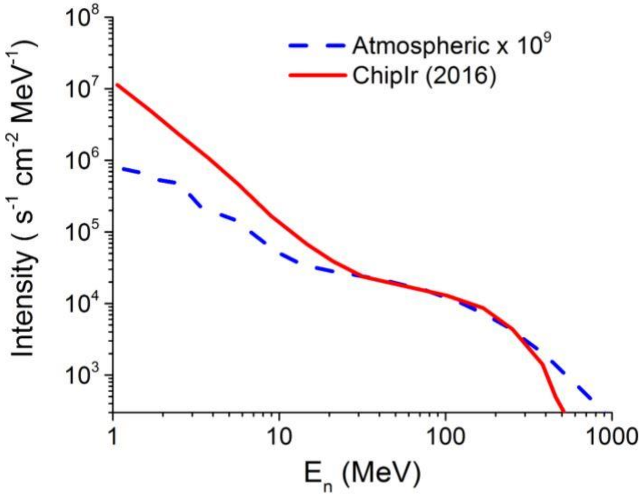
SEB with neutrons – Hypothesis from Akturk *et al.*:

- ❑ Neutrons are non-ionizing particles. **Recoiling atoms** create a large number of electron and hole **(e–h)** pairs along their trajectories, which can enter the N-drift layer.
- ❑ Hole impact ionization with associated multiplication factors, **thermal transient** and excessive lattice temperatures.
- ❑ **Local lattice sublimation**, formation of voids, loss of device blocking ability, hence a **destructive failure**.

Experimental setup and method

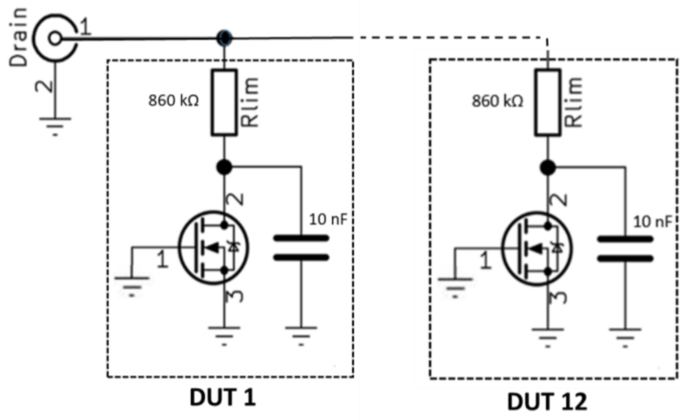
OBJECTIVE:

Investigate the effect of **atmospheric-like neutron** on different commercial SiC MOSFETs. The experiment was performed at the **ChipIr** facility, UK.



SETUP:

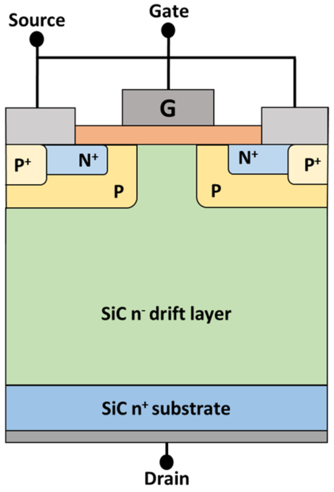
- Military standard: **MIL-STD-750E M1080.1**.
- 2 boards, each with 12 DUTs in parallel.
- **Total I_D** measured by a Keithley SMU 2410.
- A **fixed step increase** in the total I_D monitored was accounted as a failure.



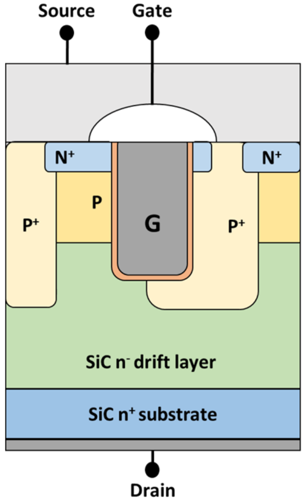
EXPERIMENT:

- Irradiations at **V_{DS} = 1100 V, 976 V, 846 V** (~92%, ~81%, 72% of 1.2 kV), V_{GS} = 0V.
- Up to 50%–70% of device failed or **fluence of 2.8 x 10^{10} n/cm^2**.

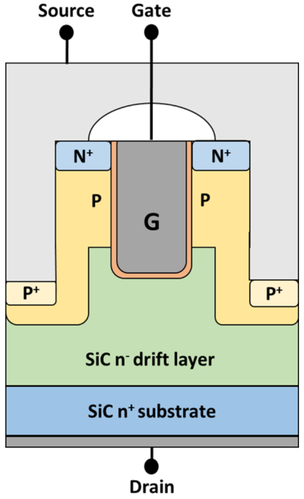
Devices under test



(a) Planar gate



(b) Trench gate



(c) Double trench

DUTs:

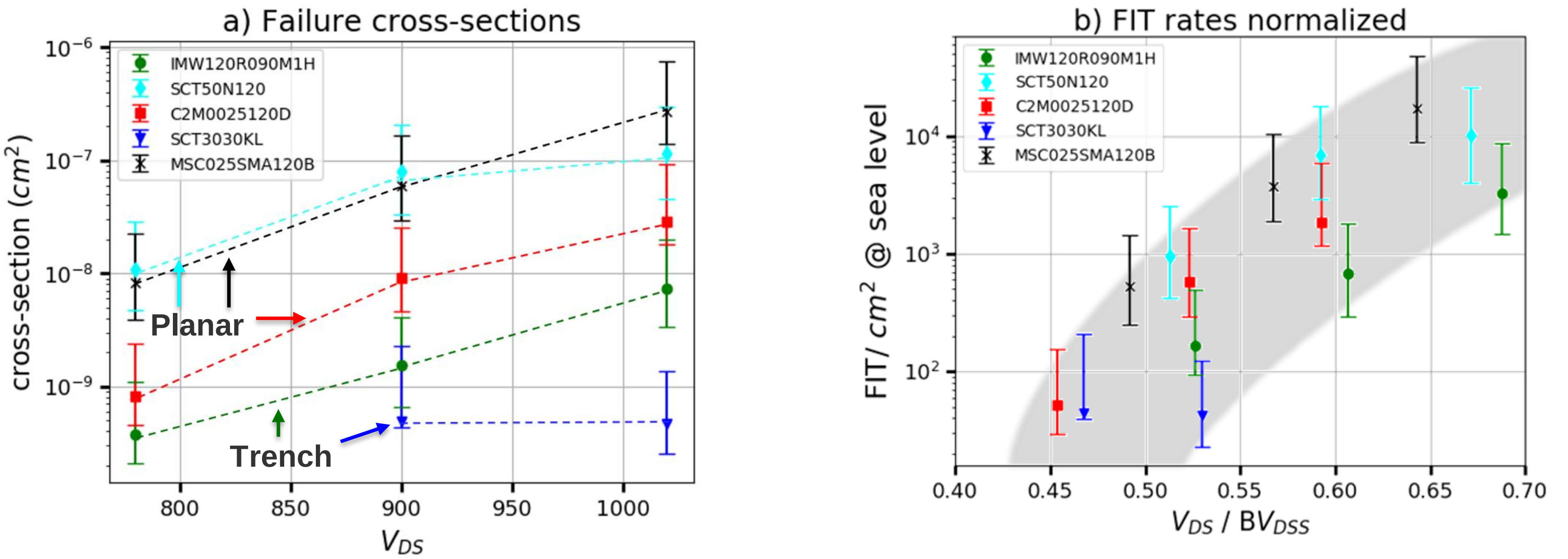
- ❑ Commercial **SiC power MOSFETs (1.2 kV)** selected following the **TE/ABT requirements** for IA design;
- ❑ 3 architectures: **planar gate**, **trench gate**, **double trench** (trench gate and source);

- ❑ **Different breakdown voltage** (i.e. I_D > 1 mA). The highest is the double-trench DUT from **Rohm** (i.e. SCT3030KL).

TABLE I
LIST OF DEVICES UNDER TEST

Reference	Man.	$R_{DS(on)}$ [mΩ]	V_{DS} [kV]	$I_{D\,@\,25'}$ [A]	VB [kV]	Gate	#DUTs
C2M0025120D	Cree/ Wolfspeed	25	1.2	250	1720	Planar (a)	51
SCT3030KL	Rohm	30	1.2	180	1926	Double trench (c)	48
MSC025SMA120B	Microsemi	25	1.2	275	1586	Planar (a)	50
SCTWA50N120	ST-Micr.	59	1.2	130	1520	Planar (a)	66
IMW120R090M1H	Infineon	90	1.2	50	1483	Trench (b)	65

Results - Cross-sections and FIT rates



- ☐ Standard 2-parameter **Weibull distribution** using a maximum likelihood estimation (MLE) method. Error bars calculated considering a **Poisson distribution** dominated by the count statistics.
- ☐ **FIT rates** normalized with the active area and scaled by the breakdown voltage. **Common voltage dependence**.
- ☐ The **trench DUTs** are more robust. The **double-trench** from Rohm (i.e. SCT3030KL) has the best performance.

Results - Post-irradiation analysis

A **planar gate from Cree/Wolfspeed** (i.e., C2M0025120D), a **trench gate from Infineon** (i.e., IMW120R090M1H) and **double trench from Rohm** (i.e., SCT3030KL) were analyzed after the irradiation.

3 different responses identified from the post I-V analysis:

(i) **No damage** observed respect to a reference pristine

→ (ii) **Partial degradation** with enhanced leakage currents

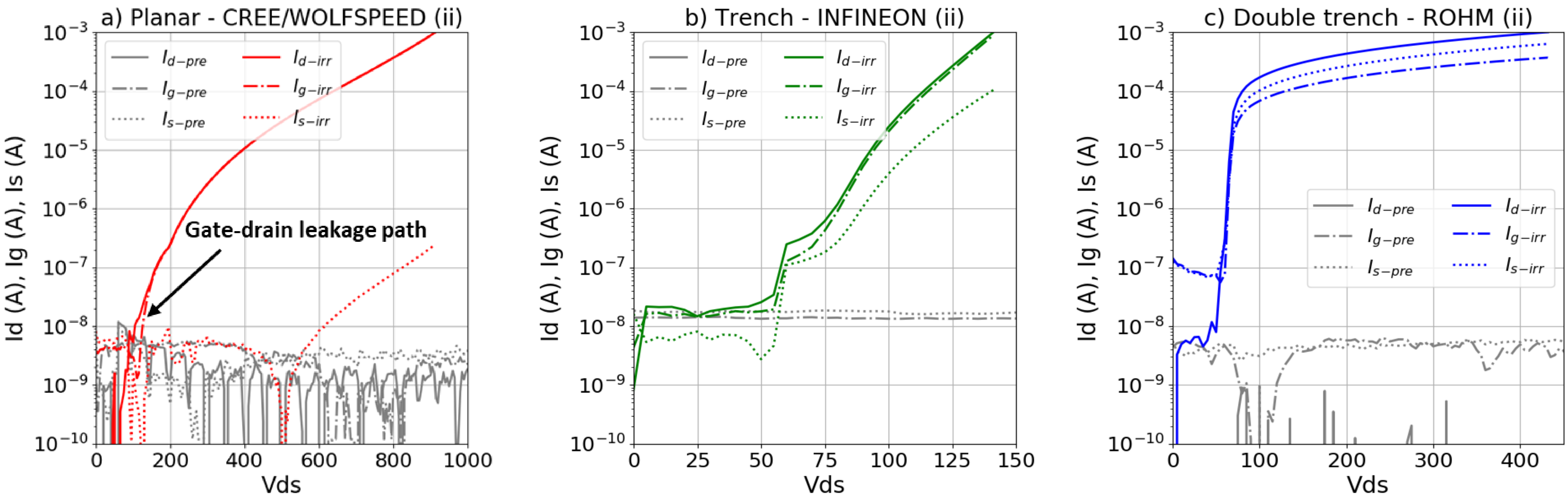
(iii) **Ohmic trend** of the leakage current caused by **SEB**

Post-irradiation analysis for DUTs (ii):

- ☐ **Avalanche breakdown** measurement at V_{GS} = 0 V, to study the degradation of the blocking capability.
- ☐ I_DV_{GS} and I_GV_{GS} at V_{DS} = 1 V to study the gate damage.

Post-irradiation analysis (ii) – Breakdown Voltage

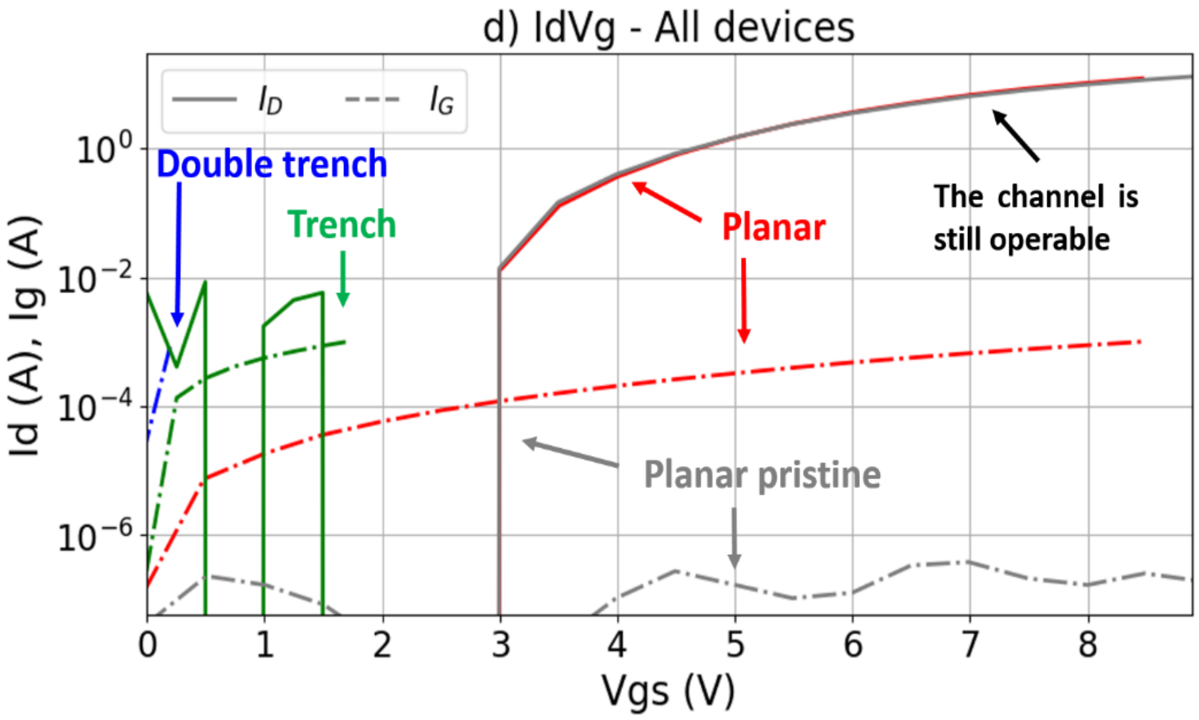
Avalanche breakdown measurement at $V_{GS} = 0$ V, to study the degradation of the blocking capability.



- Among the failed devices, no ohmic behaviour, but **higher gate and drain leakage currents** (out of spec. $I_g > 100$ nA).
- **Different leakage path** between the planar and the trench DUTs.

Post-irradiation analysis (ii) – Gate damage

I_DV_{GS} and I_GV_{GS} measurements at V_{DS} = 1 V to study the gate damage and the different leakage path.



Planar DUT:

- ❑ Very high gate leakage current;
- ❑ The **channel** is still **operable**;
- ❑ **Partial gate rupture**. Similar to SELC observed with heavy-ions.

Trench and double trench DUT:

- ❑ The channel is **not operable** anymore;
- ❑ **Complete gate rupture**.

Conclusions

- ❑ SiC power MOSFETs are a promising technology for accelerator applications, but they are still **sensitive** to neutrons.
- ❑ **Cross-sections** and **FIT rates** were presented. The trench MOSFETs appear to be more robust to failure respect to the planar ones. The **double trench** DUTs from Rohm (i.e. SCT3030KL) showed the **best performance**. This might be due to the **higher breakdown voltage** (1.9 kV) and double-trench architecture.
- ❑ Among the failed devices, **the degradation is not always the same magnitude**. From the post I-V analysis, some devices showed an ohmic trend (iii), while others were still operable, but the gate and drain leakage were out of specifications (ii).
- ❑ A **partial gate rupture** mechanism was observed for the **planar DUTs**, which exhibited very high leakage currents and a gate-drain current path, similar to SELC previously reported with heavy-ions. The **trench MOSFETs**, instead, were more sensitive to a **complete gate rupture**.

C. Martinella *et al.*, "Impact of Terrestrial Neutrons on the Reliability of SiC VD-MOSFET Technologies", under revision for IEEE TNS Journal.

Contact: corinna.martinella@cern.ch

Advanced Power Semiconductor Laboratory

JYVÄSKYLÄN YLIOPISTO
UNIVERSITY OF JYVÄSKYLÄ

Thank you for your attention!

Backup slides

Failure Analysis

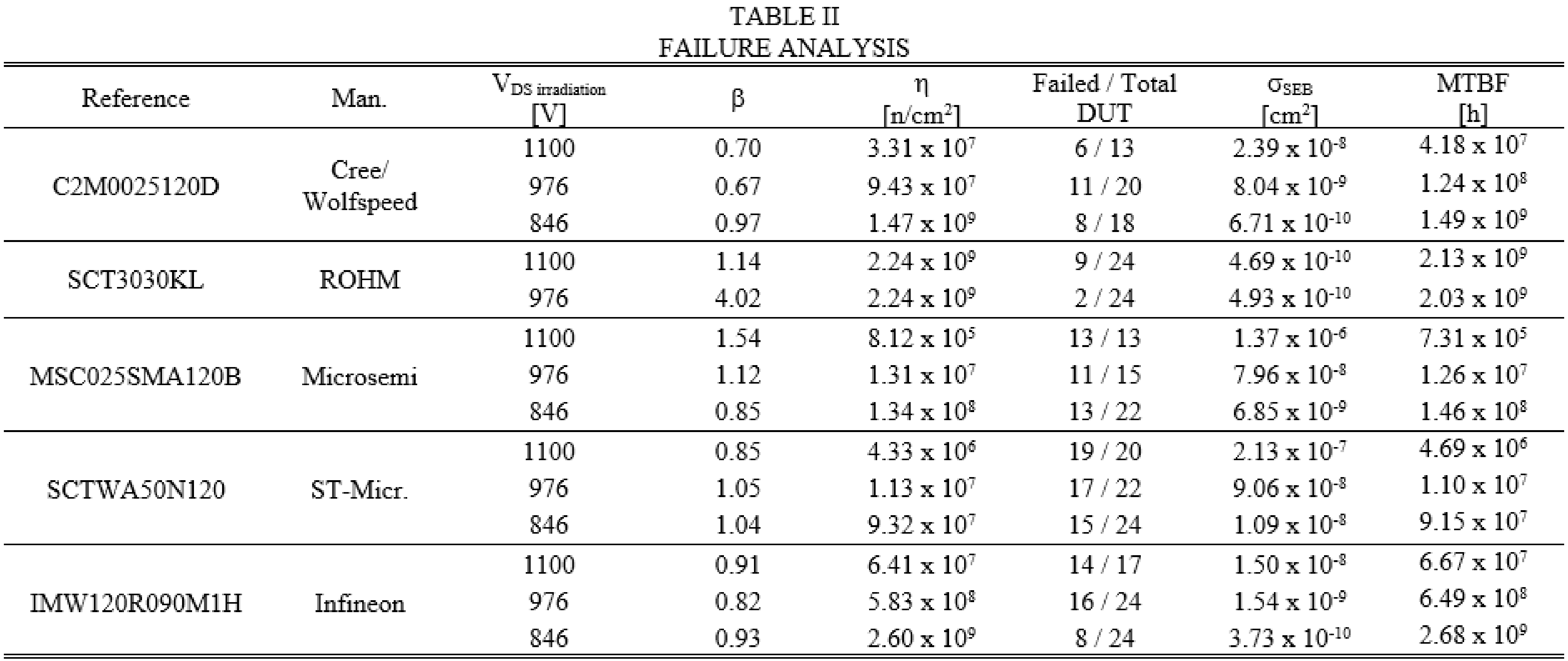
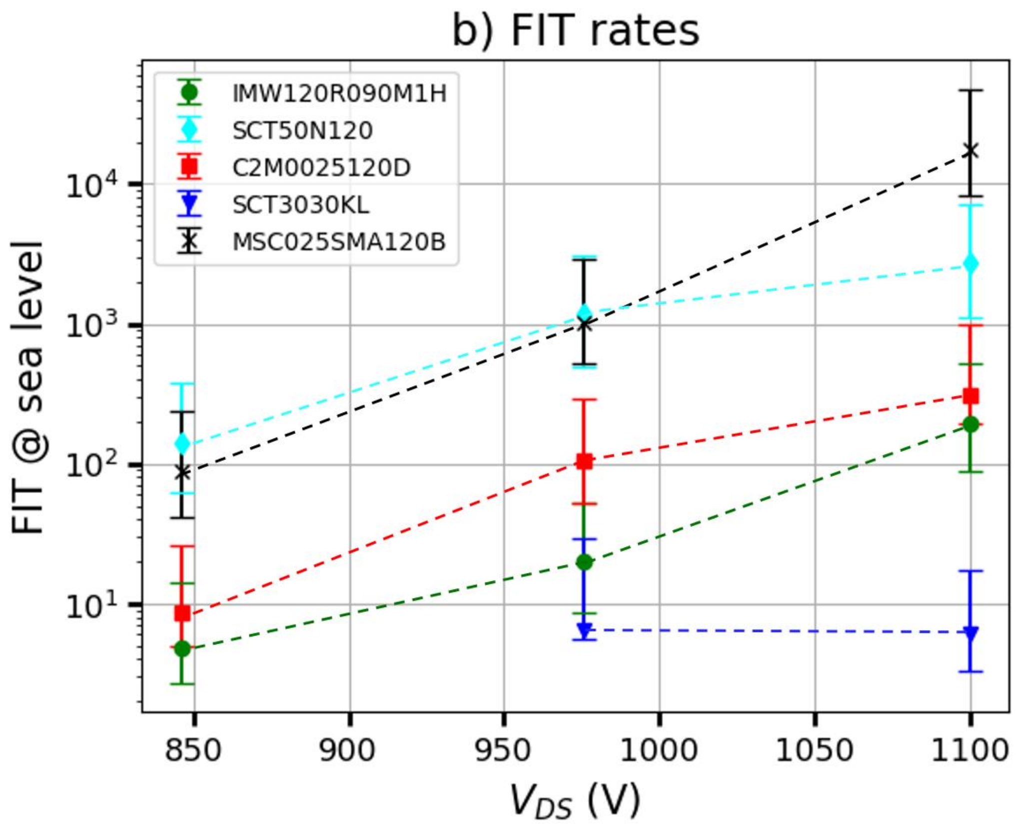


TABLE II
FAILURE ANALYSIS

Reference	Man.	$V_{DS\ irradiation}$ [V]	β	η [n/cm²]	Failed / Total DUT	σ_{SEB} [cm²]	MTBF [h]
C2M0025120D	Cree/ Wolfspeed	1100	0.70	3.31×10^{7}	6 / 13	2.39×10^{-8}	4.18×10^{7}
		976	0.67	9.43×10^{7}	11 / 20	8.04×10^{-9}	1.24×10^{8}
		846	0.97	1.47×10^{9}	8 / 18	6.71×10^{-10}	1.49×10^{9}
SCT3030KL	ROHM	1100	1.14	2.24×10^{9}	9 / 24	4.69×10^{-10}	2.13×10^{9}
		976	4.02	2.24×10^{9}	2 / 24	4.93×10^{-10}	2.03×10^{9}
MSC025SMA120B	Microsemi	1100	1.54	8.12×10^{5}	13 / 13	1.37×10^{-6}	7.31×10^{5}
		976	1.12	1.31×10^{7}	11 / 15	7.96×10^{-8}	1.26×10^{7}
		846	0.85	1.34×10^{8}	13 / 22	6.85×10^{-9}	1.46×10^{8}
SCTWA50N120	ST-Micr.	1100	0.85	4.33×10^{6}	19 / 20	2.13×10^{-7}	4.69×10^{6}
		976	1.05	1.13×10^{7}	17 / 22	9.06×10^{-8}	1.10×10^{7}
		846	1.04	9.32×10^{7}	15 / 24	1.09×10^{-8}	9.15×10^{7}
IMW120R090M1H	Infineon	1100	0.91	6.41×10^{7}	14 / 17	1.50×10^{-8}	6.67×10^{7}
		976	0.82	5.83×10^{8}	16 / 24	1.54×10^{-9}	6.49×10^{8}
		846	0.93	2.60×10^{9}	8 / 24	3.73×10^{-10}	2.68×10^{9}

FIT rates


b) FIT rates
FIT @ sea level
V_{DS} (V)
10^1
10^2
10^3
10^4
850
900
950
1000
1050
1100
IMW120R090M1H
SCT50N120
C2M0025120D
SCT3030KL
MSC025SMA120B