RADSAGA

Coupled radiation and aging effects on wide bandgap power devices

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RADSAGA Final Conference and Industrial event

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RADiation and Reliability Challenges for Electronics used in Space, Aviation, Ground and Accelerators (RADSAGA) is a project funded by the European Commission under the Horizon2020 Framework Program under the Grant Agreement 721624. RADSAGA began in Mars 2017 and will run for 5 years.

Presentation outline

Introduction: My work in the context of RADSAGA

Part 1: State of the art

- Wide bandgap materials and their applications
- Radiation environments and effects
- Test standards

Part 2: Experimental results and analysis

- Methodology and experimental details
- Radiation and aging experiments

Conclusions

Thesis goals in the context of RADSAGA

RADSAGA (RADiation and Reliability Challenges for Electronics used in
Space,
Aviation,
Ground and
Accelerators)

- Reliability is essential for safe operation within all four application areas.
- Power devices are the key components for any electronics systems and failure or degradation of power device affects the overall system reliability.

In the frame of RADSAGA, my thesis work focuses on the following:

- Radiation sensitivity assessment of emerging wide bandgap power devices
- Mutual effects of aging and radiation
  - The effect of radiation induced degradation on the lifetime of the device
  - The effect of aging on radiation sensitivity
- Development of the test methodology for assessing those effects

Part I: State of the art

From silicon to wide bandgap materials

Critical parameters: Power electronics

- The characteristics and limitations of power electronics devices are a key element in the power electronics system design
- In order to maximize the efficiency, the power loss in the semiconductor devices should be minimized
- Silicon has been the dominant semiconductor material in power electronics since the beginning

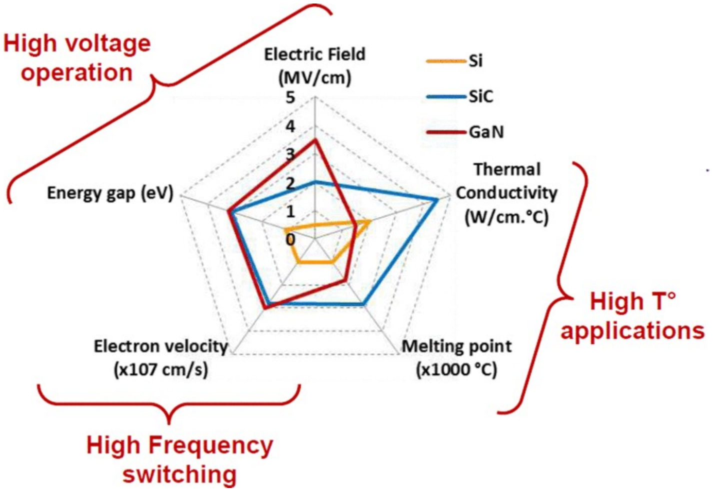


Fig. 1. Figure of merit of material parameters of Si, SiC and GaN.
Millan *et al.* 2015

Silicon has reached its limits regarding critical electric field, operating temperature and switching frequency

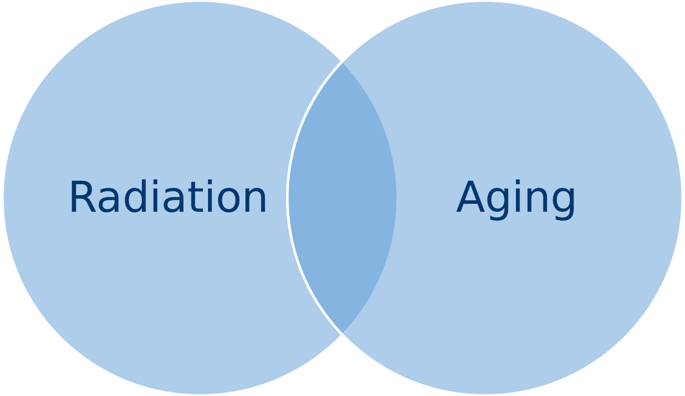
Main known stressors for WBG based power devices

Stressors

- Operation (electrical)
- Radiation
- Temperature
- Mechanical

Failure mechanisms and related failure modes

- Overload – Open circuit
- SEEs - Short-circuit
- Thermal effects
- Wear-out



Test methodologies for radiation sensitivity assessment of power electronics

Standard for assessing the power MOSFET radiation sensitivity in atmospheric environment does not exist

Document reference	Applicable to	Shortcomings
MIL-STD-750E Method 1080	Heavy ion testing for space applications	• Not applicable for atmospheric neutron testing
JESD89A	Atmospheric neutron testing for microelectronics	• No guideline for power devices
JEP151	Atmospheric neutron testing for power devices	• Not a standard • Does not take into account coupled aging and radiation effects

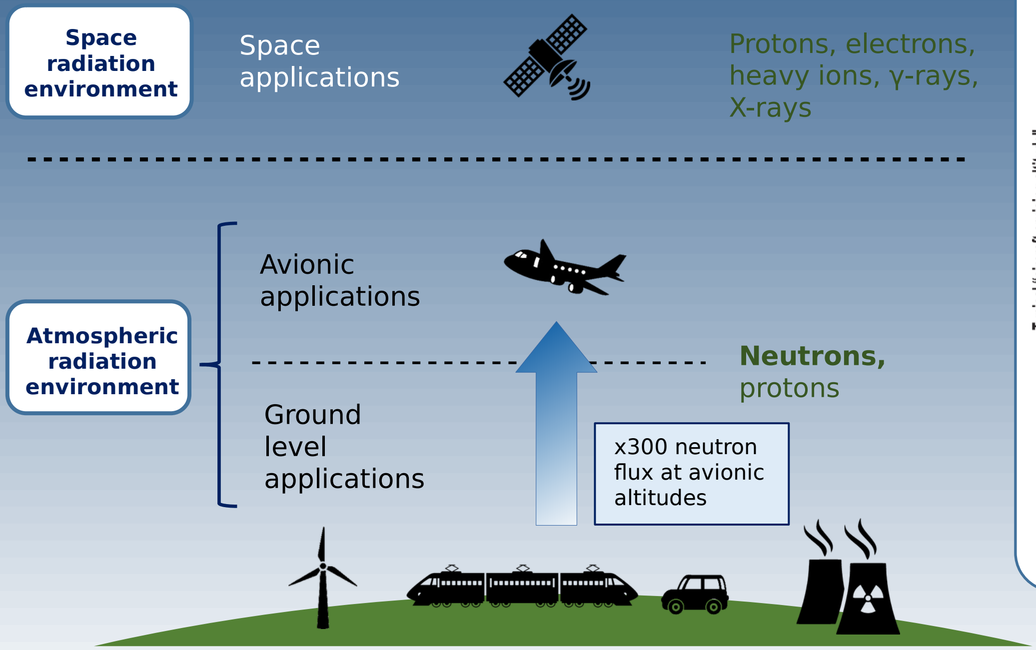
In this work, versatile methodology for reliability parameter and failure rate calculation for power devices under neutron environment is proposed.

RADSAGA

Part I: State of the art

Radiation effects on power electronics

Radiation environments



Space radiation environment

Space applications

Protons, electrons, heavy ions, γ-rays, X-rays

Atmospheric radiation environment

Avionic applications

Ground level applications

Neutrons, protons

x300 neutron flux at avionic altitudes

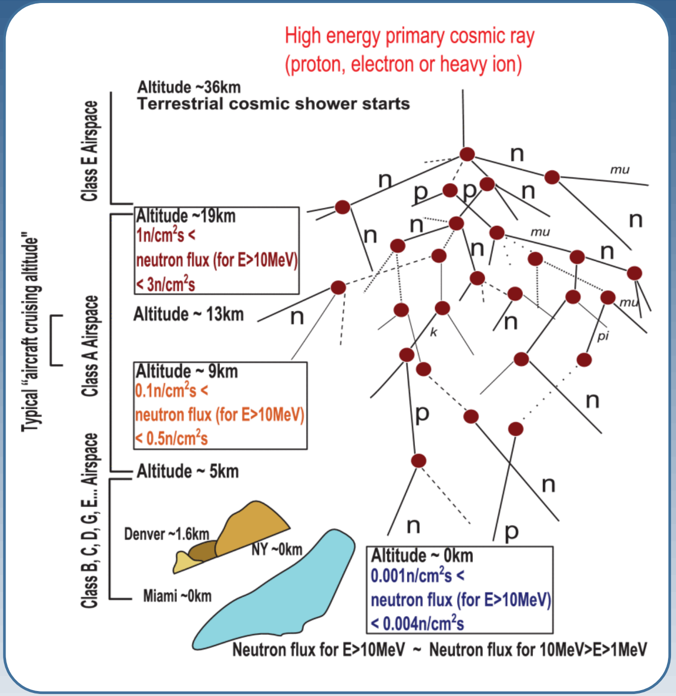


Fig. 3. Atmospheric secondary particle shower due to primary cosmic particle interaction.
Akturk *et al.* TNS, 2017

Single Event Effects: Definitions

Destructive damage caused to a device by a single energetic particle

JEDEC definitions:

- Single event burnout (SEB):
  An event in which a single energetic-particle strike induces a localized high-current state in a device that results in catastrophic failure
- Single event gate rupture (SEGR):
  An event in which a single energetic-particle strike results in a breakdown and subsequent conducting path through the gate oxide of a MOSFET

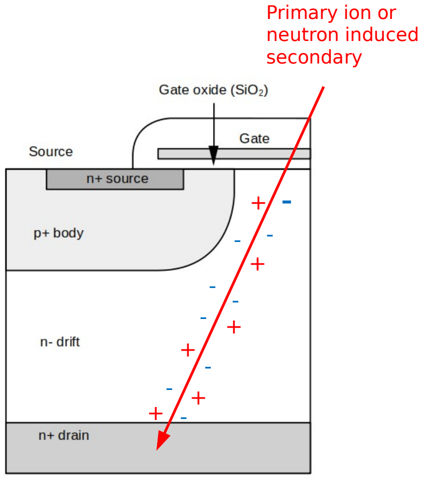


Fig. 4. Cross section representation of vertical MOSFET

From the occurrence point of view, SEB is the main concern to be considered

SEB mechanism in vertical power MOSFETs

Single event burnout is presented in following steps:

- Impacting energized particle deposits energy in the device volume. It results in charge generation (ionization) in the material along the track

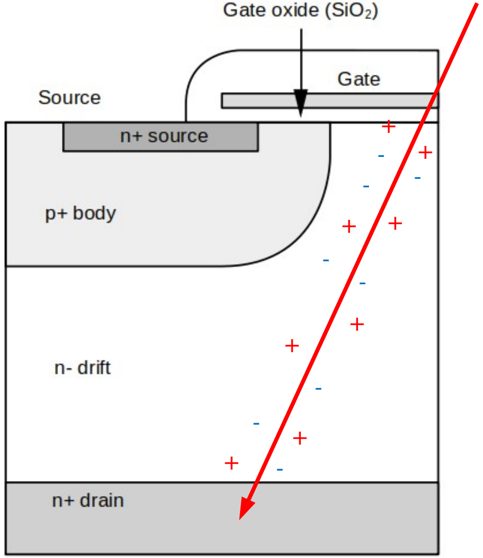


Fig. 5. Cross section representation of vertical MOSFET

Charge generation due to primary ion or neutron induced secondary

SEB mechanism in vertical power MOSFETs

Single event burnout is presented in following steps:

- Under applied electric field, electrons and holes are separated from each other and such charge transport can be observed as transient current

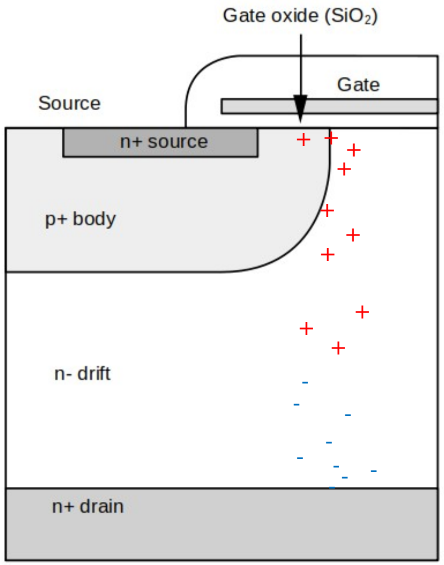


Fig. 6. Cross section representation of vertical MOSFET

Charge transport due to applied electric field

SEB mechanism in vertical power MOSFETs

Single event burnout is presented in following steps:

- If carriers reach sufficient energy, impact ionization will be initiated

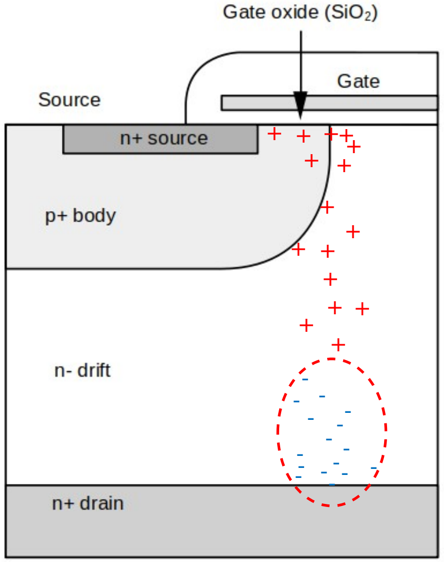


Fig. 7. Cross section representation of vertical MOSFET

Charge multiplication due to impact ionization

Impact ionization at the epi/substrate interface

SEB mechanism in vertical power MOSFETs

Single event burnout is presented in following steps:

- If the process sustains long enough, it result in thermal runaway resulting in melting of the semiconductor material

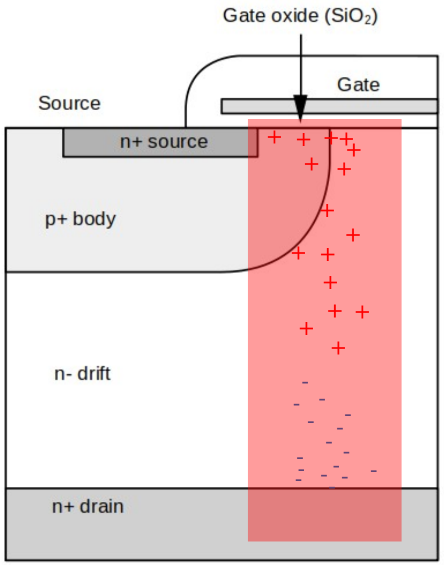


Fig. 8. Cross section representation of vertical MOSFET

Lattice melting due to thermal runaway

Part II: The experimental results and analysis

Experimental details and methodology

Experimental study outline

- Experimental setup for SEB testing
- Methodology for reliability assessment
- SiC Power MOSFET reliability under atmospheric environment
- Conclusion

Radiation environment

Neutron irradiations were performed in ChipIr facility, in Rutherford Appleton Laboratory, UK

- Atmospheric-like neutron spectrum
- Acceleration factor 10^9 compared to neutron flux at ground level
- Average flux 5×10^6 n cm^{-2} at the test position ($E_n > 10$ MeV)

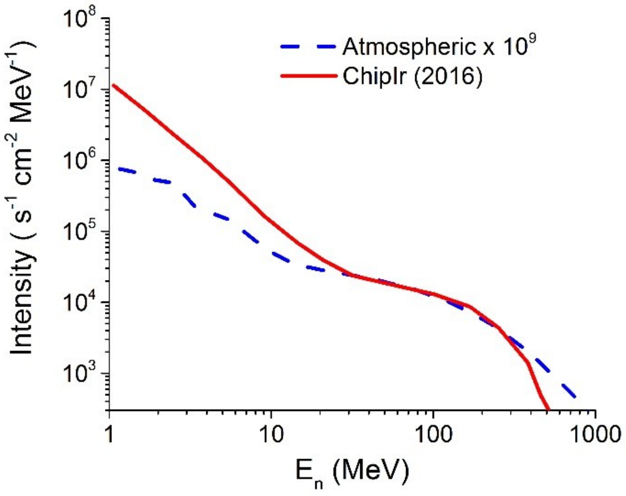


Fig. 9. Facility neutron spectrum compared with ground level flux

Due to stochastic nature of neutron-matter interaction, statistical test approach is needed

Single event burnout test setup

Test boards were developed allowing to test 32 devices in parallel

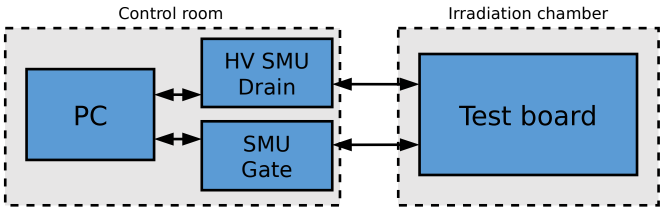

Control room
Irradiation chamber
PC
HV SMU Drain
SMU Gate
Test board

Fig. 10. Schematics of the irradiation test setup

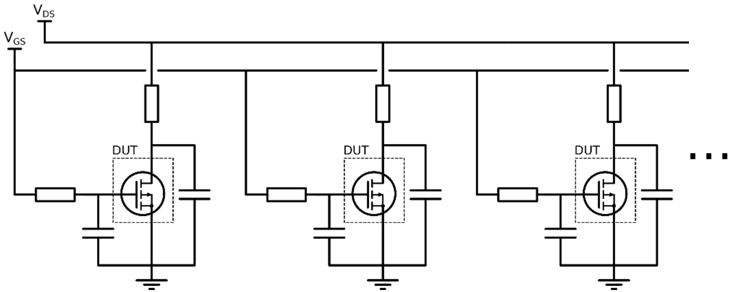


Fig. 11. Schematics of the irradiation test board

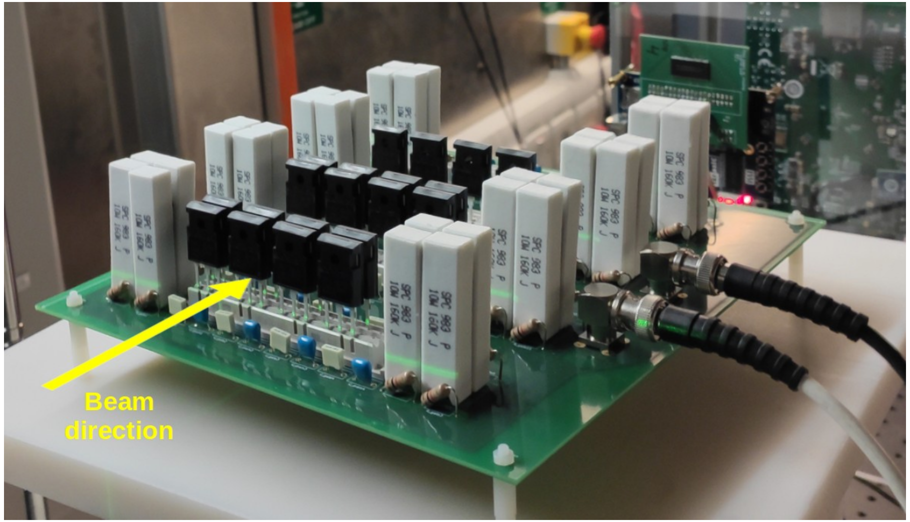


Fig. 12. Test board at the irradiation test position

Plotting of the failure points in Weibull scale

Each current step corresponds to a single device failure

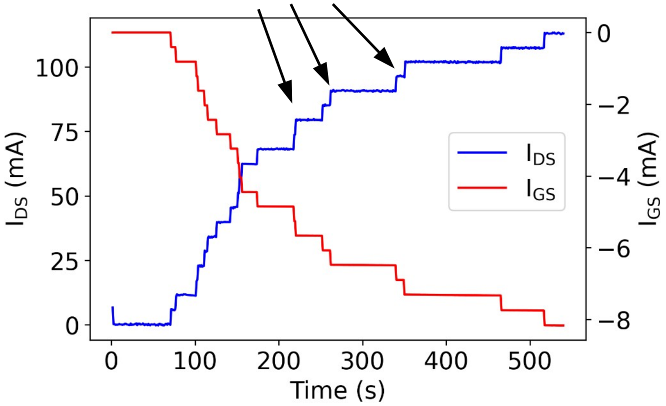


Fig. 13. Total current in the test board

Plot time of each current step as failure point

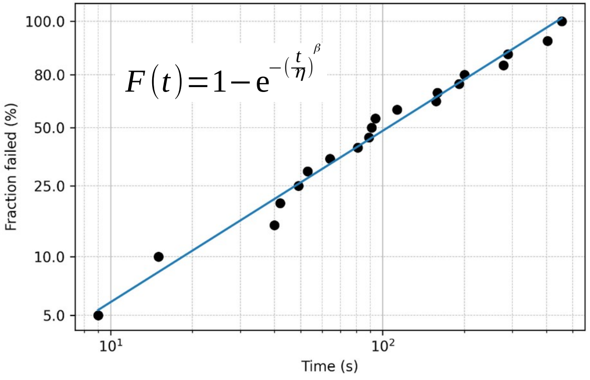


Fig. 14. Cumulative proportion of failed devices and fitted CDF

Fit Weibull cumulative distribution function (CDF) → Extract β and η

The η parameter is related to the mean value of the distribution

Decreasing failure rate with time: $\beta < 1$
Constant failure rate with time: $\beta = 1$
Increasing failure rate with time: $\beta > 1$

$\beta = 1$ is expected

Once the cumulative distribution of failed devices is plotted, β and η are extracted

Parameter extraction: Linear regression model

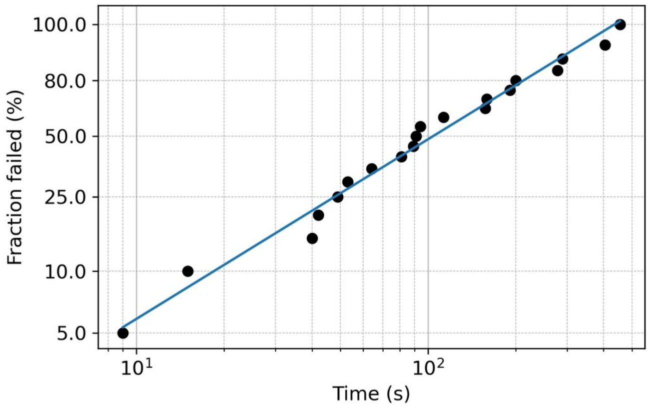
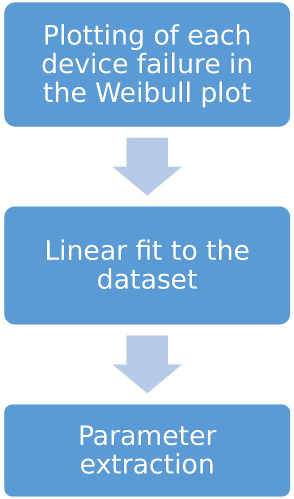


Fig. 15. Weibull plot of SEBs



Plotting of each device failure in the Weibull plot

Linear fit to the dataset

Parameter extraction

Weibull cumulative distribution function (CDF):

$$F(t) = 1 - e^{-\left(\frac{t}{\eta}\right)^{\beta}}$$

Linearization of CDF:

$$kx + c = \beta \ln(t) - \beta \ln(\eta)$$

$$\beta = \frac{k}{\ln(10)}$$

$$\eta = e^{-\left(\frac{c}{\beta}\right)}$$

Accuracy of this method will increase with fraction of failed devices. Domain of interest for extracting and with this method is when at least 65% of the devices are failed

Method for Failure In Time (FIT) calculation

Reliability of the device for the target application can be expressed with failure rate which unit is Failure In Time (FIT)

- 1 FIT corresponds to one device failure over 10^9 device hours
- Defined for application environment

Failure rate: $\lambda = \frac{10^9}{MTTF \times AF}$

where is Mean Time To Failure and $AF = \frac{Accelerator\ flux}{Atmospheric\ flux}$

From the extracted Weibull parameters $MTTF = \boxed{\eta \times \Gamma\left(1 + \frac{1}{\beta}\right)}$

Note: when $\beta = 1, MTTF = \eta$

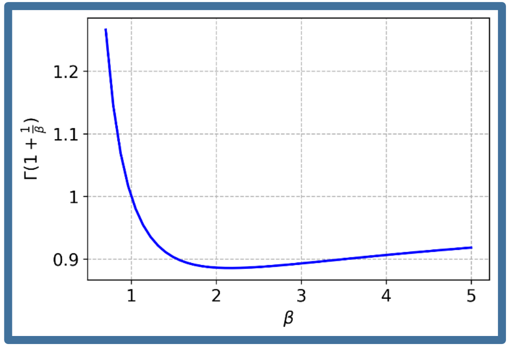
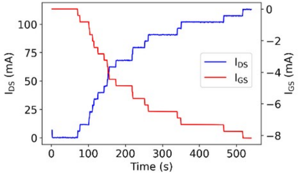
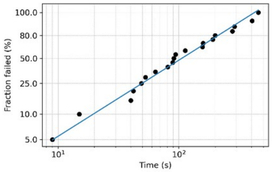


Fig. 17. Gamma function term as a function of beta

Failure In Time extraction summary

Extraction of failure times from irradiation experiments → Cumulative proportion of failed devices to Weibull plot → Extraction of β and η through LR or MLE → MTTF calculation → Calculate Failure In Time for specific application





Drain-to-source voltage dependence on SEB sensitivity and failure in time (FIT)

Drain-to-source voltage dependence on SEB failure rate is studied.

Device under test:
CREE Wolfspeed SiC MOSFET
Part number: C3M0120090D
$V_{DSmax} = 900$ V
$I_{DSmax} = 23$ A

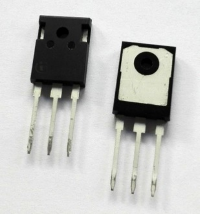


Fig. 18. Device under test

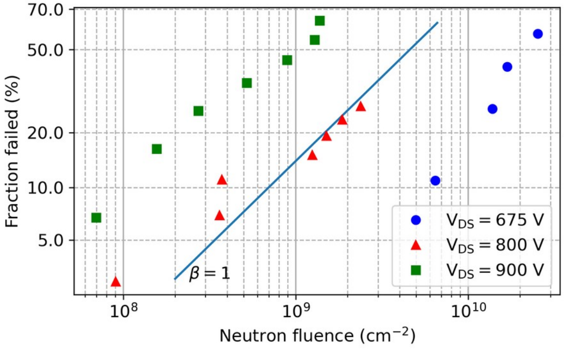


Fig. 19. Weibull plot of SEBs
Niskanen *et al.* NSREC2019, San Antonio, TX, USA

Devices were irradiated under atmospheric neutron spectrum with three V_{DS} configurations during irradiation

Average flux 5×10^6 n cm^{-2} at the test position ($E_n > 10$ MeV)

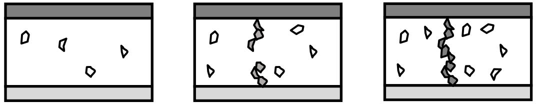
Table II: Weibull parameters for different irradiation V_{DS} configurations

V_{DS} (V)	β_{LR}	β_{MLE}	η_{LR} (cm^{-2})	η_{MLE} (cm^{-2})
675	1.52	2.07	2.73×10^{10}	2.47×10^{10}
800	0.72	0.91	1.17×10^{10}	7.83×10^{9}
900	0.84	1.04	1.43×10^{9}	1.24×10^{9}

Long term reliability assessment

Not all the devices exhibited SEB after neutron irradiation. Is the long-term reliability affected by the neutron irradiation?

Time Dependent Dielectric Breakdown (TDDB) based on constant voltage stress (CVS) is measured after irradiation in order to reveal possible degradation of gate oxide due to the neutron-induced non-destructive current transients.



Fresh oxide (some defects)

Localized defect generation due to radiation impact

Conducting path between electrodes formed during CVS

Fig. 25. Phenomenological representation of accumulated defects in the oxide

Constant voltage stress:

$V_{DS} = 0$ V, $V_{GS} = 37$ V

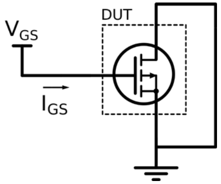
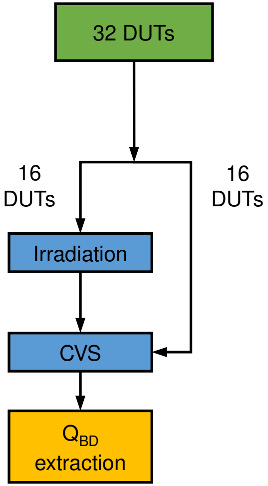


Fig. 26. CVS circuit



32 DUTs

16 DUTs

16 DUTs

Irradiation

CVS

Q_{BD} extraction

Devices were stressed until breakdown and charge-to-breakdown (Q_{BD}) was extracted

Long term reliability assessment

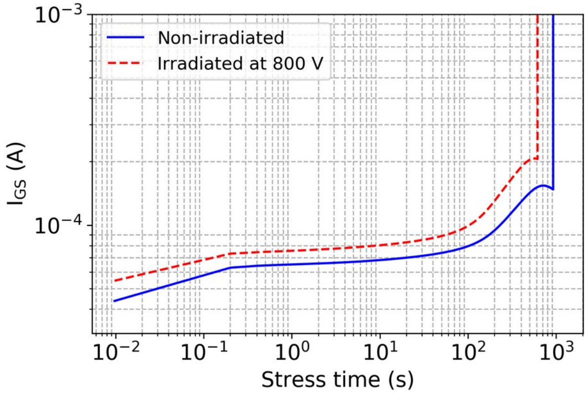
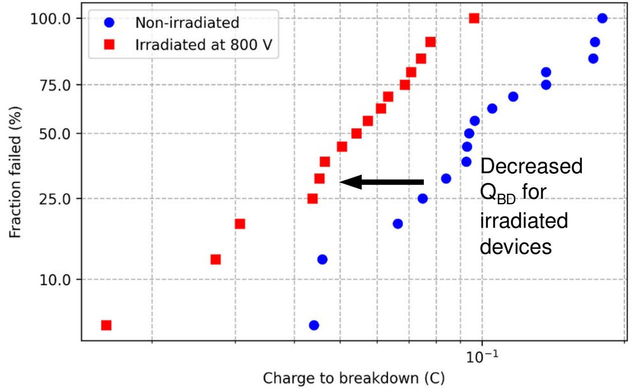


Fig. 27. Gate current during CVS for one fresh and one irradiated device

Integrate current over time



Decreased Q_{BD} for irradiated devices

Fig. 28. Weibull plot of charge-to-breakdown

After neutron irradiation, unfailed devices exhibit 50 % decrease in charge-to-breakdown

TCAD simulation of gate damage

Weakening of the gate oxide for irradiated devices is simulated with TCAD in order to address the physical mechanisms responsible to degradation.

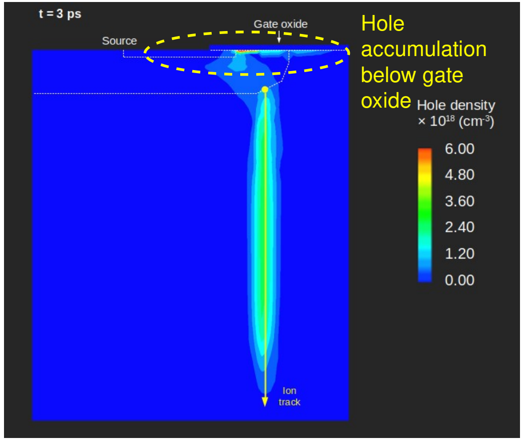


Fig. 29. Hole density during the ion interaction
Niskanen et al. IEEE TNS 2021

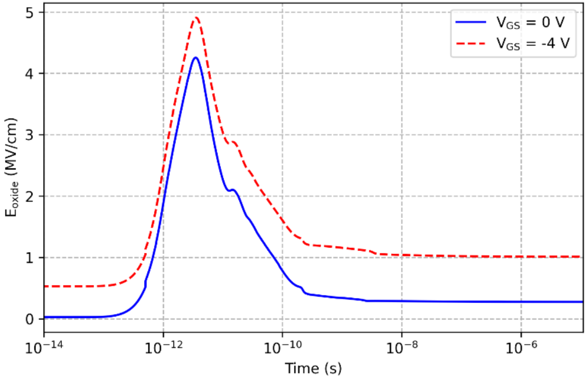
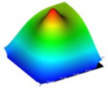


Fig. 30. Electric field evolution in the oxide during ion interaction for two gate voltage configurations
Niskanen et al. IEEE TNS 2021

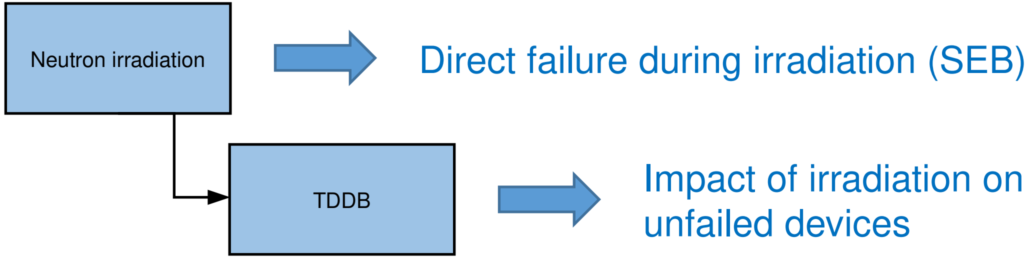


ECORCE
TCAD modeling tool

The hole accumulation under gate region might cause a localized stress in oxide layer. Latent defect generation might be enhanced in operation mode.

Mutual effects towards aging effects on radiation sensitivity

So far, I have studied radiation effects from risk of failure and long term reliability point of view



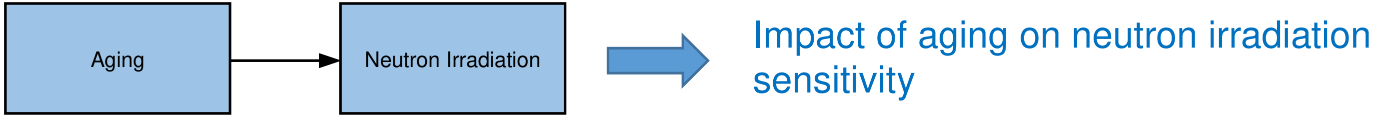
Neutron irradiation

Direct failure during irradiation (SEB)

TDDB

Impact of irradiation on lifetime of unfailed devices

Next step in the study is to show, how aging affects the radiation sensitivity of the device



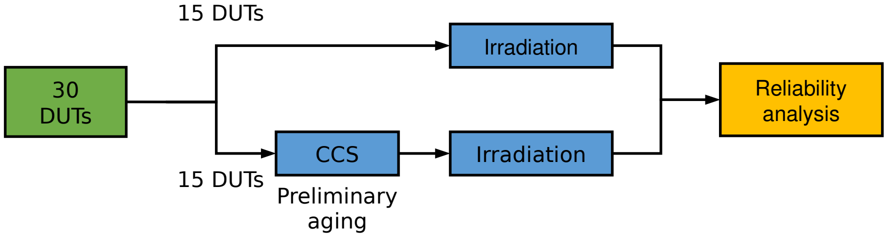
Aging

Neutron Irradiation

Impact of aging on neutron irradiation sensitivity

The effect of aging on SEB sensitivity of SiC MOSFET

In this study, the impact of preliminary electrical stress on neutron induced SEB sensitivity is evaluated. The SEB failure induced by atmospheric neutrons has been compared between fresh irradiated and preliminary stressed devices.



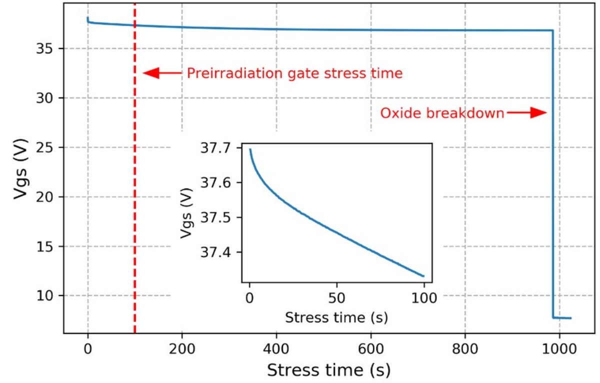


Fig. 31. Constant current stress waveform

Niskanen et al. IEEE TNS 2020

Constant current stress (CCS) applied on the gate terminal while V_{DS} = 0 V in order to induce defect clusters in the gate oxide layer and oxide/SiC interface before the irradiation experiment

The effect of aging on SEB sensitivity of SiC MOSFET

Applying the Weibull analysis for both failure sets

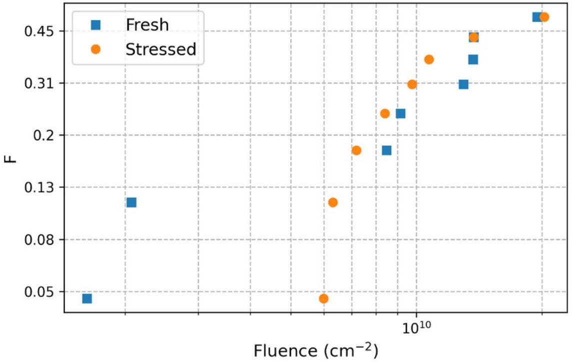


Fig. 32. Cumulative proportion of SEB failures for fresh and preliminary stressed devices
Niskanen et al. IEEE TNS 2020

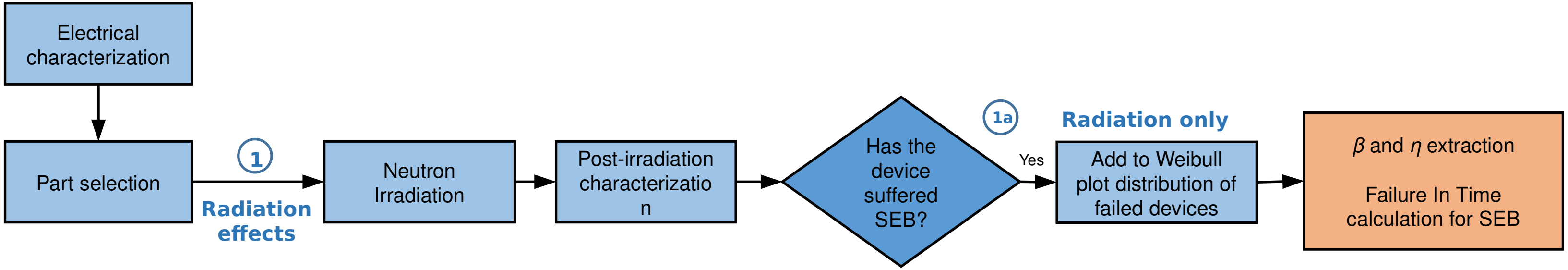
Devices were irradiated at V_{DS} = 675 V (75 % of the V_{DSmax}) while V_{GS} = 0 V

15 devices in each configuration were irradiated.

Stopping fluence: 2×10^{10} n cm^{-2}

2-parameter Weibull fit for stressed devices cannot be performed since the behaviour is not linear.

Methodology synthesis



Electrical characterization

Part selection

① Radiation effects

Neutron Irradiation

Post-irradiation characterization

Has the device suffered SEB?

Yes

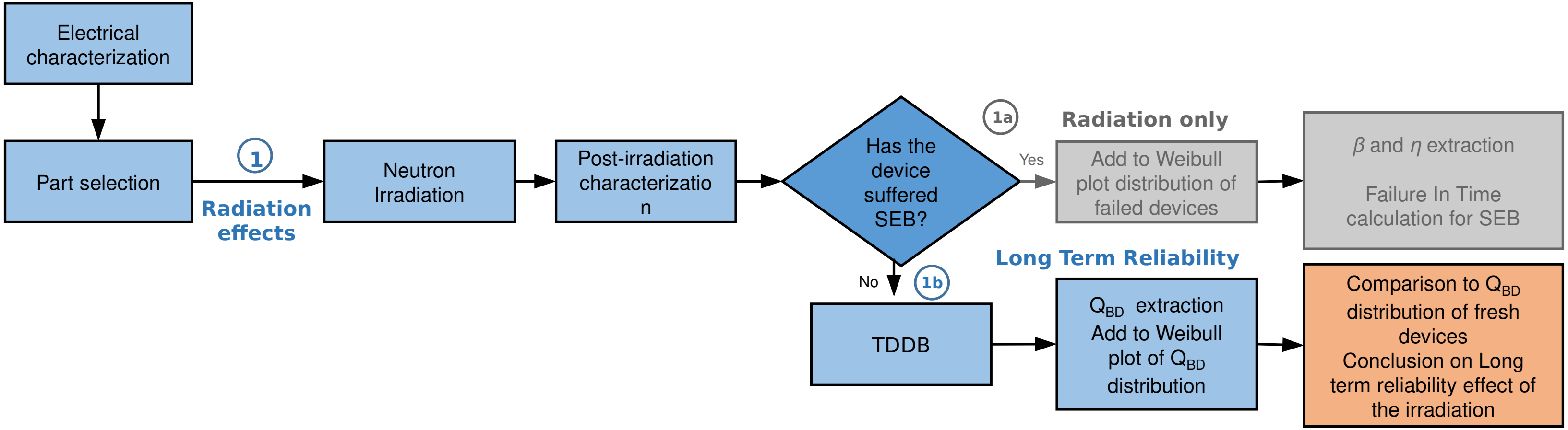
1a Radiation only

Add to Weibull plot distribution of failed devices

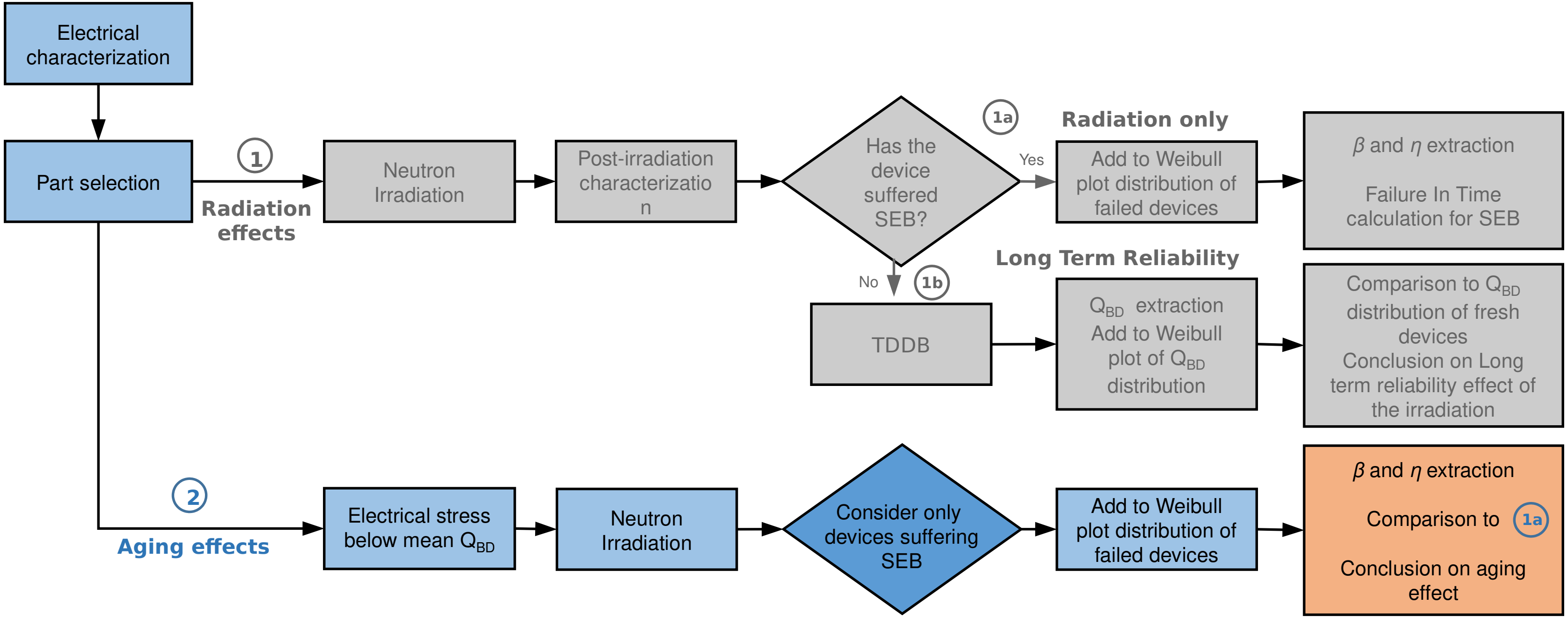
β and η extraction

Failure In Time calculation for SEB

Methodology synthesis



Methodology synthesis



Electrical characterization

Part selection

① **Radiation effects**

Neutron Irradiation

Post-irradiation characterization

Has the device suffered SEB?

Yes

1a **Radiation only**

Add to Weibull plot distribution of failed devices

β and *η* extraction

Failure In Time calculation for SEB

No

1b **Long Term Reliability**

TDDB

Q_{BD} extraction
Add to Weibull plot of Q_{BD} distribution

Comparison to Q_{BD} distribution of fresh devices
Conclusion on Long term reliability effect of the irradiation

② **Aging effects**

Electrical stress below mean Q_{BD}

Neutron Irradiation

Consider only devices suffering SEB

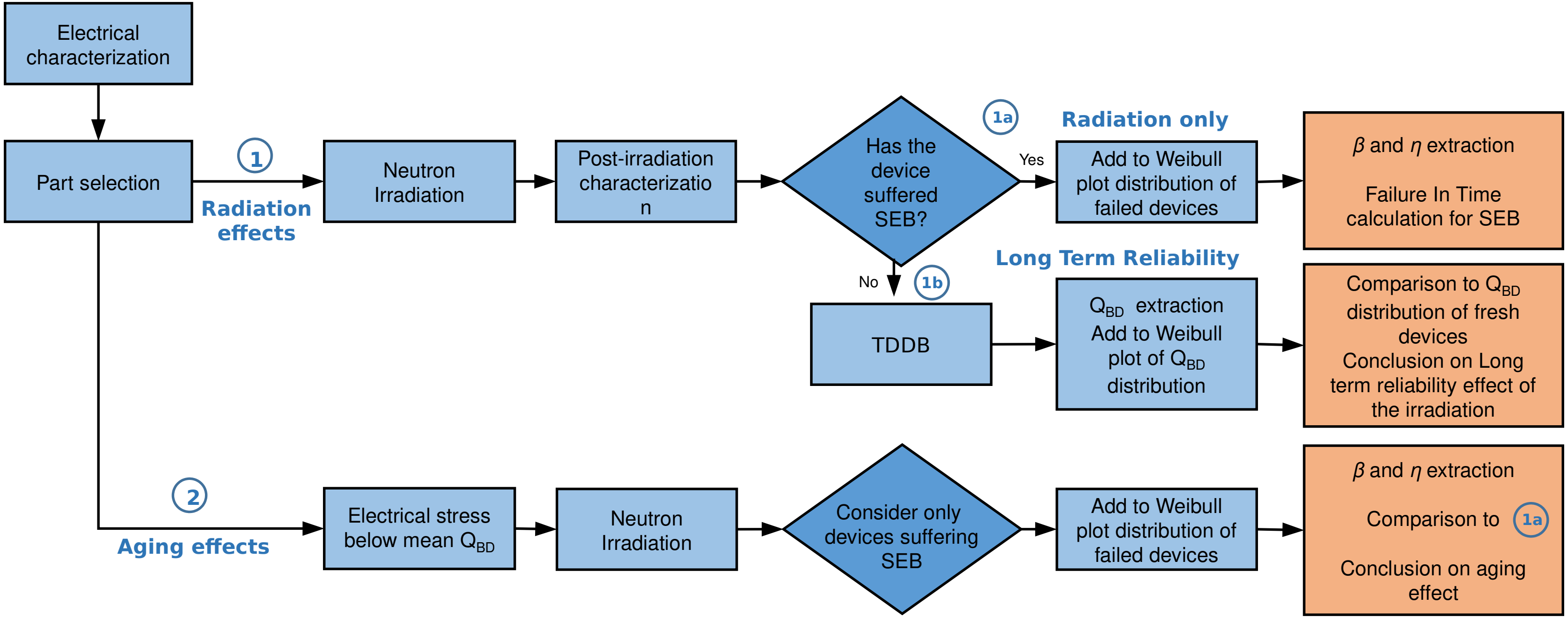
Add to Weibull plot distribution of failed devices

β and *η* extraction

Comparison to 1a

Conclusion on aging effect

Methodology synthesis



Electrical characterization

Part selection

① Radiation effects

Neutron Irradiation

Post-irradiation characterization

Has the device suffered SEB?

Yes ⓵ⓐ Radiation only

Add to Weibull plot distribution of failed devices

β and η extraction

Failure In Time calculation for SEB

No ⓵ⓑ Long Term Reliability

TDDB

Q_{BD} extraction
Add to Weibull plot of Q_{BD} distribution

Comparison to Q_{BD} distribution of fresh devices
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② Aging effects

Electrical stress below mean Q_{BD}

Neutron Irradiation

Consider only devices suffering SEB

Add to Weibull plot distribution of failed devices

β and η extraction

Comparison to 1a

Conclusion on aging effect

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Conclusions

Conclusions

- A methodology for SiC power MOSFET reliability testing under atmospheric neutron spectrum is proposed based on the Weibull statistics
- A method for long term reliability assessment was reported
- Radiation sensitivity of aged devices was evaluated and methodology was presented
- Coupled aging and radiation effects have been observed for the first time and experimental results were supported by TCAD simulations

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Thank you for your attention

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