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APS
Advanced Power Semiconductor Laboratory

Investigation of Fundamental Mechanisms of Single Event Effects with Heavy-Ion Microbeam Testing

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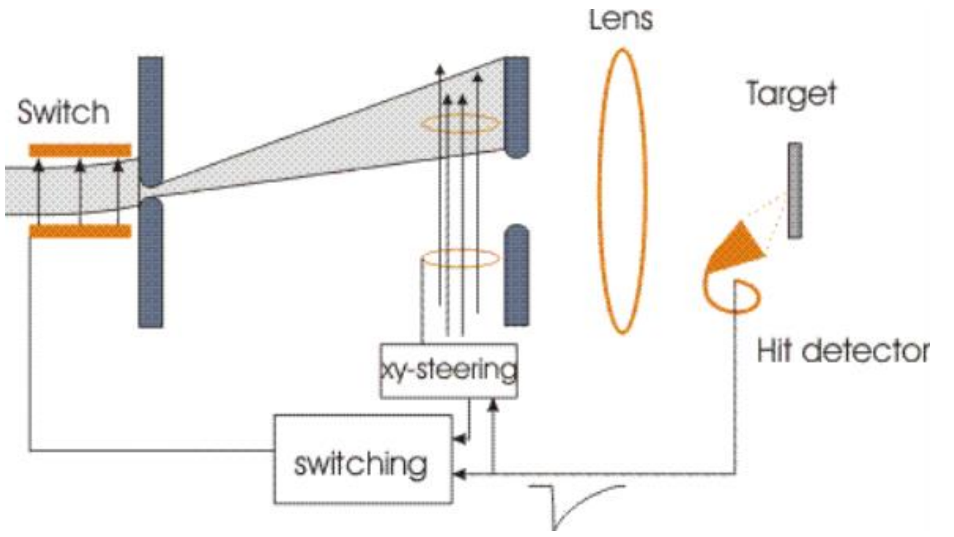
Heavy-ion microbeam facility

Microbeam testing:

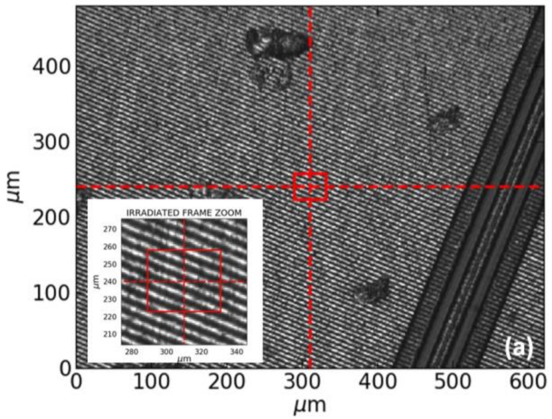
- Precise identification of **radiation-sensitive regions** in electronic components. Important information for the understanding of the **basic mechanisms of single event effects** (SEEs).
- The beam is magnetically focused to a **spot size < 1 μm** and scanned over the region of interest selected using an optical microscope.
- A channel electron multiplier discriminates the **single hits** detecting the secondary electrons emitted by the materials.
- Spatial location of charge collection (maps), prompt charge collection (fast transient systems), SEEs (SEU, SET, SEB, etc.), defects analysis.



After GSI webpage

Design the experiment:

- Size of the frame to irradiate
- Total amount of ions and distance in x-y directions
- Beam rate



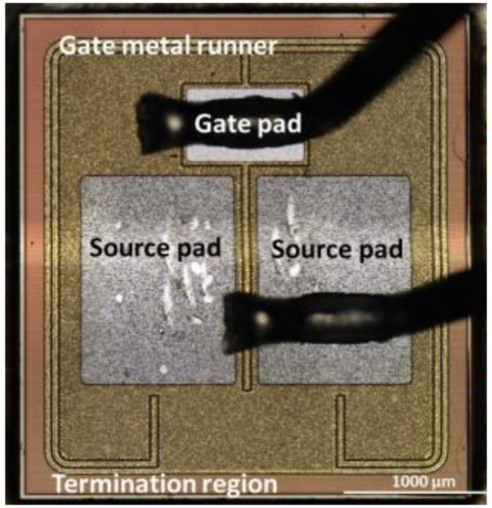
A. Javanainen, “SEE testing with broad and focused particle beams” NSREC 2019 Short Course,” University of Jyväskylä, Finland, Tech. Rep., 2019.

F. W. Sexton, "Microbeam studies of single-event effects," in *IEEE Trans. Nucl. Sci.*, vol. 43, no. 2, pp. 687-695, Apr. 1996.

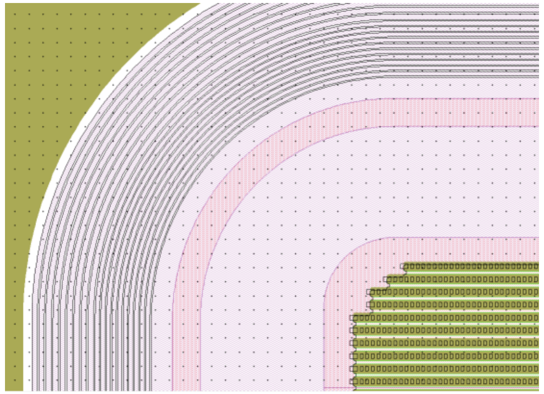
G.J.F. Legge, “A history of ion microbeams,” Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, Vol.130, n. 1–4, pp. 9-19, 1997.

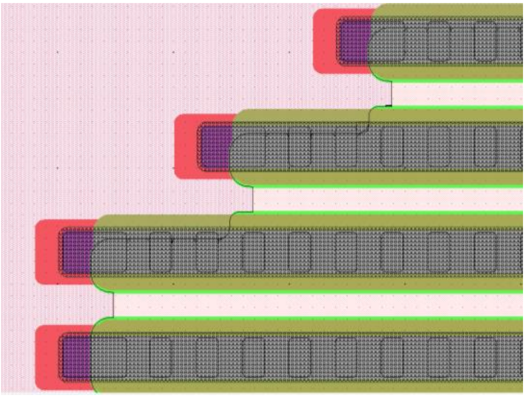
Advantages of microbeam testing

Precise identification of
radiation-sensitive regions
in the electronic device.

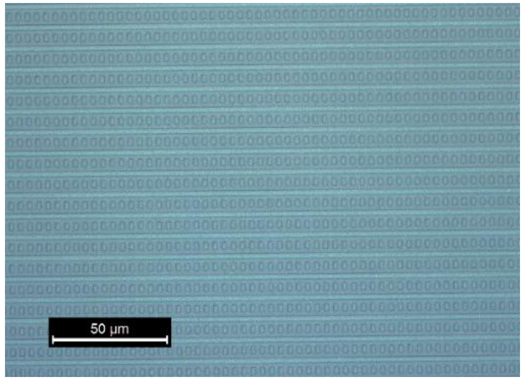


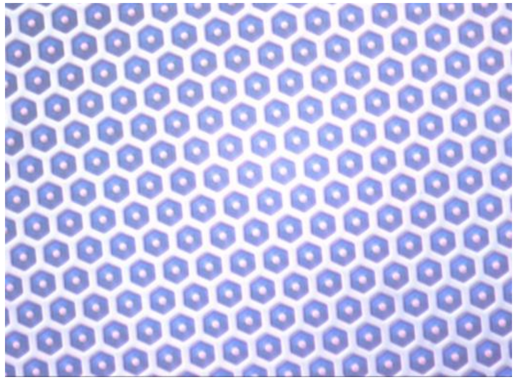
Termination region



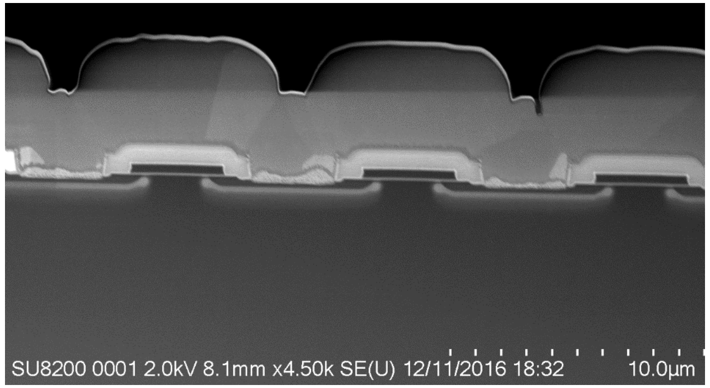


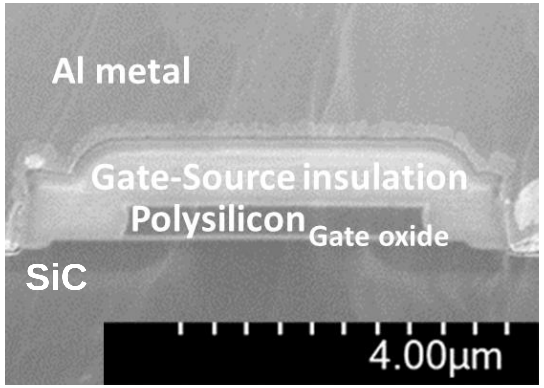
Gate structure





Unit cell layout





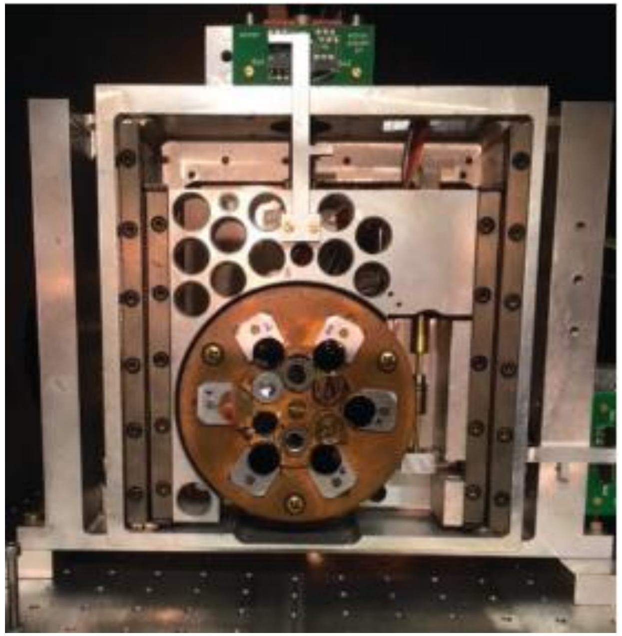
“Power Semiconductor” Lectures, Spring semester 2023, ETH course catalogue 227-0156-00L.

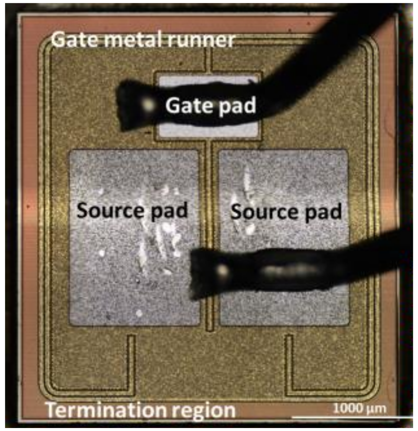
GSI UNILAC microbeam facility

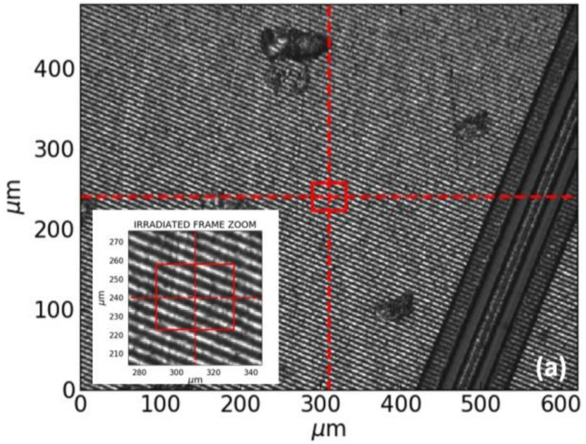
Contact Scientist at GSI:
Dr Kay Obbe Voss

GSI UNILAC facility, Darmstadt, Germany

- **Beam energy:** ~5 MeV/amu
- **Spot size FWHM:** ~0.5 µm
- **Area:** 500 µm × 500 µm / 200 µm × 200 µm
- **Distance between ions:** 1 – 500 µm
- **Beam rate:** few Hz - tens of Hz
- **Fluence and x-y coordinates** of the beam
- **Test in vacuum**



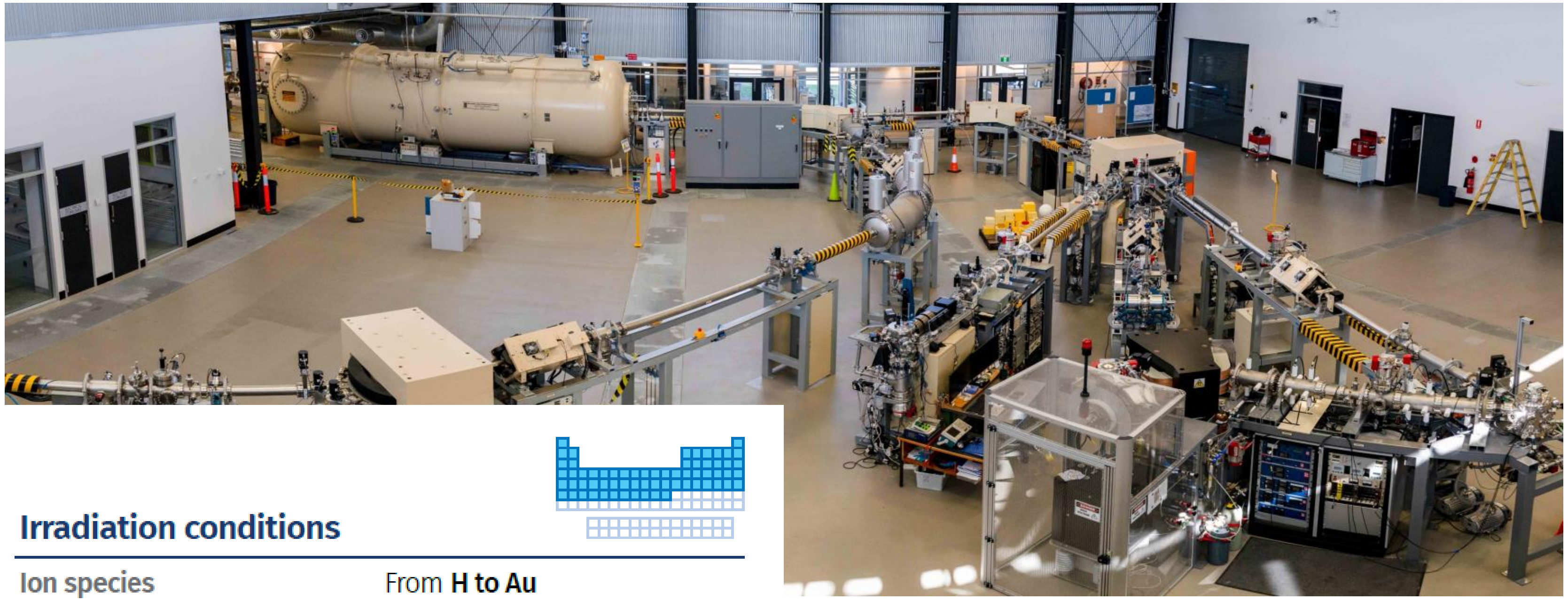




K O Voss et al 2008 New J. Phys. 10 075011.

A. Javanainen, "SEE testing with broad and focused particle beams" NSREC 2019 Short Course," University of Jyväskylä, Finland, Tech. Rep., 2019.

ANSTO microbeam facility



Z. Pastuovic *et al.*, "SIRIUS – A new 6 MV accelerator system for IBA and AMS at ANSTO", Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, Vol. 371, Pages 142-147, Mar. 2016.

Irradiation conditions

Ion species	From **H to Au**
Energies H	Up to **15 (20)** MeV
Energies Heavy ions	Up to **120** MeV
Beam Current	**pA to µA**
Single ion regime	**100 – 1000** particle/s
Flux	10^4 – 10^9 particles/cm^2.s
Fluence	10^4 – 10^{15} particles/cm^2
Beam spot in vacuum	**0.5 – 1** µm
Beam spot in air	**10** µm
Beam scan area	**100** µm^2 – **12** mm^2
Stage scan area	Up to **50 x 50** mm^2

ANSTO facility, Sydney, Australia

- Two linear accelerators: 6 and 10 MV
- Two Heavy ion Nuclear Microprobe beamlines for SEEs testing
- Access:
  - Free Merit Access
  - Commercial Rapid and Proprietary
  - Collaborative

Microbeam for SEEs studies - I

Charge collection in Silicon Super-junction-power MOSFETs

- Three-dimensional maps of charge collection in Si SJ-MOS obtained with focused beams of different species, LETs, and ranges.

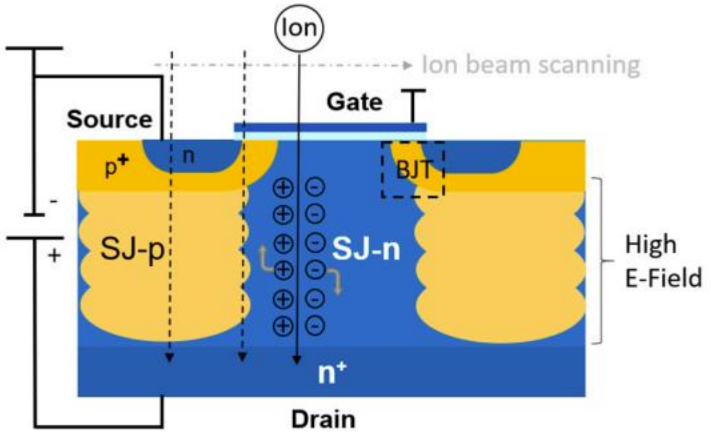


Fig. 3. Cross-sectional view of SEE Ion mapping of a SJ-MOS with multiple locations, charge injection, -collection and areas of interest (drift region: SJ-n channel, SJ-p channel, BJT region).

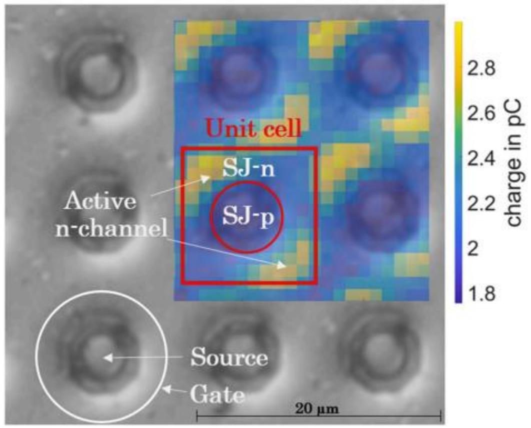


Fig. 24. Superposed charge collection map for a 55 MeV Carbon mapping at 400 V on a microscope picture of frontside demetallized MOSFET with indication of the internal doping layout.

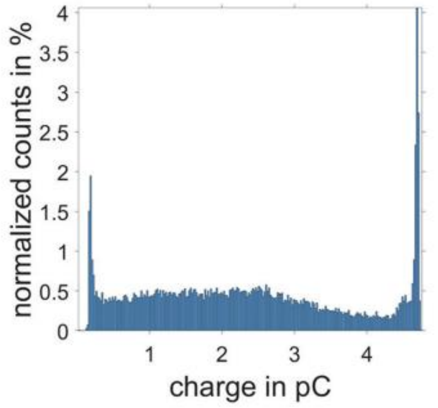


Fig. 17. Charge spectrum of SJ-MOS at 400 V, 55 MeV C, ion range 13 μm.

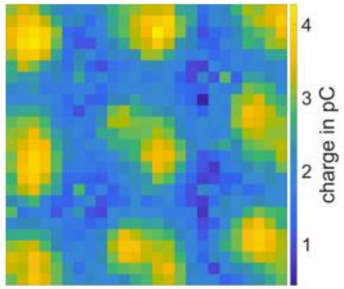


Fig. 18. 25 × 25 μm charge collection map of SJ-MOS at 400 V, 55 MeV C, ion range 13 μm.

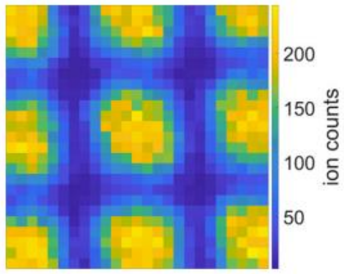


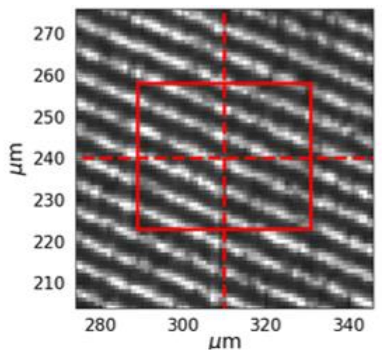
Fig. 19. 25 × 25 μm detected event count map of SJ-MOS at 400 V, 55 MeV C, ion range 13 μm.

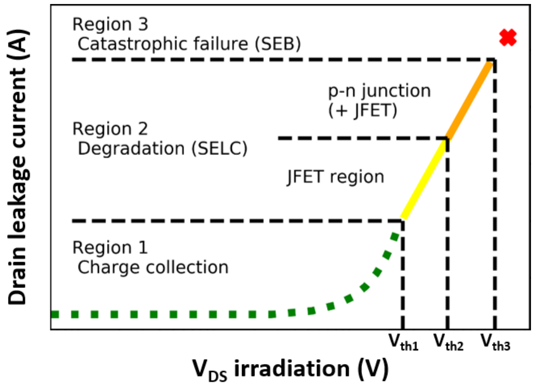
M. Gerold *et al.*, "Sensitivity study of super-junction power MOSFETs by spatial and depth resolved heavy ion SEE mapping with various bias, LETs and ion ranges," *Microelectr. Reliab.*, Vol. 155, art. no. 115309, 2024.

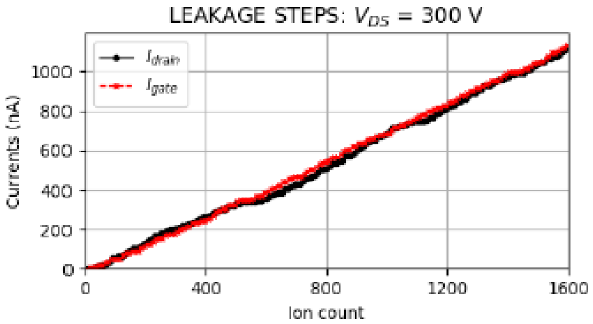
Microbeam for SEEs studies - II

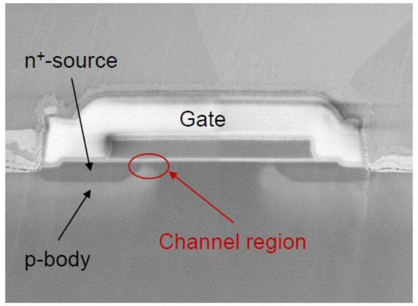
Spatial sensitivity of Single Event Leakage Current (SELC) in SiC power MOSFETs

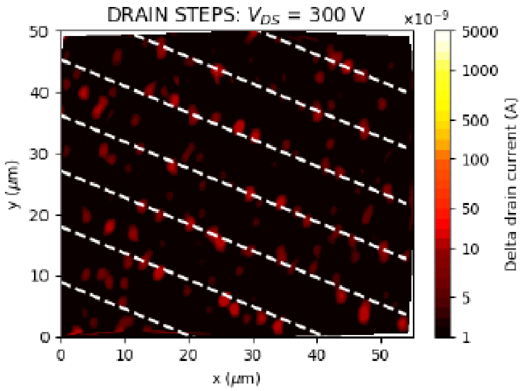
- Ion-induced steps in the gate and drain leakage currents were analyzed as a function of the x–y coordinate within the scanned frame (945 MeV Au).
- Spatial periodicity of SELC, reflecting the striped structure of the power MOSFET investigated.
- Two different SELC mechanisms:
  - low drain-source bias in the gate-oxide region;
  - higher bias in the p-n junction region.

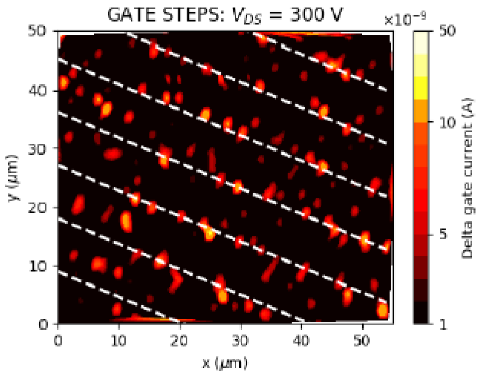










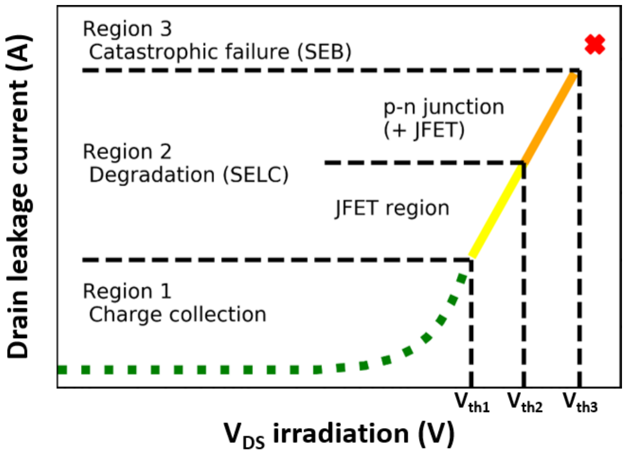


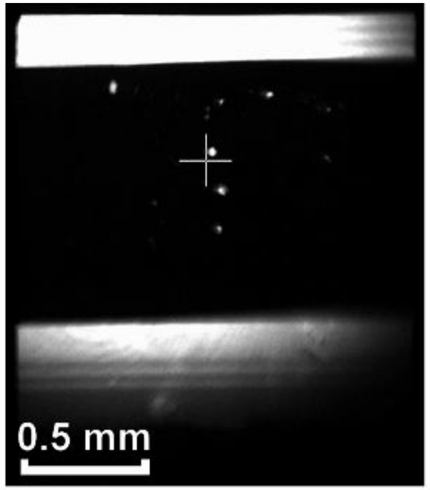
C. Martinella *et al.*, "Heavy-Ion Microbeam Studies of Single-Event Leakage Current Mechanism in SiC VD-MOSFETs," in *IEEE Trans. on Nucl. Sci.*, vol. 67, no. 7, pp. 1381-1389, July 2020.

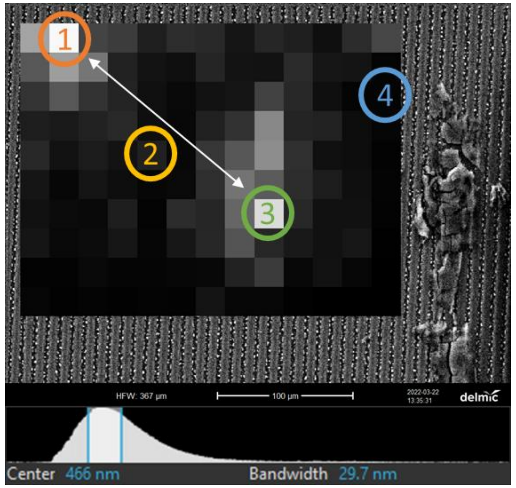
Microbeam for SEEs studies - III

Analysis of defects associated with SEEs in SiC power MOSFETs

- Investigation of defects related to SEEs:
  - Photoluminescence (PL) spectroscopy
  - Chatodoluminescence (CL) spectroscopy
  - Deep-level transient spectroscopy (DLTS)
  - Raman spectroscopy
  - X-ray topography (XRT)







C. Martinella *et al.*, “Photoluminescence analysis of heavy-ion-degraded SiC power MOSFETs”. presented at ICSCRM 2023, Sorrento, Italy.

C. Martinella *et al.*, “Heavy-Ion-Induced Defects in Degraded SiC Power MOSFETs,” MSF 2023;1090:179–84.

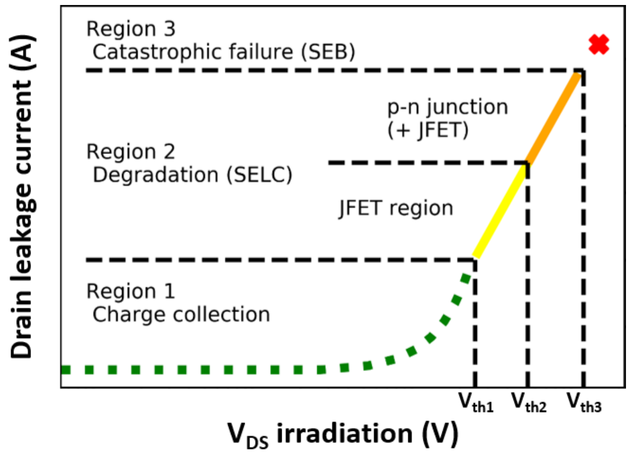
N. Für, M. Belanche, *et al.*, , "Investigation of Electrically Active Defects in SiC Power Diodes Caused by Heavy Ion Irradiation," in *IEEE Trans. Nucl. Sci.*, vol. 70, no. 8, pp. 1892-1899, Aug. 2023.

Microbeam for SEEs studies - IV

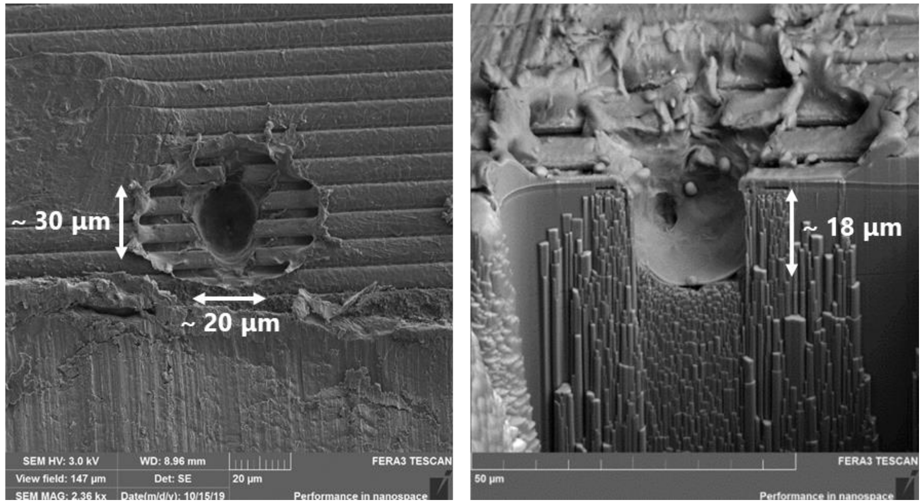
Failure analysis in SiC power MOSFETs – SEB, SEGR, post-irradiation failure

- Failure analysis:
  - Scanning electron microscopy (SEM)
  - Transmission electron microscopy (TEM)

C. Martinella *et al.*, “Heavy-ion induced single event effects and latent damages in SiC power MOSFETs,” *Microelectron. Reliab.*, vol. 128, art. no. 114423, 2022.



FIB-SEM analysis of a failed SiC power MOSFETs (ScopeM, ETH Zurich)



Microbeam for SEEs studies – Additional literature

- J. A. Pellish *et al.*, "Heavy Ion Microbeam- and Broadbeam-Induced Transients in SiGe HBTs," in in *IEEE Trans. Nucl. Sci.*, vol. 56, no. 6, pp. 3078-3084, Dec. 2009.
- H. Toshio *et al., "*Studies on single-event phenomena using the heavy-ion microbeam at JAERI," Nuclear Instruments and Methods in Physics Research Section B: Beam Interactions with Materials and Atoms, Volume 210, pp. 227-231, 2003.
- A. Evans *et al.*, "Heavy-Ion Micro Beam and Simulation Study of a Flash-Based FPGA Microcontroller Implementation," in *IEEE Trans. Nucl. Sci.*, vol. 64, no. 1, pp. 504-511, Jan. 2017.
- H. Li, *et al.*, "Heavy-Ion Microbeam Fault Injection into SRAM-Based FPGA Implementations of Cryptographic Circuits," in *IEEE Trans. Nucl. Sci.*, vol. 62, no. 3, pp. 1341-1348, Jun. 2015.
- H. Sun *et al*., "Study on Single Event Upsets in a 28 nm Technology Static Random Access Memory Device Based on Micro-Beam Irradiation'" *Electronics* **2022**, vol. *11*, no. 20, art. no. 3413, 2022.
- W. Yang *et al*., "Single-event-effect propagation investigation on nanoscale system on chip by applying heavy-ion microbeam and event tree analysis," NUCL SCI TECH 32, 106 (2021).
- W. Yang *et al*., "Microbeam Heavy-Ion Single-Event Effect on Xilinx 28-nm System on Chip," in *IEEE Trans. Nucl. Sci.*, vol. 65, no. 1, pp. 545-549, Jan. 2018.

Microbeam facilities

Available microbeam facilities:

- RADNEXT webpage: https://radnext.web.cern.ch/ (accessed June 10, 2024).
- A. Javanainen, “SEE testing with broad and focused particle beams” NSREC 2019 Short Course,” University of Jyväskylä, Finland, Tech. Rep., 2019.
- CERN, CERN Facilities DB, (n.d.). https://irradiation-facilities.web.cern.ch/ (accessed June 10, 2024).
- S. Martin Barbero, S.K. Höffgen, G. Berger, H. Guerrero, A. Koziukov, I. Tuzhikova, J. Pellish, P. Chubunov, P. Paillet, R. Ecoffet, V. Anashin, Compendium of International Irradiation Test Facilities, Moscow, 2015

Conclusions

- The ability to map regions sensitive to heavy-ion strikes makes the microbeam technique a valuable tool in the study of single event effects, providing important information for the understanding of the basic mechanisms not accessible with broad-beam testing.
- Microbeam testing allows spatial analysis of charge collection, prompt charge collection, SEEs (SEU, SET, SEB, SELC, etc.), and localized damage for defect spectroscopy, and failure analysis.
- Designing the experiment involves the choice of ion species and energy, dimensions of the irradiated frame, total amount of ions, distance among the ion-hits, frequency of irradiation. These parameters should be adjusted based on the technology under test to enable the best resolution.
- Further studies are needed to compare results from experiments with the broad-beam and microbeam.

Acknowledgements

U. Grossner
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Thanks for your attention!

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